MAPPING IN-FIELD COTTON FIBER QUALITY AND RELATING IT TO SOIL MOISTURE

A Dissertation

by

YUFENG GE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2007

Major Subject: Biological and Agricultural Engineering

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Approved by:

Chair of Committee,	J. Alex Thomasson
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ABSTRACT

Mapping In-field Cotton Fiber Quality and
Relating It to Soil Moisture. (August 2007)
Yufeng Ge, B.S., Nanjing Forestry University;
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Chair of Advisory Committee: Dr. J. Alex Thomasson

The overarching goal of this dissertation project was to address several fundamental aspects of applying site-specific crop management for fiber quality in cotton production.

A two-year (2005 and 2006) field study was conducted at the IMPACT Center, a portion of the Texas A&M Research farm near College Station, Texas, to explore the spatial variability of cotton fiber quality and quantify its relationship with in-season soil moisture content. Cotton samples and *in-situ* soil moisture measurements were taken from the sampling locations in both irrigated and dry areas. It was found that generally low variability ($CV < 10\%$) existed for all of the HVI (High Volume Instrument) fiber parameters under investigation. However, an appreciable level of spatial dependence among fiber parameters was discovered. Contour maps for individual fiber parameters in 2006 exhibited a similar spatial pattern to the soil electrical conductivity map. Significant correlations (highest $r = 0.85$) were found between most fiber parameters (except for micronaire) and in-season soil moisture in the irrigated areas in 2005 and in the dry area in 2006. In both situations, soil moisture late in the season showed higher correlation with fiber parameters than that in the early-season. While this relationship did not hold for micronaire, a non-linear relationship was apparent for micronaire in 2006. This can be attributed to the boll retention pattern of cotton plants at different soil moisture levels.

In addition, a prototype wireless- and GPS-based system was fabricated and developed for automated module-level fiber quality mapping. The system is composed of several subsystems distributed among harvest vehicles, and the main components of the system include a GPS receiver, wireless transceivers, and microcontrollers. Software was developed in C language to achieve GPS signal receiving, wireless communication, and other auxiliary functions. The system was capable of delineating the geographic boundary of each harvested basket and tracking it from the harvester basket to the boll buggy and the module builder. When fiber quality data are available at gins or classing offices, they can be associated with those geographic boundaries to realize fiber quality mapping. Field tests indicated that the prototype system performed as designed. The resultant fiber quality maps can be used to readily differentiate some HVI fiber parameters (micronaire, color, and loan value) at the module level, indicating the competence of the system for fiber quality mapping and its potential for site-specific fiber quality management. Future improvements needed to make system suitable for a full-scale farming operation are suggested.

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CHAPTER I

INTRODUCTION

Cotton is the world's most important fiber crop and the second most important oil seed crop. It has been utilized for thousands of years for clothing people all around the world. The primary economic product of the cotton plant is the lint (or bulk fiber), which provides a source of high quality fibers for the textile industry. Cotton seeds, the major byproduct of lint production, are an important source of oil for human consumption, and a high protein meal used as livestock feed. The waste after ginning is used for fertilizer and is a potential energy source, and the cellulose from the stalk can be used for products such as paper and cardboard.

Worldwide, cotton is planted on over 35 million ha, and the total production in 2005 was 120 million bales [around 500 lb or 218 kg per bale; USDA – FAS (Foreign Agricultural Service), 2005]. The five largest cotton producers are China (with an estimate of 29 million bales in 2005), the United States (23 million bales), India (19 million bales), Pakistan (11 million bales), and Brazil (6 million bales). Cotton is planted in the 17 states of the cotton belt in the U.S., stretching from Virginia to California. Approximately 30 thousand farms and more than 5.5 million ha of land are involved in U.S. cotton production [NCC (National Cotton Council of America), 2005]. The cotton industry has great influence upon the U.S. economy, creating more than 443 thousand

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jobs and a total business revenue estimated at 40 billion dollars. The consumers of raw cotton fibers are textile mills that process fibers into yarn and thread. These intermediate products are then consumed downstream in producing hundreds of items including wearing apparel, home furnishings (such as draperies, upholstery fabrics, towels, and rugs), and industrial use products (Koplan et al., 2001).

COTTON FIBER QUALITY AND ITS IMPORTANCE

From a textile processing point of view, fiber quality is very important because many fiber properties are strongly correlated with the properties of finished yarns and fabrics and the ease with which these finished products are manufactured. For example, the strength of fibers largely determines the strength of yarns, while the maturity of fibers determines the dye uptake property of fabrics. Raw cotton with unfavorable fiber quality causes problems (such as excessive yarn breaks) in the textile mill, and sometimes the problems are so severe that equipment must be brought to a complete halt. Due to the importance of raw cotton fiber quality to the textile industry, the USDA – AMS (Agricultural Marketing Service) requires that all cotton bales in the government loan program be classed before entering the trading market; and the loan value of a bale of cotton is determined by its bulk fiber quality. Thus, samples are pulled from each bale and sent to a classing office for analysis.

Cotton Fiber Quality Parameters and Quantification Methods

The HVI (High Volume Instrument) system in USDA – AMS classing offices employs standard bulk fiber quality quantification methods, and it is used by both cotton growers and textile processors for cotton pricing and marketing. The HVI system reports a series of fiber quality parameters according to which bale premiums and discounts are defined. These fiber quality parameters include micronaire, fiber length, length uniformity, fiber strength, color grade, trash, and leaf grade (NCC, 2006; USDA, 1994; USDA, 2001).

Micronaire is a composite measure of both fiber fineness and maturity. Fiber fineness can be taken as the effective diameter of a fiber, and maturity describes how completely a fiber's interior is filled with cellulose. The fineness factor in micronaire is considered more important in spinning, while fiber maturity tends to relate to dye up-take and fiber strength. Micronaire values that are either very low or very high (outside the 3.5 to 4.9 range) are undesirable and subject to price penalties. Within a given cotton variety, fiber fineness tends to be constant, while fiber maturity can vary greatly as a result of variations in field conditions during the growing season. Micronaire is important to cotton growers and textile processors, and deserves special attention in fiber-quality related research.

Fiber length is a measurement of the average length of the longest half of a bale's fibers. Longer fiber length is preferred by textile mills, as it improves spinning efficiency during yarn production, as well as yarn strength and fineness. Consequently, cotton with longer staple fiber receives a price premium.

Length uniformity is an index describing how uniform the lengths in a bundle of fibers are. It is based upon the ratio of the bundle’s mean length to its upper half mean length and expressed as a percentage. Cotton with low length uniformity may experience excessive fiber breakage during the yarn spinning process and not produce uniform yarns.

Fiber strength is reported as the force in grams necessary to break a bundle of fibers one tex in size (g/tex). A cotton fiber's strength is important for withstanding the stresses encountered in ginning, carding, drawing, roving, and spinning into yarn. Fiber strength is also an important predictor of the ultimate strength of yarns.

Color is determined by the degrees of reflectance (Rd) and yellowness (+b). Rd indicates how bright or dull a sample is, and +b indicates the degree of color pigmentation. For Upland Cotton, color grade is a three-digit code determined by locating the point at which the Rd and +b values intersect on the Nickerson-Hunter cotton colorimeter diagram. There are 25 official color grades for American Upland Cotton plus five categories of below-grade color.

Trash is a measure of the amount of non-lint material in cotton, such as leaf and bark from cotton plants. The surface of the cotton sample is scanned by a video camera, and the percentage of the surface area occupied by trash particles is calculated. The classer’s leaf grade is a visual estimate of the amount of cotton plant “leaf” particles in a cotton sample.

In recent years, the USDA – AMS has considered incorporating additional fiber quality parameters to improve cotton marketing and utilization (Knowlton, 2000). Of special interest are short fiber content, stickiness, and elongation. Short fiber content is defined as the percentage of fibers in a sample, by weight, which is less than 12.7 mm (0.5 in.). Immature cotton tends to have high short fiber content. In textile mills, short fiber adversely affects yarn strength, yarn imperfections, and yarn evenness. Sticky cotton is caused by the deposition of insect (such as whitefly or aphid) excretions on cotton fibers before harvest. Stickiness can cause textile machines to be clogged and in some extreme cases, could shut down a yarn mill. Like many other elastic materials, cotton fibers deform when external forces are applied and restore when the exerted forces are released. Elongation is defined as the ratio of maximum deformation to fiber length before the testing bundle breaks (exceeding the fibers' elastic limit). Elongation is correlated with both yarn strength and yarn elongation.

In addition to HVI, another widely used fiber quality quantification method is AFIS (Advanced Fiber Information System). While HVI recommends 100 g of composite sample for laboratory fiber testing, AFIS requires a much smaller sample size of 100 mg per test (Bradow et al., 1997). This makes it possible to measure fiber quality at the plant, boll, and lock levels, and facilitates various studies such as plant mapping (Bradow et al., 1997; Johnson et al., 2002). Fiber quality parameters reported by AFIS include short fiber content, circularity, perimeter, immature fiber fraction, cross sectional area, fine fiber fraction, micronAFIS (an AFIS equivalent of micronaire), etc.

More recently, interest has increased in the cotton research community concerning microscopic image analysis for measuring single cotton fibers non-instrumentally (Thibodeaux and Rajasekaran, 1999; Hequet and Wyatt, 2001). A set of morphological parameters such as cell wall area and perimeter are used to describe fiber cross section by means of digital image processing. Strong correlations have been found between these morphological parameters and instrumental parameters, indicating the possibility of using microscopic image analysis as an alternative method for fiber quality measurement. An apparent advantage of the image analysis method is that it can separate fiber fineness and maturity and measure them independently. Disadvantages are that it is extremely time-consuming and costly, and due to the very small cotton fiber samples, the results may not be representative of the bale and thus are currently not suitable for practical use.

Increasing Demands on Cotton Fiber Quality

The U.S. cotton industry is currently facing increasing demands on fiber quality. A direct reflection of this trend is that USDA – CCC (Commodity Credit Corporation) has modified the Schedule of Premiums and Discounts for Upland and ELS (Extra Long Staple) Cotton. The most notable modifications were the inclusion of fiber length uniformity and a positive shift of the fiber strength base (the range of fiber strength within which no price premium or discount is received; Craig et al., 2002). Another reflection of this trend, as mentioned previously, is that USDA – AMS has continued attempts to integrate additional fiber quality parameters (such as short fiber content and stickiness) into the HVI testing, and proposed the inclusion of these parameters into the commercial system for cotton pricing and marketing. Raw cotton could thus be subject to more stringent inspections before entering the textile mill.

Stringent fiber quality demands can be largely attributed to the following facts: (1) the U.S. cotton market has shifted from domestic consumption to export-dominant, and foreign mills require higher quality in terms of color and trash content; (2) more exacting fiber quality requirements have been caused by rapid technological progress in yarn spinning and fabric manufacturing; and (3) there has been intense pressure from manmade synthetic fibers which are extremely consistent in terms of quality, requiring higher and more uniform performance of natural cotton fiber.

SITE SPECIFIC CROP MANAGEMENT FOR COTTON PRODUCTION

Site Specific Crop Management (SSCM) is an information- and technology-based agricultural management system that identifies, analyzes, and manages spatial and temporal variability within fields for optimum profitability and protection of the environment (Johnson et al., 2002). According to Thomasson et al. (2001), two things are fundamental to the success of SSCM: (1) obtaining accurate site-specific data about crop and field conditions, (2) the ability to vary agronomic inputs site-specifically (also referred to as VRT or Variable Rate Technology).

Cotton yield monitors have been researched intensively since SSCM was first introduced in cotton production (Thomasson et al., 1999; Wilkerson et al., 2001; Thomasson and Sui, 2003; Sui et al., 2004). In commercial cotton yield monitors, light emitter and detector pairs are mounted on a harvester's conveyor chute, and the amount of light attenuation is measured and related to the cotton mass flow rate. The literature has shown that yield maps generated by cotton yield monitors can satisfactorily indicate the spatial variability of lint yields, and in some cases help to identify the yield-limiting factors in the field. Ag Leader® Technology manufactures the FP 3000 and FP Advantage cotton yield monitors, and they are now installed on a fairly large number of cotton harvesters around the country.

In addition to yields, obtaining site specific data about other field variables has also been studied with real-time sensors or remote-sensing. Sui and Thomasson (2006) developed a ground based system which can measure cotton plant canopy reflectance and height with an optical sensor and an ultrasonic sensor, respectively. The information can then be integrated to predict the plant nitrogen status. Beck and Searcy (2001) developed an optical sensor to make cotton plant height measurements which could be used for variable rate growth regulator applications. Plant et al. (2000) found that NDVI (normalized difference vegetation index) of color-infrared aerial images was strongly correlated with lint yields under conditions where there was a significant water or nitrogen stress. NDVI was also correlated with nodes above white flower and nodes above cracked boll. Yang et al. (2005) used three-band airborne imagery to classify two cotton fields into healthy and phymatotrichum root-rot areas. Buffer zones around the root rot areas were generated and will be useful for site-specific management of the disease.

With respect to VRT, Fridgen et al. (2004) retrofitted a commercial aerial applicator to achieve variable rate application of harvest-aid chemicals based on remote-sensing imagery. Khalilian et al. (2003) retrofitted conventional four-row injection equipment with a variable rate pump, a GPS receiver, and an onboard computer for variable rate nematicide application. Many researchers (Perry et al., 2004; Pocknee et al., 2004; Khalilian et al., 2005; Moore et al., 2005) have used real-time data (such as sensed crop water stresses, soil moisture, weather data, etc) to achieve variable rate irrigation in cotton fields.

IMPLICATIONS

With the increasing demands on fiber quality, U.S. cotton farmers must produce high quality fibers to (1) maintain their competitiveness in the international market and (2) increase their profits. For a long time, farmers have relied heavily on lint yields for their monetary return. Their consideration of fiber quality is usually limited to pre-planting and post-harvest events such as variety selection, module storage, ginning machinery, etc., and it is uncommon for them to think about improving fiber quality at the field level. Recent literature, however, suggests that fiber quality could be a profit determiner as important as yields (Tronstad et al., 2003). Suppose there is a cotton field with an initial yield of 1200 lb/ac (1345 kg/ha) sold at a base loan rate of 52 ¢/lb. Assume also that the farmer decides to deploy advanced field management practices to (1) obtain an additional lint yield of 50 lb/ac. (57 kg/ha), or (2) enhance fiber quality such that an additional 5 ¢/lb can be received (according to the USDA – CCC Loan Schedule, a length difference of 3/32 in. would generate a loan price difference of 5 ¢/lb). While the second option may be more difficult to accomplish throughout the field, if it were accomplished it would increase the farmer’s revenue by 60 $/ac. (150 $/ha), more than twice as much as the first option of 26 $/ac. (65 $/ha). Placing strong emphasis on the importance of fiber quality, Bradow and Davidonis (2000) stated that it is the quality, not the quantity, of fibers ginned from seed cotton that decides the end use and economic value of cotton and consequently, is a major determiner of the profit for both producers and processors.

Numerous studies have shown that appreciable levels of variability exist for fiber quality in the field (Elm et al., 2001; Johnson et al., 2002; Ping et al., 2004; Wang, 2004), and significant correlations between fiber quality and some agronomic factors (such as soil properties) have been observed. Furthermore, Bradow and Davidonis (2000) pointed out that, even with the modern cropping technologies, only 35 to 40% of the total reproductive potential (including both yield and fiber quality) of cotton plants has been exploited. The literature, nevertheless, indicates that most of the SSCM systems in cotton production are yield- and biomass-oriented. It is thus reasonable to envision a SSCM system that could encompass both lint yields and fiber quality in cotton production such that farmer's profit potential can be maximized before harvest.

GOAL OF DISSERTATION

The overarching goal of this dissertation was to address some fundamental aspects of applying SSCM to cotton fiber quality management. Specifically, these include (1) documenting in-field variability of cotton fiber quality and relating it to an important agronomic factor, soil moisture content; and (2) developing a hardware and software system that can be used to map cotton fiber quality automatically.

Analogous to SSCM employed in other cropping systems, this study is anticipated to provide basic but important information on applying SSCM to cotton fiber quality. Documented fiber quality variability (or fiber quality maps) would be beneficial for delineating different management zones and is a preliminary step towards more sophisticated technologies such as decision-making and VRT. The relationships between fiber quality and soil moisture content, on the other hand, would aid in irrigation scheduling and variable rate irrigation for fiber quality optimization.

CHAPTER II

IN-FIELD VARIABILITY OF COTTON FIBER QUALITY AND ITS RELATIONSHIPS WITH IN-SEASON SOIL MOISTURE CONTENT

PROBLEM STATEMENT

To date, the in-field variability of fiber quality has been mainly determined by collecting cotton samples manually from various locations in the field and summarizing the data in terms of descriptive statistics such as the standard deviation and coefficient of variation (Elms et al., 2001; Ping et al., 2004; Wang et al., 2004). However, as a naturally occurring phenomenon, cotton fiber in the field should exhibit spatial correlation as most crop and soil properties do (Trangmar et al., 1985; Solie et al., 1999; Iqbal et al., 2005). In the other words, cotton fiber quality at locations near to each other should be more similar than at locations farther apart. Geostatistics would thus be a better technique to quantify its variability, and has been tried to a limited extent in some studies. For example, Wang (2004) calculated the Moran's I statistic to detect the spatial correlation existing in micronaire. Johnson et al. (2002) employed semivariance analysis and found that a noticeable level of spatial dependence existed in many HVI (such as micronaire and length) and AFIS (such as microAFIS and circularity) fiber parameters.

According to Trangmar et al. (1985), there are several merits of using geostatistics over traditional statistical methods. Firstly, geostatistics would account for the spatial dependence in field variables and provide a more appropriate framework for data analysis. Secondly, it would provide a statistically optimal method (kriging) to predict target variables at unvisited locations. To fully realize SSCM in cotton production for both fiber quality and lint yields, it is important to consider that fiber quality may depend on agronomic and environmental conditions in a manner different from that of lint yields. If so, then maps of lint yields and fiber quality parameters would exhibit different spatial patterns, and subsequently different management zones would be delineated and different decisions would be made. Under the current conditions in which no adequate method is available to measure fiber quality at the field level exhaustively and automatically (Sassenrath et al., 2005), geostatistics becomes especially important as it provides appropriate methods to produce high resolution fiber quality maps from coarsely spaced sample data. When comparing fiber quality maps to other spatial data (such as soil property maps), agronomic factors which would have important effects on fiber quality could be easily identified.

Soil moisture content has long been recognized as one of the most important agronomic factors for some fiber parameters. However, the relationship between the two has not been fully understood. The conventional method to study the soil-crop relationship, where soil properties are sampled once throughout the season, is deemed insufficient for soil moisture due to the following reasons. Unlike some soil properties such as clay content which is quite stable, soil moisture tends to vary greatly during the entire season, making one time sample not representative. Secondly, a cotton plant is indeterminate in nature. Its requirement for water varies greatly for each growth stage, and it can adapt to different levels of water stress by altering its growth behavior (such as boll shedding). In this study, the author measured soil moisture content over a long period of time during the season such that a long term relationship can be explored.

LITERATURE REVIEW

In-field Variability of Fiber Quality and Its Relationships with Soil Properties

Elms et al. (2001) conducted a three-year (1996 to 1998) study to measure the in-field variability of fiber quality parameters (micronaire, length, and strength) and important soil physical (sand, silt, and clay) and chemical properties [organic matter (O.M.), nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), pH, cation exchange capacity (CEC), zinc (Zn), Manganese (Mn), iron, and copper]. The field of study was a 13-ac. (5.3-ha) irrigated field located at the Erskine Research Farm at Texas Tech University, Lubbock, Texas. Cotton and soil samples were collected from a 57-point grid with 30.5-m intervals. They found in 1996 that micronaire ranged from 3.9 to 6.1 with a CV (Coefficient of Variation) of 10.4%; length ranged from 24 to 30 mm with a CV of 4.2%; and strength ranged from 28.0 to 65.0 g/tex with a CV of 15.4%. In 1997 micronaire ranged from 3.9 to 5.1 with a CV of 4.5%; length ranged from 26 to 29 mm with a CV of 2.3%; and strength ranged from 27.9 to 35.3 g/tex with a CV of 3.9%. In 1998 micronaire ranged from 4.2 to 5.4 with a CV of 5.8%; length ranged from 25 to 29 mm with a CV of 3.0%; and strength ranged from 28.0 to 31.0 g/tex with a CV of 2.2%.

No successful attempts to relate fiber quality to soil properties were reported. They concluded that in-field variability could be found in cotton fiber quality, and the variability was different across the growing seasons.

Johnson et al. (2002) conducted a two-year (1996 and 1997) study on a 0.5-ha experimental site in a producer's field in Florence, South Carolina. Soil and fiber samples were collected from a regular grid (129.2 by 45.6 m, 7.6-m interval). Soil properties determined included soil moisture, sand, silt, clay, O.M., pH, Ca, magnesium (Mg), P, and sodium (Na). Fiber quality parameters determined with AFIS included fiber length by number [L(n)] and weight [L(w)], short fiber content by weight [SFC(w)] and number [SFC(n)], diameter by number, circularity, immature fiber fraction (IFF), cross-sectional area, fine fiber fraction (FFF), micronAFIS, and perimeter. Parameters determined with the HVI method included micronaire, length, elongation, uniformity, strength, leaf grade, and color (Rd and +b). Fiber strength and elongation percentage were also determined with the stelometer method. In 1996, CVs for the soil properties ranged from 9.1% for pH to 73.6% for P; and CVs for the fiber parameters ranged from 1.7% for uniformity to 20.1% for FFF. In 1997, CVs for the soil properties ranged from 10.6% for pH to 73.7% for P; and CVs for the fiber quality parameters ranged from 1.4% for uniformity to 21.0% for FFF. Semivariance analysis revealed that only a few fiber parameters exhibited a pure nugget effect, indicating no spatial correlations. In 1996 these parameters included SFC(w), SFC(n), strength and elongation with both stelometer and HVI, and uniformity, Rd, and +b. In 1997, these included L(w), L(n), SFC(w), SFC(n), elongation by stelometer, uniformity, and strength by HVI. Data from the both years were combined for correlation analysis. The strongest correlations were found between soil moisture and strength by stelometer (with r, the correlation coefficient = 0.7), soil moisture and elongation by stelometer (r = 0.56), soil moisture and +b (r = -0.51), pH and cross sectional area (r = -0.51), and pH and micronAFIS (r = -0.51).

Ping et al. (2004) conducted a three-year (1998, 1999, and 2000) experiment to identify relationships among cotton yield, quality, and soil properties. The study site was a 49-ha center-pivot irrigated cotton field near New Deal, Texas. Soil and cotton samples were taken from a 1.0-ha grid system (39 nodes). Soil samples were collected at depths of 0 to 150, 150 to 300, and 300 to 610 mm, and soil properties determined were N, P, O.M., CEC, sand, silt, clay, pH, Exchangeable K, Exchangeable Mg, Exchangeable Ca, depth to caliche, and depth to free carbonate. Fiber quality parameters included micronaire, length, and strength. They found that in 1998 micronaire ranged from 3.5 to 5.5 with a CV of 10.6%; length ranged from 25.7 to 29.7 mm with a CV of 3.2%; and strength ranged from 26.0 to 33.6 g/tex with a CV of 5.7%. In 1999 micronaire ranged from 3.9 to 5.1 with a CV of 6.6%; length ranged from 25.1 to 28.7 mm with a CV of 2.3%; and strength ranged from 26.8 to 32.8 g/tex with a CV of 4.6%. In 2000, micronaire ranged from 2.7 to 4.2 with a CV of 10.9%; length ranged from 25.7 to 28.4 mm with a CV of 2.8%; and strength ranged from 25.2 to 32.8 g/tex with a CV of 5.9%. CVs for the soil properties ranged from 1.48% for pH to 44.6% for N. Correlation analysis revealed that fiber length was the only fiber quality parameter significantly correlated with most of the soil properties under investigation for all three years. In 1999 the only soil property correlated with micronaire was pH, and no soil property was correlated with strength. In 2000 only pH was correlated with strength, and no soil property was correlated with Micronaire. Different regression techniques [Ordinary Least Squares regression (OLS), Partial Least Squares regression (PLS), and Principal Component Regression (PCR)] were attempted to identify the soil-crop relationships and address inter-correlation among soil properties.

Wang (2004) conducted a two-year (1999 and 2000) experiment to study the relationships between fiber quality and soil properties. Soil and cotton samples were collected from two 0.4-ha grids located on two cotton fields (referred to as South and North Field) in Brooksville, Mississippi. Fiber quality parameters measured were micronaire, length, uniformity, strength, Rd, and +b. Soil properties determined included clay, sand, silt, Ca, K, Mg, Na, and P. In 1999, CVs for fiber quality ranged from 1.32% for length uniformity to 9.98% for micronaire. In 2000, CVs for fiber quality parameters ranged from 1.05% for length uniformity to 6.29% for strength. Significant correlations (with α, the level of significance, smaller than 0.01) were found between length and sand, length and silt, length and Ca, length and K, micronaire and clay, micronaire and silt, micronaire and K, micronaire and Mg, micronaire and P, and uniformity and K. Multiple linear regression was attempted to develop a micronaire prediction model by using soil properties. The result showed that over both years, micronaire can be estimated by soil properties with reasonable accuracy (r^2, the coefficient of determination, reached 0.35).

Influence of Soil Moisture Content on Cotton Fiber Quality

Many researchers have studied the relationships between soil moisture content and cotton fiber quality parameters, from not only an agronomic perspective, but also from physiological and biological perspectives. Garrett and Russell (1954) reported that fiber length increased by 3/32 in. (2.4 mm) with a supplemental irrigation in August at College Station, Texas. The water was applied during the only drought period of the season, indicating the importance of adequate moisture when cotton fiber is in the process of elongation. Other researchers (Marani and Amirav, 1971; Shimishi and Marani, 1971; Hearn, 1976) have concluded that the occurrence of moisture deficits during the early flowering period did not alter fiber length. However, when drought occurred later in the flowering period, fiber length was decreased. Hearn (1994) found that severe water deficits during the fiber elongation stage reduced fiber length, apparently relating directly to the mechanical and physiological processes of cell expansion. Grimes et al. (1969) and Spooner et al. (1958) found that irrigation increased mean fiber length and upper half mean length. Bradow et al. (1997) found that different irrigation methods (drip irrigation with tubing under or between plant rows) modified fiber length distributions. In India, Singh and Bhan (1993) found that moisture conservation practices (mulching) increased fiber length.

Hearn (1994) found that abundant water availability could delay fiber maturation (cellulose deposition) by stimulating competition for assimilates between early-season bolls and vegetative growth. Adequate water could also increase the maturity of fibers from mid-season flowers by supporting photosynthetic C fixation. Singh and Bhan

(1993) found that both added water and mulching tended to increase fiber fineness. Aberrations in cell-wall synthesis due to drought stress were detected and characterized with glyco-conjugate analysis (Murray, 1996).

An adequate water supply during the growing season allowed maturation of more bolls at upper and outer fruiting positions, but the mote counts tended to be higher in those extra bolls, and the fibers within those bolls tended to be less mature (Hearn, 1994; Davidonis et al., 1996). Bradow et al. (1997) found that rainfall and the associated reduction in insolation levels during the blooming period resulted in reduced fiber maturity. Munk and Wroble (2000) concluded that because reductions in photosynthate production occurred as crop water stress increased, there was some expectation to find variations in how primary and secondary fiber cell wall components were deposited, thereby diminishing key fiber quality characteristics.

OBJECTIVES

Based on the literature, studies to explore in-field variability of fiber quality have been conducted in various locations around the country. However, few of them have been done in a geostatistical context. No study has attempted to associate the fiber quality issue with some critical aspects of production such as farmers' profitability and management decision-making, leaving the significance of fiber quality studies not fully established. Non-uniform conclusions have been made about the relationship between post harvest cotton fiber quality and in-season soil moisture, an aspect deserving further research.

The objectives of this study were to: (1) document the spatial variability of cotton fiber quality by means of manual sampling and geostatistical analysis, (2) demonstrate the in-field variation of cotton loan price caused by the variability of fiber quality, and (3) explore the relationships between fiber quality and in-season soil moisture content.

MATERIALS AND METHODS

Study Site

The study site was the IMPACT Center within the Texas A&M University Research Farm in Burleson County (latitude 30.529758° N, longitude 96.436291° W), about 16.0 km southwest of College Station, Texas. The IMPACT Center is approximately 130 ha in size. Soil survey data from UDSA – NRCS (Natural Resource Conservation Service) indicate five dominant soil types in the study site (table 1). Cotton, corn, and grain sorghum are the primary crops planted at the center. Historically, the IMPACT Center was divided into six irrigated areas (referred to as *I1* through *I6*) and eight dry areas (referred to as *D1* through *D8*) for research and management purposes (figure 1). The irrigated areas are irrigated with a center pivot irrigation system.

In the 2005 season, three cotton varieties were grown on the IMPACT Center: DP 444 GB/RR (Delta and Pine Land Company, Scott, Miss.) in *I1*, *I2*, *I4*, and *I5*; DP 555 BG/RR in *D1*; and FiberMax 960 BR (Bayer CropScience, Germany) in *D3* and *D4*. On 14 April 2005, cotton was planted in *I1* and *I2* at a seeding rate of 128,000 seeds per ha and a row spacing of 0.76 m (30 in.). On the same day, cotton was plant in *D1* at a seeding rate of 128,000 seeds per ha and a row spacing of 1.02m (40 in.). In the 2006 season, one variety (DP 455 BG/RR) was planted in the *I3*, *I6*, *D1*, and *D6* areas. On 4 April 2006, cotton was planted in *D1* at a seeding rate of 128,000 seeds per ha. The row spacing was 0.76 m (30 in.).

Table 1. USDA – NRCS dominant soil types in the IMPACT Center.

Map unit symbol	Soil type	Taxonomic class
BaA	Belk clay, 0 to 1 percent slopes, rarely flooded	Fine, mixed, thermic Entic Hapluderts
RrA	Roetex clay, occasionally flooded	Very fine, mixed, active, thermic Aquic Hapluderts
WwA	Weswood silty clay loam, 0 to 1 percent slopes, rarely flooded	Fine-silty, mixed, superactive, themic Udifluventic Haplusepts
WeA	Weswood silty loam, 0 to 1 percent slopes, rarely flooded	Fine-silty, mixed, superactive, themic Udifluventic Haplusepts
YaB	Yahola fine sandy loam, 0 to 2 percent slopes, rarely flooded	Coarse-loamy, mixed, superactive, calcareous, thermic Udic Ustifluvents

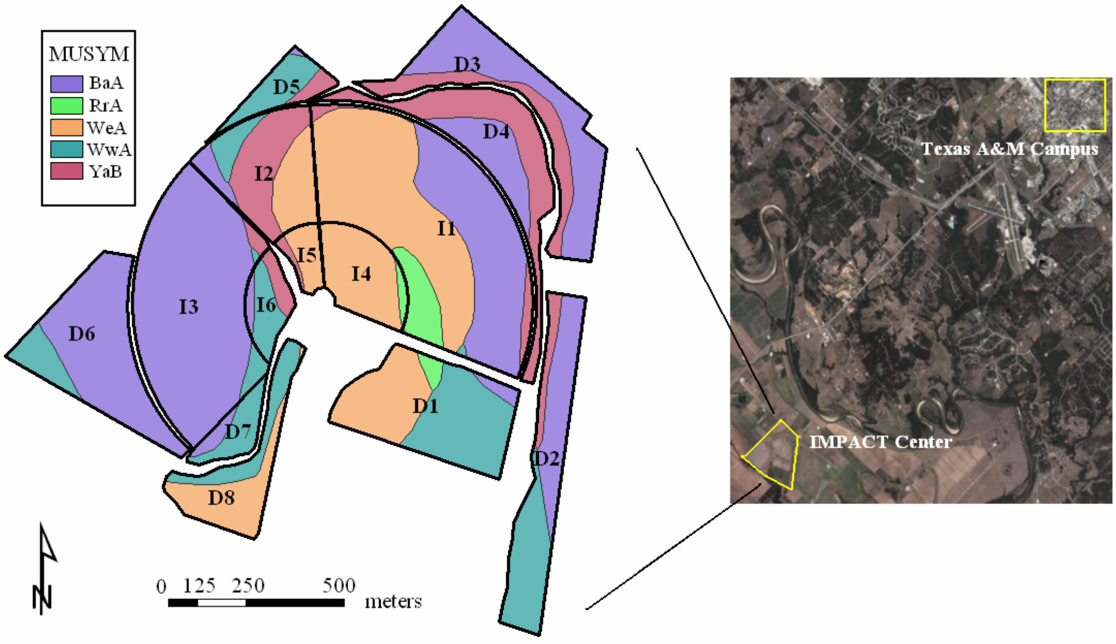


Figure 1. Geographical location, soil types, and management areas of the IMPACT Center, MUSYM stands for map unit symbol.

Experiment Design and Data Collection

Sampling Points

In 2005, three areas (*I1*, *I2*, and *D1*) were selected for the field experiment. The selected areas included two water application regimes (irrigated versus dry) and covered different soil types. The use of these areas virtually guaranteed a wide range of soil moisture content among the sampling points. Three equilateral regular grid systems containing a total of 76 sampling points were laid out for data collection, with 36 points (points 51 – 86) covering the entire *D1* area and 40 points (points 1 – 40) covering portions of the *I1* and *I2* areas (figure 2). The average interval of the grid systems was around 55 m. A different sampling scheme was used in 2006. Sampling points in *I1* and *I2* were discarded because no cotton was grown in those areas. An additional 30 points were inserted into the grid in *D1*, yielding an irregular grid containing 66 sampling points (figure 3). An explanation on how the position of the additional sampling points was selected is given in the Data Analysis section.

In both years, the position of each sampling point was established by using a Global Positioning System (GPS) receiver – iFINDER^{TM} (Lowrance Electronics, Inc., Tulsa, Okla.). This GPS receiver can receive the WAAS (Wide Area Augmentation System) signal to improve its positioning accuracy (within seven m). For the first field visit, each point was found as indicated by the GPS receiver and a flag was then placed permanently for future field visit.

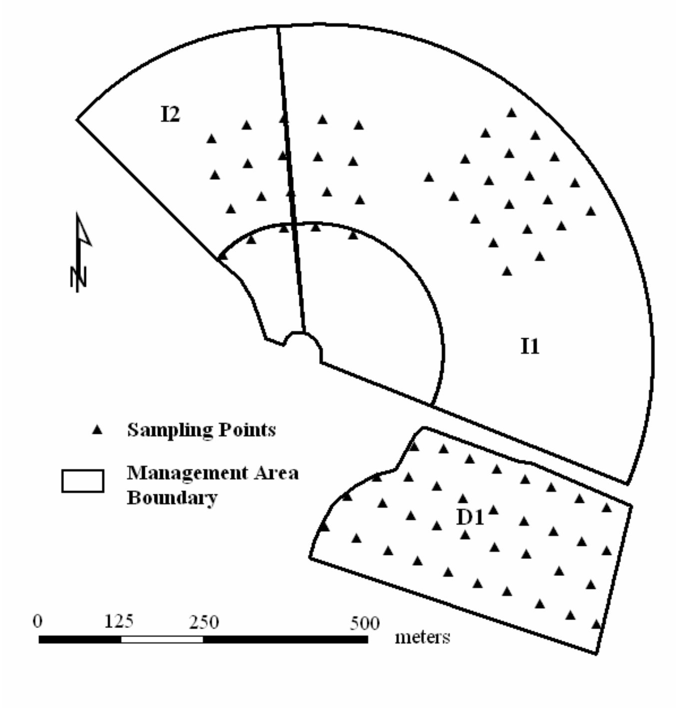


Figure 2. Field boundary of *I1*, *I2*, and *D1* areas and locations of sampling points in 2005.

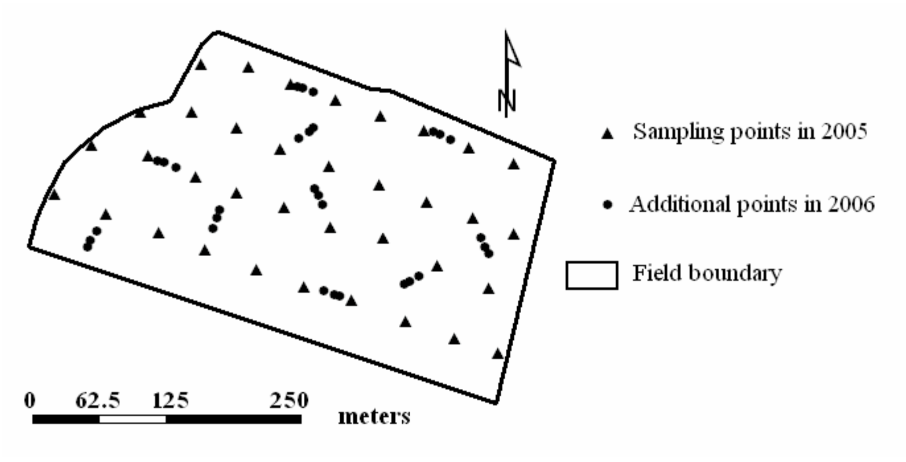


Figure 3. Field boundary of *D1* area and locations of sampling points in 2006.

In-season Soil Moisture Content Measurement

An ML2X ThetaProbe Soil Moisture Sensor [referred to as ThetaProbe (Dynamax Inc., Houston, Texas)] and an HH2 Moisture Meter [referred to as HH2 (Dynamax Inc., Houston, Texas)] (figure 4) were used for in-season soil moisture content measurement and data logging, respectively. The sampling devices of the ThetaProbe are four rods, which sample a cylinder of soil that is 40 mm in diameter and 60 mm in length. It measures volumetric (%) bulk soil moisture content at a nominal depth of 30 mm. The HH2 is connected to the ThetaProbe via a serial cable. It reads electronic signals from the ThetaProbe (which are proportional to volumetric soil moisture content) and converts them to digital numbers representing soil moisture readings.

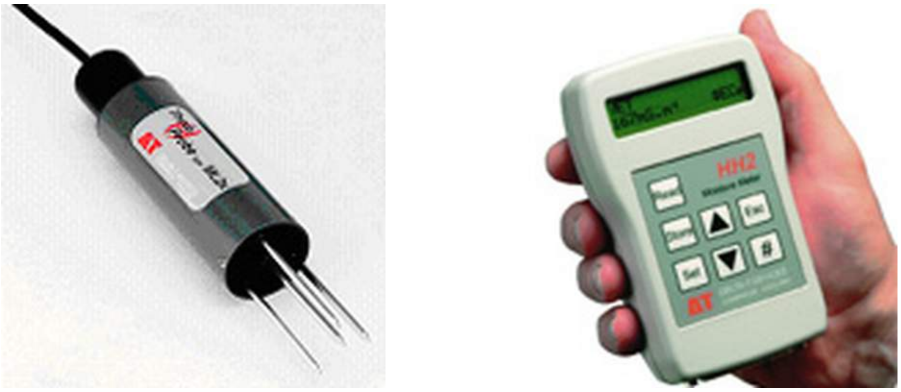


Figure 4. ML2X ThetaProbe soil moisture sensor (left) and HH2 moisture meter (right).

In 2005, soil moisture content at each sampling point was measured once a week from 5 June to 27 August (12 times). It was expected that soil moisture content early in the cotton growing season (such as germination and emergence) would be more important for vegetative growth and have less effect on post-harvest fiber quality. Thus moisture measurement was started in the middle of the season when the vegetative growth had already been vigorous. A preliminary examination of the data revealed that weekly moisture measurements were highly correlated from one week to the next. This suggested that there was redundant information, and one-week sampling interval might be more frequent than necessary. In 2006, therefore, soil moisture was measured bi-weekly from 6 June to 2 August (5 times). At each sampling point, three readings were taken at three random locations within one meter surrounding the flag. The locations were on the two neighboring rows with the flag in the middle (figure 5). The readings were averaged and rounded to the nearest tenth and then considered as the measured soil moisture content for the given sampling location.

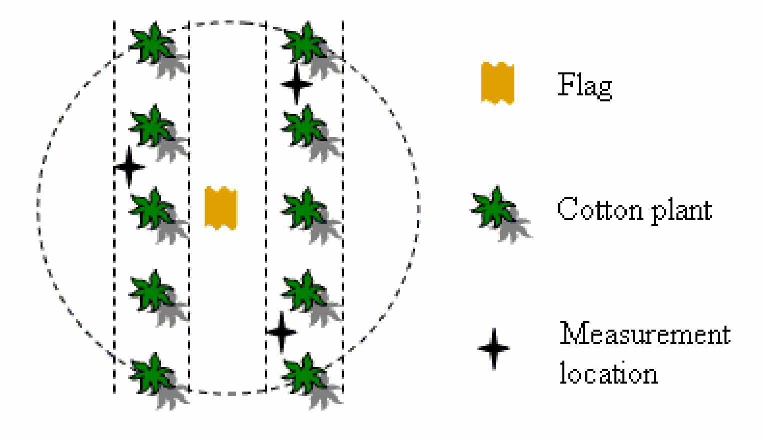


Figure 5. Soil moisture content measurement scheme.

It should be noted that ThetaProbe is capable of inducing significant levels of measurement error in different situations. To improve the measurement accuracy, a soil-specific sensor calibration process is recommended. The procedure involves laboratory analysis (such as oven drying and weighing) of soil samples and calibrating (linear conversion) the field measurement with the lab measurement. Because this study was mainly concerned with the linear relationship between cotton fiber quality and soil moisture content, a calibration process was considered unnecessary, and the un-calibrated measurements were deemed sufficient for statistical analysis (correlation). Soil moisture content data in 2005 and 2006 are given in tables A-1 and A-2 (Appendix A), respectively.

Fiber Quality Data Collection

Cotton samples were hand-harvested at the sampling points from 30 August to 1 September in 2005 and from 3 to 5 August in 2006, in each case about three days after defoliants were applied. Around 454 g (one lb) of seed cotton was harvested from each point and placed in a numbered paper bag, with the bag number corresponding to the sampling point number. Cotton samples were collected from plants on the two neighboring rows around the flag, matching the pattern of soil moisture measurement. There were some concerns that large variations of cotton fiber quality might be observed among bolls from different plants and fruiting sites (Bradow et al., 1997). To make sure that samples were not biased to an individual cotton plant or a specific fruiting site, cotton was harvested from at least 10 plants at each location, and bolls from the top, middle, and bottom parts of the plant were evenly picked. Seed cotton from small, immature, and partially opened bolls was not harvested.

In 2005, cotton samples were transported to the Cotton Production and Processing Research Unit at Lubbock, Texas and ginned on a 10-saw laboratory gin equipped with an incline cleaner, an extractor feeder, and a saw-type lint cleaner. In 2006, cotton samples were ginned locally at the Cotton Improvement Laboratory, Texas A&M University. The ginning machine was a 10-saw, portable, laboratory-scale gin without any seed-cotton cleaning or lint cleaning (Continental Eagle Corporation, Prattville, Ala.). In both ginning systems, seed cotton was fed manually into the gin and the lint was collected manually from the outlet. To avoid lint mixture between adjacent samples, the portion of lint that came out first during ginning was discarded for each sample. Ginned lint was transported to the International Textile Center, Texas Tech University (Lubbock, Texas) and subjected to HVI line testing. The testing reported nine fiber quality parameters including micronaire, length, length uniformity, strength, elongation, Rd, +b, leaf grade, and color grade. Fiber quality data from 2005 and 2006 are given in tables A-3 and A-4 (Appendix A), respectively.

Data Analysis

It must be noted that the following three factors could introduce unexpected sources of variation in the fiber quality dataset:

1. Cotton variety. Three varieties were involved in the experiment, and different varieties can have different fiber quality potential.

2. Plant and harvest date. Cotton was planted around 10 days earlier and harvested 25 days earlier in 2006 than in 2005. Fibers in different years could have different levels of maturation.
3. Ginning machinery. It has been proven that ginning sequences have significant effects on some fiber quality parameters such as color grade, length, and short fiber content. Compared to the Continental Eagle gin used in 2006, the Lubbock gin used in 2005 has two stages of seed-cotton cleaning and one stage of lint cleaning, none of which the former gin has. This difference could give rise to another source of fiber quality variation.

To eliminate these potential sources of variation, the entire fiber quality dataset was divided into three subsets – irrigated 2005, dry 2005, and dry 2006 – such that these factors are uniform within each subset.

Exploratory Statistics

Exploratory data analysis (EDA) was performed on the three grouped subsets to explore the in-field variability of cotton fiber quality. Among the nine HVI fiber quality parameters, leaf grade and color grade are categorical in nature and require special statistical tools (e.g., logistic regression) for analysis and interpretation. For the sake of simplicity, these two parameters were excluded from all statistical procedures in this study. More importantly, compared to other intrinsic fiber quality parameters such as micronaire, leaf grade and color grade could be more easily affected by non-agronomic factors such as mechanical harvesting, module storage, and the ginning process. Hence, research on in-field variability and relationships with soil properties for leaf grade and color grade appears to be less important since this study deals with hand-picked samples. The univariate statistics reported for the remaining fiber quality parameters include the maximum value (Max), minimum value (Min), mean, standard deviation (SD), CV, skewness, kurtosis, and Shapiro-Wilkes statistic. These exploratory statistics provided informative summaries of the datasets (e.g., outliers and deviation from normal) and are suggestive of possible actions (e.g., variable transformation to obtain normality) that should be taken before other statistical approaches are applied. EDA was performed with the SAS Procedure UNIVARIATE (SAS Institute, Cary, N.C.).

Geostatistics

Semivariance analysis was performed on the dry 2005 and dry 2006 subsets to reveal and quantify spatial dependence in fiber quality parameters. It was not performed on the irrigated 2005 subset because both sampling grids in this area didn't contain enough points (20 points each) to accurately estimate semivariance at each lag distance. Since no apparent trend was found in an initial posting of the data, a weak form of stationarity could be reasonably assumed and thus no trend surfaces were fitted. It was also assumed that the spatial structure was omni-directional, because the numbers of cotton samples in both data subsets (36 and 66 in dry 2005 and 2006, respectively) were not enough to specify an anisotropic structure. Sample semivariance was calculated from the following equation (Isaaks and Srivastava, 1989):

$$\gamma(h) = \frac{1}{2 \times N(h)} \sum_{i=1}^{N(h)} [z(s_i) - z(s_i + h)]^2 \qquad (1)$$

where $N(h)$ is the number of sample pairs separated by the lag distance h; and $z(s_i)$ and $z(s_i + h)$ stand for the fiber quality parameter measured from sample locations s_i and $(s_i + h)$, respectively.

The geometry of the 2005 sampling grid caused some limitations in sample variogram calculation. First, the minimum spacing of 55 m made the establishment of short-range semivariance (i.e., < 55 m) not possible. Secondly, the omni-directional model was biased because more point pairs were available in the cotton row direction than any other directions (figure 2). In 2006, ten closely-sampled transects (each transect contained three sampling points with separation distances of 20, 10, and 5 m) were placed in four separate directions (with 0, 45, 90, and 135 degrees to the row direction) across the 2005 grid. The purposes of the additional sampling points were to: (1) enable the establishment of semivariance at shorter separation distance, (2) neutralize the effect the directional bias (again, along the cotton row), and (3) increase the number of point pairs at each lag. These would allow more accurate estimation of sample variograms.

Each sample variogram was fitted with a theoretical model that provides three basic parameters (C_0 as the nugget, $C_0 + C_1$ as the sill, and a as the range) describing the spatial structure of the fiber parameter. There are different types of theoretical semivariogram models such as linear, exponential, spherical, Gaussian, etc. A visual inspection suggested that the spherical model (equation 2) could fit all sample variograms satisfactorily. The nugget, sill, and range were estimated by the Autofit function in the Surfer 7 software package (Golden Software, Inc., Colden, Colo.): Firstly a rough estimate of all three parameters was made by visual inspection of the sample variogram; then the Autofit function finely tuned the parameters in a least-squared sense. It should be noted that the fitting procedure was a somewhat try-and-error process, and the fitted models thus might not be optimal in reflecting the true spatial structure.

$$\gamma(h)=\begin{cases} C_0+C_1\times[\frac{3}{2}\times\frac{h}{a}-\frac{1}{2}\times(\frac{h}{a})^3] & h<a \\ C_0+C_1 & h\geq a \end{cases} \qquad (2)$$

Block kriging was then applied to produce contour maps for all fiber quality parameters. Compared to point kriging, block kriging estimates the average value of the target variable within an area (or block). Maps generated with block kriging contain fewer local extremes and are more visually-pleasing, as most local details are smoothed into blocks (Trangmar et al., 1985; Isaak and Srivastava, 1989). This smoothing feature of block kriging was desirable in this study, because cotton price is based on its bulk fiber quality, and it is thus more useful to demonstrate the general trend of fiber quality distribution rather than some extreme values at certain locations. The block used was 2×2 m in size, and each block was discretized into four points. A mathematical expression of block kriging is given in equation (3)

$$\hat{z}(V)=\sum_{i=1}^{n}\lambda_i\times z(x_i) \qquad (3)$$

where $\hat{z}(V)$ is the kriged value of a fiber quality parameter at any block V centered at x_0; $z(x_i)$ is the fiber quality parameter at the known sampling location x_i; and λ_i are the kriging weights determined by the spatial structure and geometry between the block and n known samples.

Correlation Analysis

In order to explore the relationships between post-harvest fiber quality parameters and in-season soil moisture content, Pearson's correlation analysis was performed on the grouped subsets with the SAS Procedure CORR (SAS Institute, Cary, N.C.). It was expected that the magnitude of the correlation coefficients between fiber quality and soil moisture would vary in the season, verifying the hypothesis that soil moisture at various growth stages has different levels of significance relative to post-harvest fiber quality. It is worth noting that in some other studies [such as that of Johnson et al. (2002)], combined multi-field and multi-year datasets was evaluated in hopes of discovering broad and long-term relationships between fiber parameters and soil moisture over a wide moisture content range. However, the cotton plant may respond to soil moisture differently in different growing environments, due to its complex physiology. In other words, fiber parameters and soil moisture may be positively correlated in one field at a specific growing stage and negatively correlated in another field at the same growing stage. Therefore, grouping data according to the water regime appears to be more appropriate. Furthermore, from a statistical perspective the combined dataset might deviate from a normal distribution (e.g., bi-modal or multi-modal), which would be inconsistent with the normality assumption for correlation analysis. This potential problem is another reason why analysis on the combined dataset was not implemented in this study.

RESULTS AND DISCUSSION

Exploratory Statistics

Exploratory statistics for fiber quality data from irrigated 2005, dry 2005, and dry 2006 are presented in tables 2, 3, and 4, respectively. In 2005, most of the fiber quality parameters possessed a normal distribution with relatively low skewness and kurtosis values (skewness and kurtosis for a normal distribution are both zero). Exceptions were micronaire from irrigated 2005 and strength from dry 2005. Micronaire had a high negative value of skewness, meaning it was left-skewed. Its high positive kurtosis value indicated that there were likely some outliers in the data, most probably on the left side of the distribution. With respect to strength, a relatively high positive skewness value was exhibited, meaning it was right-skewed. There were some other fiber quality parameters also showing relatively high skewness and kurtosis values (including +b and length from the irrigated area and length and Rd from the dry area), even though the normality test found these parameters were reasonably normally distributed. In 2006, micronaire had the highest skewness and kurtosis, indicating the likelihood of a few outliers on the right side of the distribution. Other parameters that exhibited moderate skewness and/or kurtosis were uniformity and elongation. The normality test, however, showed that all of the fiber quality parameters were reasonably normally distributed. For the sake of simplicity, the non-normal variables (micronaire from irrigated 2005 and strength from dry 2005) detected by the normality test were not transformed, as is suggested by many statistics textbooks. This is appropriate since normality is required only for part of geostatistical and correlation analysis, such as constructing confidence intervals for kriged values and calculating levels of significance for correlation coefficients. Cautions should be taken if pertinent statistical inferences have to be made about the non-normal variables.

Table 2. Exploratory statistics of fiber quality parameters in irrigated areas in 2005 (n = 40).

Fiber parameter	Max	Min	Mean	SD	CV (%)	Skewness	Kurtosis	Normality †
Micronaire	4.60	3.50	4.36	0.223	5.12	-1.69	4.27	0.842 *
Length (mm)	30.2	26.4	28.7	1.02	3.54	-0.471	-0.766	0.937 ^{ns}
Uniformity (%)	85.7	81.8	83.9	0.931	1.11	-0.560	-0.046	0.954 ^{ns}
Strength (g/tex)	31.7	27.4	29.5	1.07	3.63	-0.317	-0.432	0.960 ^{ns}
Elongation (%)	5.90	4.50	5.10	0.326	6.39	0.439	0.138	0.970 ^{ns}
Rd	81.7	77.9	79.9	0.825	1.03	-0.618	0.211	0.954 ^{ns}
+b	10.1	8.30	8.90	0.355	3.97	1.02	1.99	0.941 ^{ns}

^{ns} Not significant.

* Significant at the 0.01 level.

† Shapiro-Wilkes statistic (*W*) for the normal distribution test. Significant *W* indicates that data are not normally distributed.

Table 3. Exploratory statistics of fiber quality parameters in dry area in 2005 (n = 36).

Fiber parameter	Max	Min	Mean	SD	CV (%)	Skewness	Kurtosis	Normality †
Micronaire	5.10	4.00	4.54	0.248	5.45	-0.222	0.015	0.974 ^{ns}
Length (mm)	31.0	29.6	28.6	0.991	3.46	0.818	0.828	0.926 ^{ns}
Uniformity (%)	84.1	80.6	82.2	0.926	1.13	0.291	-0.861	0.964 ^{ns}
Strength (g/tex)	35.0	28.9	31.2	1.57	5.03	0.939	0.158	0.900 *
Elongation (%)	4.40	3.60	3.93	0.208	5.30	0.250	-0.379	0.960 ^{ns}
Rd	83.5	78.7	81.7	1.22	1.50	-0.873	0.265	0.927 ^{ns}
+b	9.00	7.90	8.36	0.280	3.35	0.337	-0.487	0.965 ^{ns}

^{ns} Not significant.

* Significant at the 0.01 level.

† Shapiro-Wilkes statistic (*W*) for the normal distribution test. Significant *W* indicates that data are not normally distributed.

Table 4. Exploratory statistics of fiber quality parameters in dry area in 2006 (n = 66).

Fiber parameter	Max	Min	Mean	SD	CV (%)	Skewness	Kurtosis	Normality †
Micronaire	4.87	3.05	3.62	0.34	9.48	0.72	1.44	0.956 ^{ns}
Length (mm)	31.5	25.4	28.2	1.54	5.47	0.46	-0.43	0.957 ^{ns}
Uniformity (%)	84.5	77.3	81.5	1.30	1.59	-0.27	1.04	0.981 ^{ns}
Strength (g/tex)	31.6	25.8	28.1	1.34	4.75	0.35	-0.29	0.982 ^{ns}
Elongation (%)	6.10	4.20	5.35	0.35	6.54	-0.56	0.73	0.973 ^{ns}
Rd	81.7	75.2	78.2	1.24	1.59	0.40	0.39	0.984 ^{ns}
+b	10.9	8.70	9.84	0.50	5.08	-0.32	-0.43	0.964 ^{ns}

^{ns} Not significant at the 0.01 level.

† Shapiro-Wilkes statistic (*W*) for the normal distribution test. Significant *W* indicates that data are not normally distributed.

In 2005 CVs for fiber quality parameters ranged from 1.03% for Rd to 6.39% for elongation in irrigated cotton, and from 1.13% for uniformity to 5.45% for micronaire in dryland cotton. In 2006, CVs ranged from 1.59% for uniformity and Rd to 9.48% for micronaire. It is interesting that CVs for the HVI fiber quality parameters exhibited a similar pattern regardless of the water regime and growing season. Micronaire and elongation always had the highest CVs; uniformity and Rd consistently had the lowest CVs; and other fiber quality properties had moderate CVs. As mentioned earlier, micronaire is a composite index of both fiber maturity and fineness, and fineness is generally constant within a certain variety. Because data grouping guaranteed the same variety within each group, micronaire could be treated as a direct reflection of fiber maturity. Hence the consistently high CV for micronaire seems to provide support for the argument that fiber quality parameters related to maturity would be more influenced by the growth environment than other parameters (such as length and strength).

In general, the CVs for fiber parameters found here are in good agreement with other studies (Elms et al., 2001; Johnson et al., 2002; Wang, 2004), where CVs for lint yields and soil properties were much higher than those of the fiber quality parameters. USDA – AMS (2001) specifies the level of repeatability of HVI measurements (table 5). For example, micronaire has a measurement repeatability of ±0.15 unit, which is only slightly smaller than the standard deviation found for micronaire in the data in this study. For this reason, it is worth considering that the true variability of the fiber parameters could be even lower than the levels reported. On the other hand, since repeated measurements were made and consistent patterns were evident in the data (as will be seen), it is clear that much of the variability was real and not associated with measurement error.

Table 5. HVI equipment performance specifications in USDA – AMS (2001).

Fiber parameters	Length (mm)	Uniformity (%)	Strength (g/tex)	Micronaire	Rd	+b
Repeatability	± 0.45	± 1.20	± 1.5	± 0.15	± 1.0	± 0.5

Furthermore, low CVs found in fiber parameters are not surprising in that they are, to a large extent, genetic traits and thus tend to be less responsive than yields to the growing environment. In this study, in-season soil moisture content (not summarized here) also exhibited consistently higher levels of CV, ranging from 8% to more than 50%, and generally near 25%. One might argue that low CVs for fiber quality parameters (which are, again, less responsive to environmental factors than lint yields) would not support a SSCM system for fiber quality management. On the other hand, geostatistical analysis of fiber quality parameters, as will be seen in the following section, indicates that a large loan price difference could be induced by this level of variability. Great potential can be foreseen for SSCM applications to improve fiber quality at the field level and increase farmers' profit.

Geostatistics

Semivariance Analysis

The sample variograms and fitted spherical models of individual fiber quality parameters are shown in figure 6 (dry 2005) and figure 7 (dry 2006). The maximum separation distance for semivariance calculation was 300 m, around two thirds the diagonal extent of the study site. The number of sample pairs at each lag distance was greater than 70, allowing an accurate estimation of semivariance (SAS suggests at least 30 point pairs at each lag distance in estimating sample semivariogram). All of the fiber parameters under investigation exhibited a noticeable level of spatial dependence, with their sample variograms increasing from near the origin and then reaching a plateau at certain lag distances. Due to the additional sampling points in 2006, semivariance can be observed at shorter separation distance for that year, allowing better modeling of the spatial structure of the fiber quality variables.

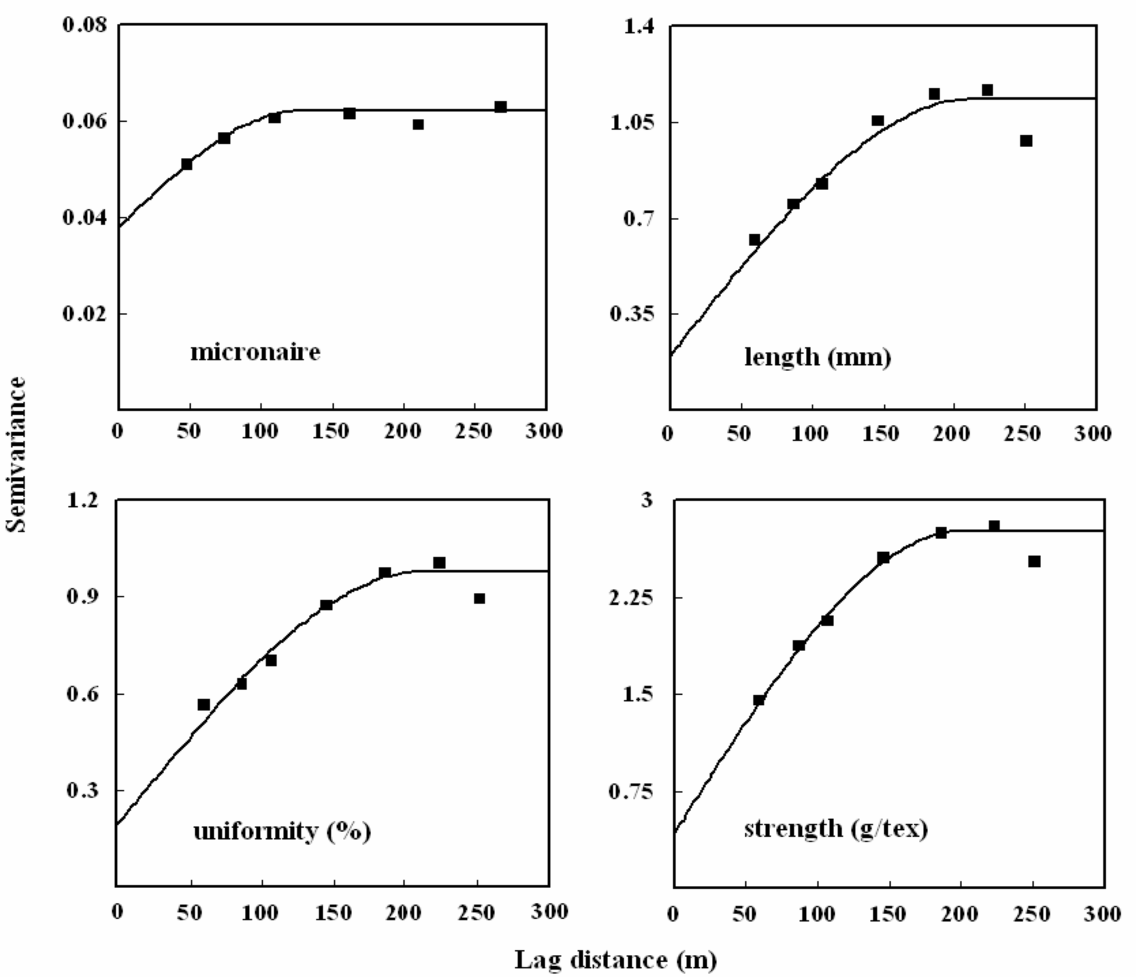


Figure 6. Sample variograms (■) and fitted models (—) for fiber quality parameters in dry area in 2005 (n = 36).

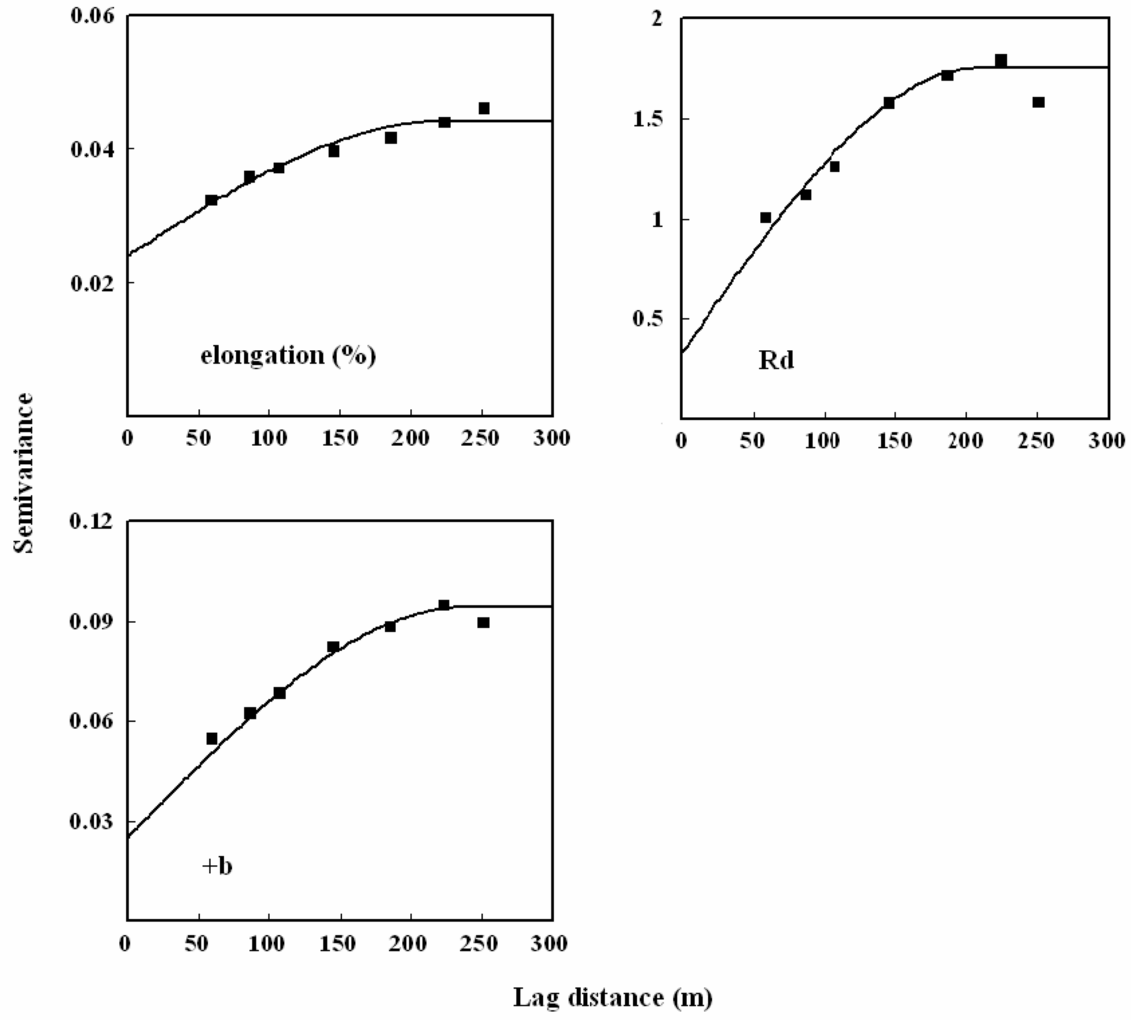


Figure 6. Continued.

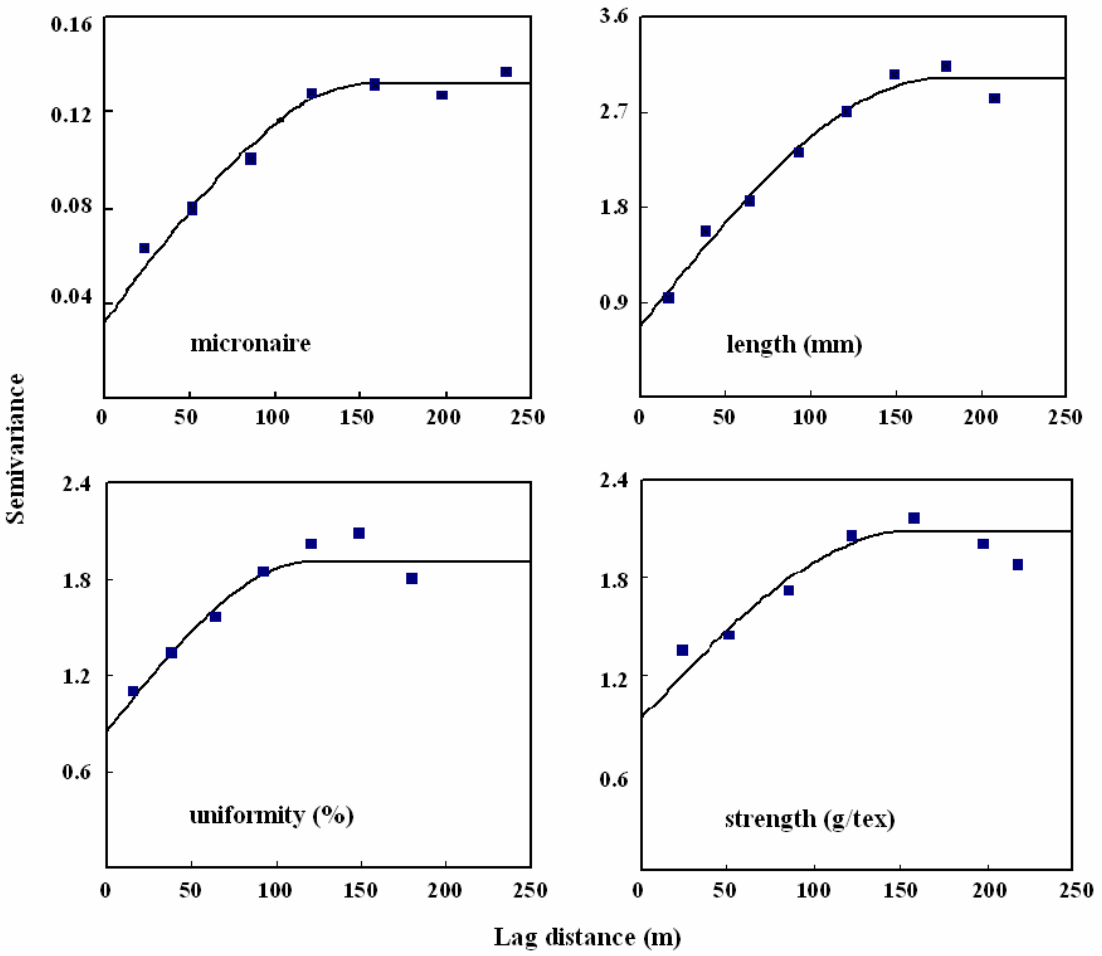


Figure 7. Sample variograms (■) and fitted models (—) for fiber quality parameters in dry area in 2006 (n = 66).

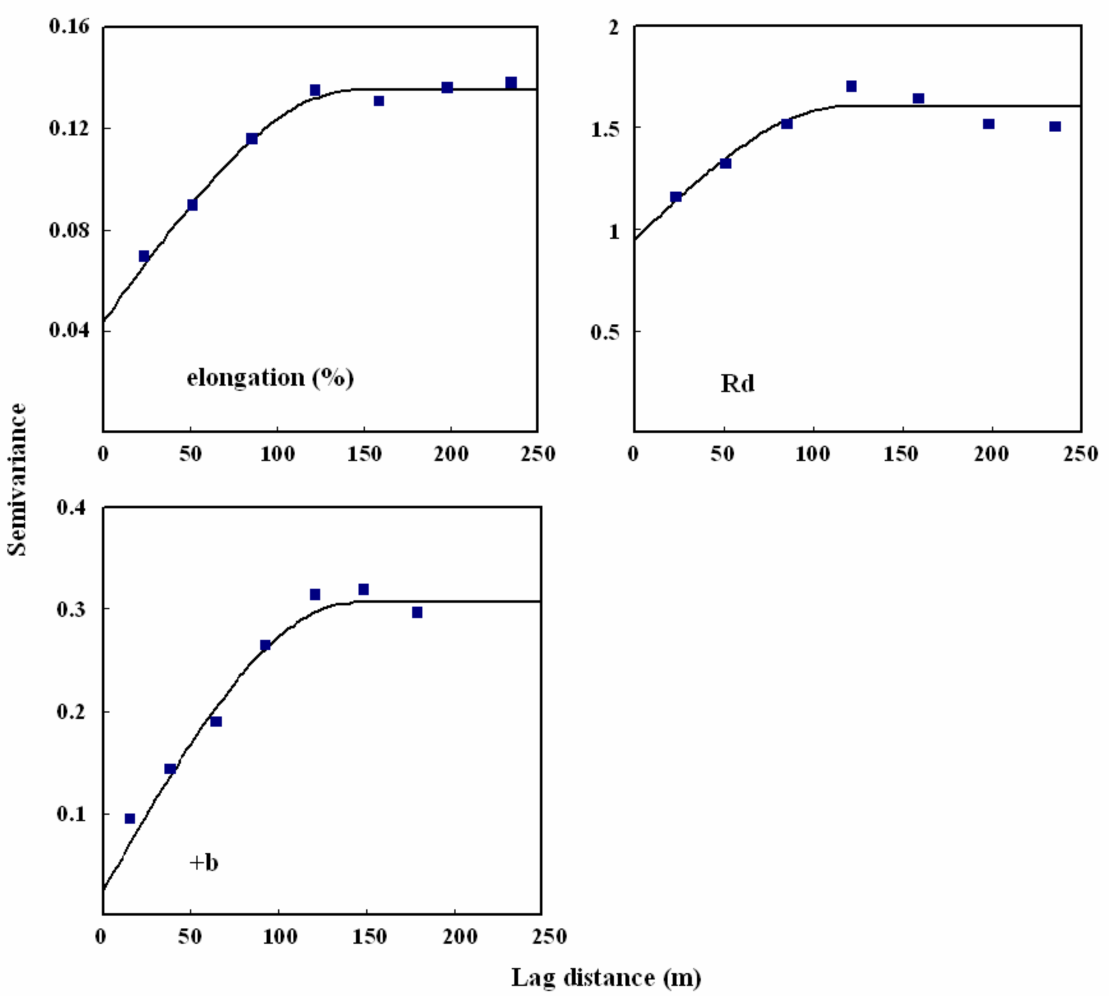


Figure 7. Continued.

Table 6 summarizes the parameters of the fitted models which quantified the spatial structure of each fiber quality parameter. The R^2 values (an objective measure of the goodness of fit) indicated that all sample variograms could be fitted with a spherical model satisfactorily.

In 2005, micronaire exhibited a smaller range of 126 m than other fiber quality parameters (larger than 200 m). This indicates that micronaire had a more random pattern in the field while other fiber quality parameters had a more continuous pattern. Length, uniformity, strength, and Rd had a strong level of spatial dependence, with their percent nugget (nugget / sill * 100%) smaller than 25%. Micronaire, elongation, and +b had a moderate level of spatial dependence, with their percent nugget between 25% and 75%.

Table 6. Parameters of fitted spherical models for each fiber parameter in dry area in both years.

Fiber parameter	R^2 ¶	Range	Nugget	Sill	Nugget (%) §	Spatial class †
			Dry 2005 (n = 36)			
Micronaire	0.93	126	0.038	0.062	61	M
Length (mm)	0.89	214	0.198	1.132	17	S
Uniformity (%)	0.94	213	0.192	0.978	20	S
Strength (g/tex)	0.96	200	0.425	2.755	15	S
Elongation (%)	0.91	220	0.024	0.044	54	M
Rd	0.96	208	0.33	1.75	19	S
+b	0.99	238	0.025	0.093	27	M
			Dry 2006 (n = 66)			
Micronaire	0.97	156	0.033	0.132	25	S
Length (mm)	0.98	174	0.68	2.99	23	S
Uniformity (%)	0.93	120	0.85	1.91	45	M
Strength (g/tex)	0.89	154	0.94	2.08	45	M
Elongation (%)	0.99	144	0.044	0.135	33	M
Rd	0.86	117	0.95	1.60	59	M
+b	0.98	141	0.025	0.305	8	S

¶ R^2 provides an objective measure of the goodness of fit between sample variograms and fitted models

§ Percent nugget is calculated as Nugget / Sill × 100.

† Spatial class: S = strong spatial dependence (percent nugget $\leq$ 25); M = moderate spatial dependence (25 < percent nugget < 75).

A different picture of the fiber quality spatial structure was found in 2006. Ranges for each fiber quality parameter were quite similar, from 117 for Rd to 174 for length. Micronaire, length, and +b exhibited a strong level of spatial dependence; uniformity, strength, and Rd exhibited a moderate level of spatial dependence.

It is worth mentioning that all fiber quality parameters from both years exhibited considerable nuggets. In semivariance analysis, the nugget effect is usually composed of two factors: (1) the micro-scale variance, and (2) the measurement error. Because each cotton sample contained around 454 g of seed cotton collected from more than 10 individual plants, the between plant variation would be inevitably integrated into the sample variance and reflected as the micro-scale variance. Furthermore, the fiber quality variation between bolls within a plant (Bradow et al., 1997) would also introduce the micro-scale variance that can not be accounted for by using semivariance analysis. Limitations of HVI equipment measurement accuracy and repeatability (table 5) would give rise to the measurement error component in the nugget. It can be generalized that in fiber quality analysis where samples are collected from a support much larger than a single boll, a noticeable level of nugget is likely to be observed in its variogram.

Kriged Maps of Fiber Quality Parameters

The kriged maps for the fiber quality parameters are presented in figure 8 (dry 2005) and figure 9 (dry 2006). Individual fiber parameters exhibited different spatial distributions. In 2005, micronaire had high values in the southwestern portion and northeastern corner of the field, and low values in the southeastern portion and northwestern corner. Length, strength, and uniformity exhibited a somewhat similar spatial pattern, with high values in the southern portion and low values largely in the northern portion of the field. Low values were found for elongation in the southern portion of field and high values in the northeastern portion. Rd and +b exhibited an opposite pattern, with high Rd and low +b in the northwestern portion of the field, and low Rd and high +b in the southwestern portion.

In 2006, different but more interesting spatial patterns were observed. It can be seen in figure 9 that length, uniformity, strength, and Rd exhibited a similar pattern, with high values in the north central portion of the field and low values in the southwestern and mid-eastern portions. An opposite pattern was shown in elongation and +b, with low values in the north central and high values in the southwestern and mid-eastern portions. Micronaire exhibited a different pattern, with low values largely in the eastern portion of the field.

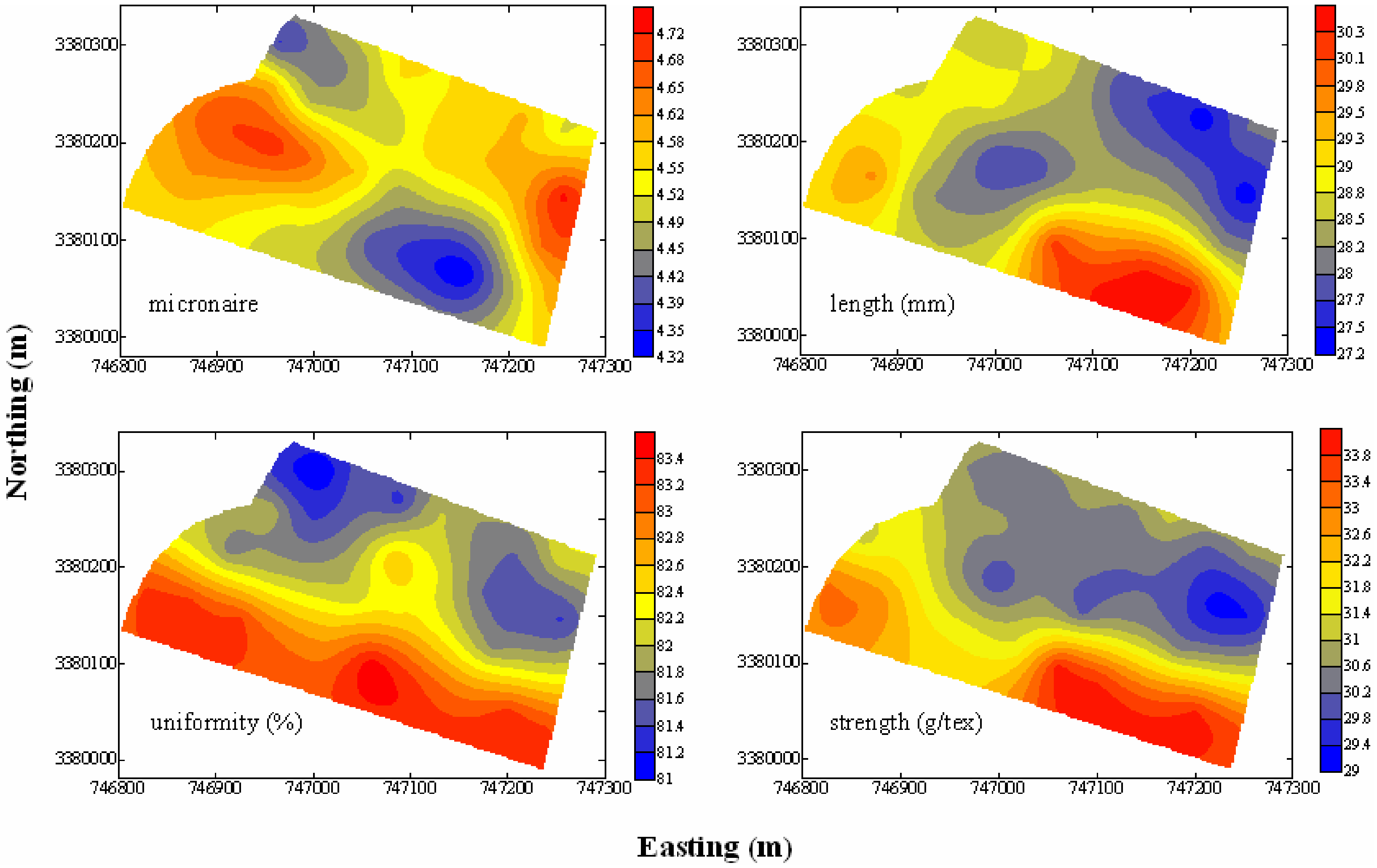


Figure 8. Contour maps of fiber quality parameters in dry area in 2005.

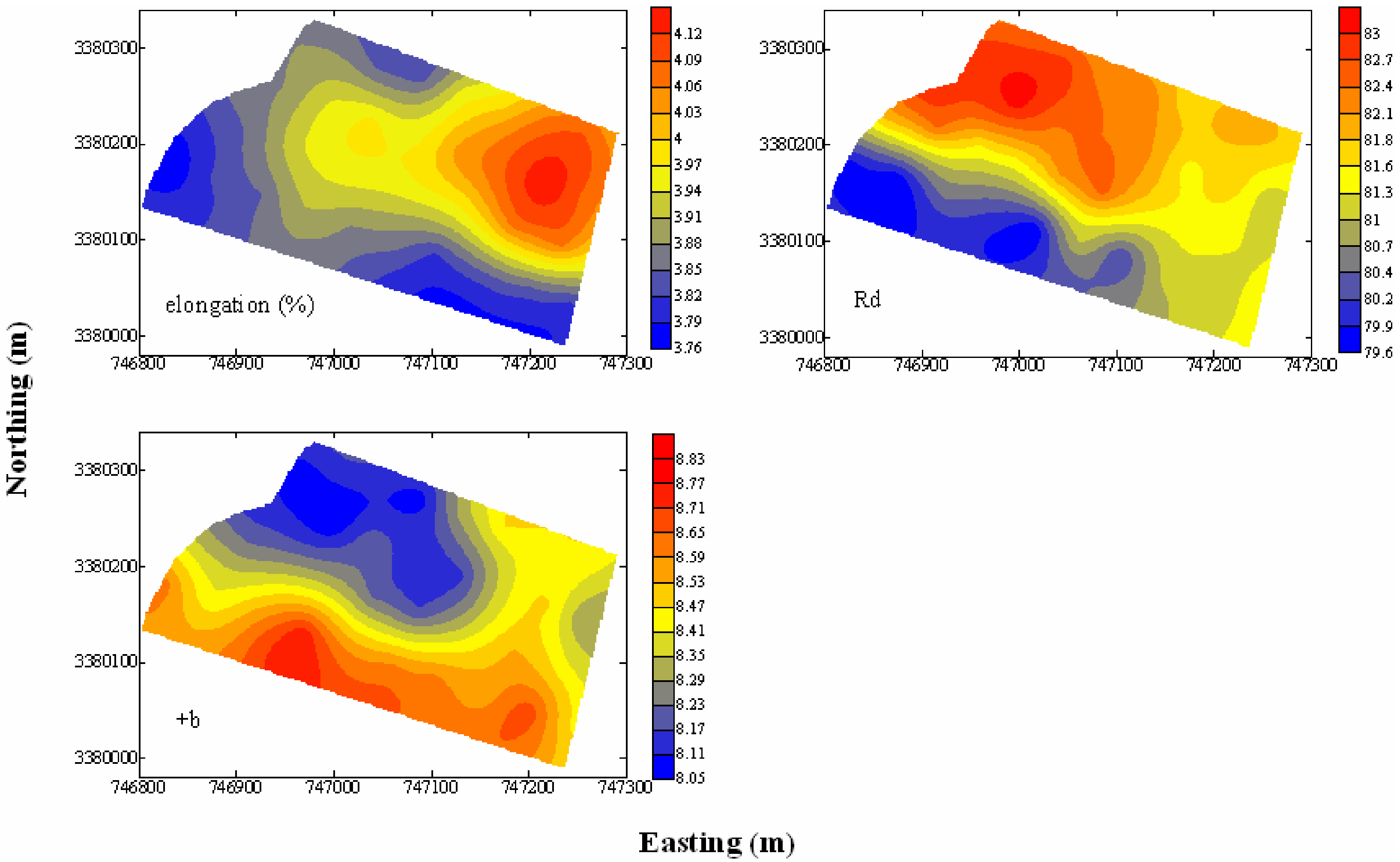


Figure 8. Continued.

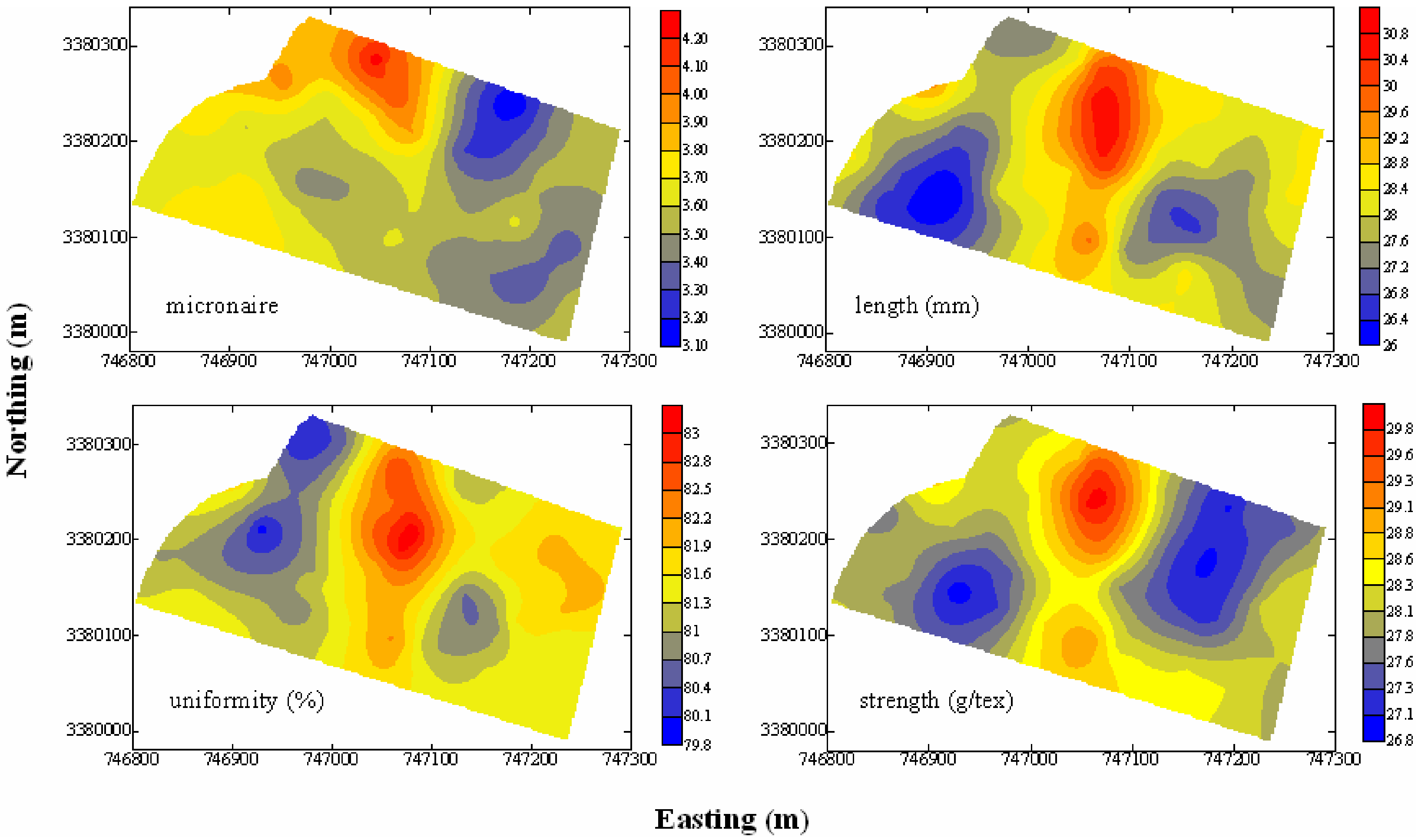


Figure 9. Contour maps of fiber quality parameters in dry area in 2006.

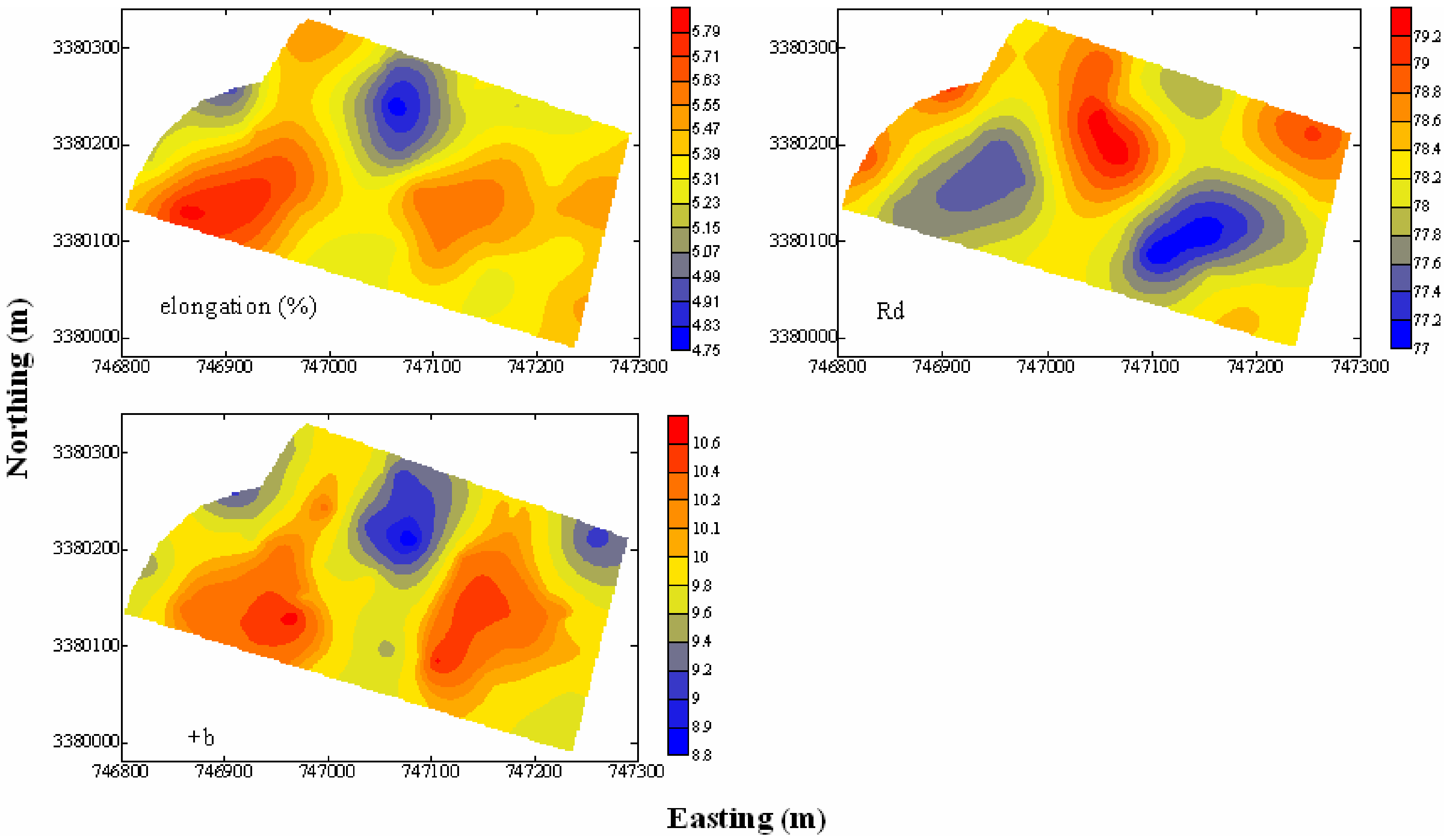


Figure 9. Continued.

Upon combining the two years of data, some long-term relationships among the individual fiber parameters were observed. Length, uniformity, and strength consistently exhibited a similar spatial pattern, indicating that they were positively correlated with each other. All of them exhibited an opposite spatial pattern from elongation, meaning that they were negatively correlated with it. These relationships are in good agreement with other research (Elms et al., 2001; Ping et al., 2004), and they also indicate that these fiber properties might respond to the same agronomic and environmental stimuli. Rd and +b consistently showed an opposite spatial pattern, indicating they were negatively correlated. This fact makes good sense in that high-quality fibers tend to possess high Rd (brighter) and low +b (less yellow), while low-quality fibers tend to have low Rd and high +b. Micronaire consistently exhibited a distinct spatial pattern compared to other fiber parameters, indicating a different interaction between it and certain field conditions. To provide a quantitative measurement, table 7 presents the cross correlation coefficients among individual fiber parameters in both years in the *D1* area.

Table 7. Cross correlation coefficients among individual fiber quality parameters for both years in *D1* area. ¶

	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b
Micronaire	-0.49*	ns	ns	ns	ns	ns
	ns	ns	ns	ns	ns	ns
Length		0.55*	0.79*	-0.45*	ns	ns
		0.72*	0.62*	-0.73*	0.53*	-0.72*
Uniformity			0.74*	ns	-0.53*	0.56*
			0.49*	-0.42*	0.38*	-0.50*
Strength				-0.55*	-0.45*	0.51*
				-0.52*	0.35*	-0.53*
Elongation					ns	ns
					-0.50*	0.62*
Rd						-0.66*
						-0.69*

¶ Correlation coefficients in 2005 (n = 36) are given in the top row; and those in 2006 (n = 66) are in the bottom row. Note that the level of significance calculated for the correlation coefficients is based on the normality assumption and may not be appropriate for strength in 2005 (table 3).
ns Not significant.
* Significant at the 0.01 level.

As stated earlier, an advantage of using geostatistics is that it can allow the crop-soil relationship to be more readily perceptible. Figure 10 is a map of soil apparent electrical conductivity (EC_a) of the study field measured with an electromagnetic induction sensor (EM-38, Geonics Ltd., Mississauga, Ontario Canada) and DGPS (Akbar et al., 2004; Akbar et al., 2005). Except for the field boundary areas, the spatial pattern for EC_a is quite similar to that of fiber quality parameters (except for micronaire) in 2006. Of particular interest is the north central area with high EC_a values, which coincides with the area that also exhibited superior fiber quality. Since soil EC_a is strongly correlated with texture, and thus soil moisture content, it is reasonable to speculate that moisture content may have been a limiting factor for some fiber growth processes (such as fiber elongation) in 2006. Apparent differences in the spatial distribution of micronaire, nevertheless, may suggest the involvement of more complex growth processes (such as secondary and tertiary cell wall deposition) that cannot be simply attributed to soil EC_a. Table 8 gives correlation coefficients (r) between the fiber parameters and soil EC_a in the *D1* area in 2006.

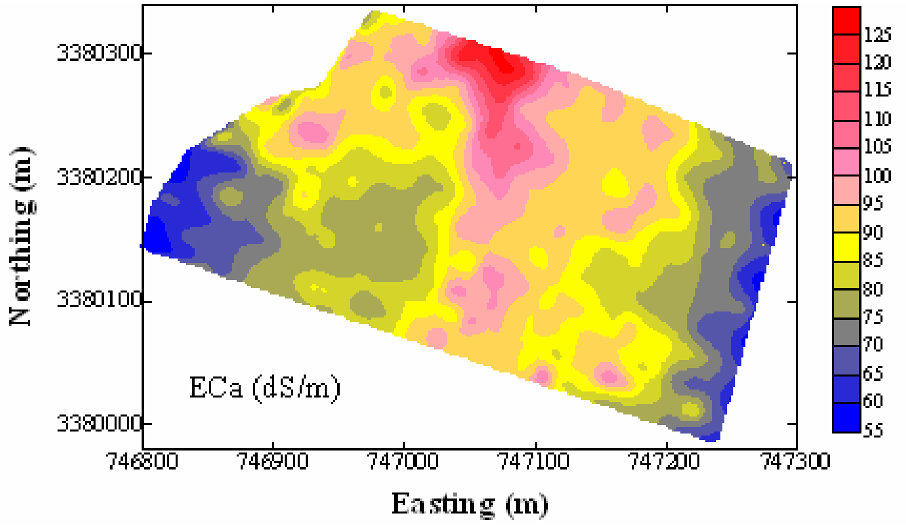


Figure 10. Map of soil apparent electrical conductivity in *D1* area.

Table 8. Correlation coefficients between cotton fiber parameters and soil ECa in *D1* area in 2006.

	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation	Rd	+b
r	0.39	0.64	0.48	0.44	-0.65	0.43	-0.59

¶ Sampling points located in the field boundary area (Point 51, 61, 70, 78, and 79) were excluded from correlation analysis. All correlation coefficients were significant at the 0.01 level.

Loan Price Maps

In the USDA – CCC Loan Schedule for Upland Cotton (NCC, 2006), cotton premiums or discounts are generally based on four separate components (three are determined by micronaire, strength, and uniformity, and the fourth is jointly determined by length and color and leaf grades). Accordingly, four loan price component layers were produced in order to develop loan price maps. Component layers for micronaire, uniformity, and strength were converted directly from their corresponding contour maps in figures 8 and 9. The component layer for length and color and leaf grades was generated as follows. Firstly, the price component of each sample point was calculated from the sample measurement of length and color and leaf grades. Then a block kriging procedure was applied at the same 2-m resolution (to ensure a pixel by pixel overlay operation with the other three layers; recall that the resolution for fiber quality contour maps was two m) to produce the loan price component layer caused by length and color and leaf grades.

The four component layers were then overlaid in ArcGIS to represent the final loan price induced by fiber quality (assuming a base loan price of 52 ¢/lb, figure 11). In 2005, the high loan price areas were largely in the southern portion of the field, and the low price areas were at the northeastern portion. A minimum rate of 4 ¢/lb in premium was found. This fact was a result of good overall fiber quality (most of the fiber quality parameters over the entire field fell in the premium ranges). In 2006, on the other hand, the loan price difference ranged from 2.5 ¢/lb in discount to 6.5 ¢/lb in premium. The high price area was in the north central portion of the field, while the low price areas were largely in the southwestern and eastern portions. When comparing the loan price map to the individual fiber quality maps, it is clear that the penalty received in the southwestern portion was due to low strength, length, and color and leaf grade. The penalty in the eastern portion, however, was a composite effect of low micronaire, strength, length, and color and leaf grade.

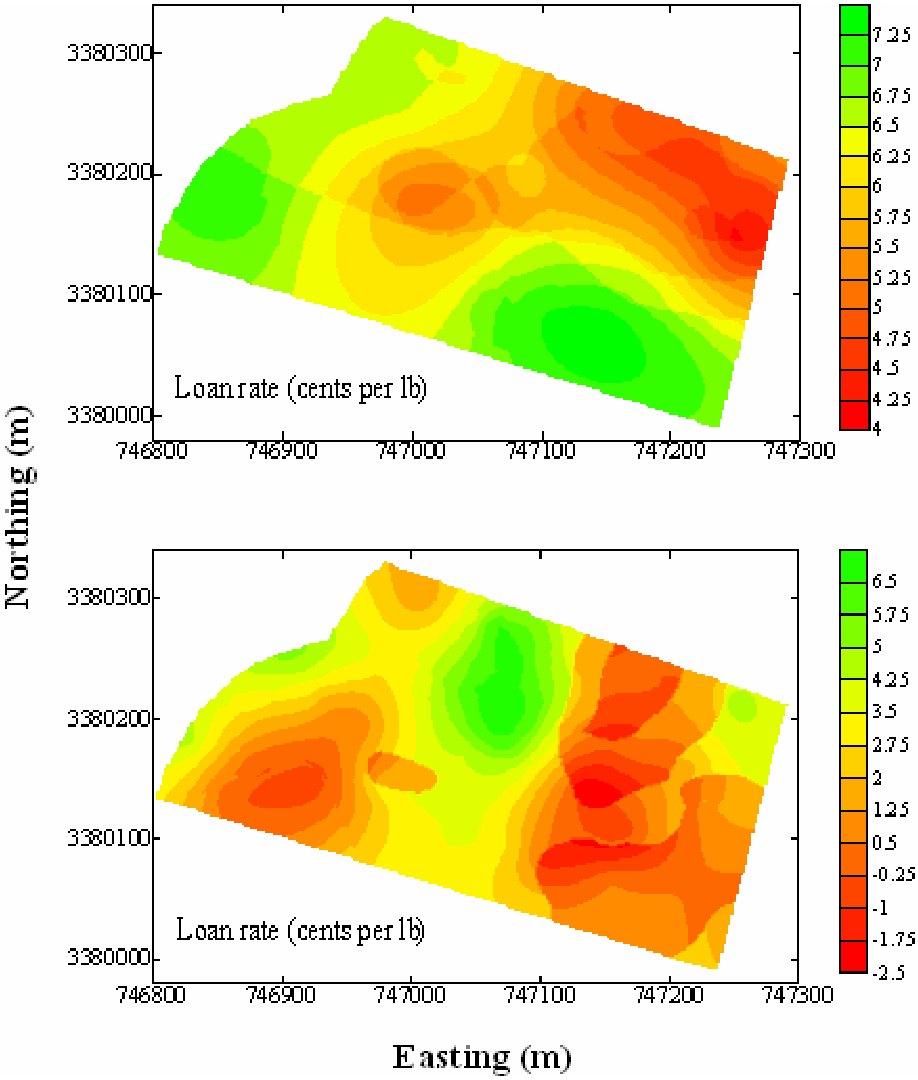


Figure 11. Fiber quality induced loan price maps (supposing a 52 ¢/lb base loan price) in *D1* area in 2005 (top) and 2006 (bottom).

The fiber-quality induced loan price maps presented in the foregoing paragraphs have several practical benefits. Firstly, maps like these would allow farmers to better understand their crop's value and variability for marketing purposes. For example, in the *D1* area of the research field in 2006, more than half of the field produced relatively low-quality fibers that would have received a price penalty (red and orange hues), and the rest of the field produced relatively high-quality fibers that would have received a price premium (green and yellow hues). Assuming an average yield of 2.0 bale/ac. (roughly 1000 lbs fiber) and a 4.5-¢/lb average price difference (half the maximize price difference) between the two types of fiber, a benefit of 112.5 $/ha (45 $/ac.) could be gained if the poorer-quality fiber were improved to match the quality of the higher-quality fiber. This means an $1800 price difference for this 40-ac. *D1* area. Extrapolating this idea a little further, if a farmer had 2000 ac. of cotton fields under similar circumstances, he could obtain a $90,000 increase in revenue by improving fiber quality alone. Of course this scenario assumes the ability to achieve uniformly high-quality fiber throughout the field, which is virtually impossible in real situations, but it is a good starting point to demonstrate the importance of fiber quality in the field. An SSCM system that could encompass not only lint yields but also fiber quality to improve farmer profit appears very attractive.

Secondly, the loan price maps may suggest different management zones in the field. In the *D1* area for example, the north-central portion could be regarded as a zone with high fiber quality potential and thus deserving of more management attention and inputs. Given limited resources such as time, labor, water, fertilizer, etc., a sound management practice should give higher priority to zones like this one that have higher fiber quality and thus profit potential.

Finally, loan price maps could also be used for harvest planning purposes. Currently, cotton is harvested across a field area that makes sense in a harvesting-traffic sense but includes no consideration of variations in fiber quality, and the cotton is combined into a harvester basket. Each basket then ends up in a module combined with other baskets, again without regard to fiber quality. Therefore, any higher quality fibers are mixed with lower quality fibers and their premium value is largely lost. A farmer's profit could be increased by separating higher quality fibers from lower quality fibers during harvest so that the former could be sold at a higher price. One possible improvement is to lay out harvest patterns that incorporate both traffic-pattern efficiency and considerations of likely fiber quality variations. Furthermore, the cotton harvesting equipment industry is considering new harvesting technologies that could bring about fiber segregation (personal communication with Mr. Tim Deutsch, Manager of Cotton Worldwide Agricultural Equipment Division, Deere and Company, Des Moines, Iowa). These new technologies might include a harvester-based system that could segregate fibers into baskets or basket segments that are likely to have different fiber quality characteristics based on historical fiber-quality maps and GPS-based field position. The segregated fibers could then be stored in separate modules. Bales ginned from high-quality modules could then be sold at higher loan price.

Correlation Analysis

As has been mentioned, soil moisture measurement in 2005 was highly correlated from one week to the next. High correlations were also observed in the 2006 bi-weekly data, though to a lesser extent. In order to handle these correlated soil moisture data statistically, in-season soil moisture measurement was categorized into different groups, with each group representing a particular cotton plant development stage. Moisture readings in the same stage were then averaged to give one value for each stage. It was believed that the averaged value represented soil moisture over a relatively long time window and should be further de-correlated. Another advantage of this procedure was that the correlation results were easier to interpret, as moisture measurement could be related to different plant development stages.

Since cotton was planted on different dates and weather varied greatly between the two years, Degree Days with a lower-threshold temperature of 15.5°C (referred to as DD15.5) were used to distinguish different plant development stages on a relatively equal basis. DD15.5 has been widely employed (Pettigrew, 2002; Davidonis et al., 2004; Viator et al, 2005) to calculate and evaluate different cotton plant development stages. DD15.5 is calculated with the following equation.

$$DD15.5 = \sum[(T_m + T_n)/2 - 15.5] \qquad (4)$$

where T_m and T_n stand for the maximum and minimum daily temperature, respectively; DD15.5 stands for the thermal units exceeding 15.5°C accumulated for each day starting from the date of planting.

Plant development in cotton proceeds through five growth stages: germination and emergence, vegetative, squaring and flowering, boll enlargement, and maturation (Freeland et al., 2006). Based on various sources of information (Young et al., 1980; Boyd et al., 2004; Freeland et al., 2006) along with the field observations, the following DD15.5 cut-offs were used for plant development stages in this study: 35 for germination and emergence, 400 for vegetative, 670 for squaring and flowing, 1100 for boll enlargement. Although DD15.5 for maturation is also recommended, it was assumed that fibers continued the maturation process until harvest.

The time window of each plant development stage, as indicated by DAP (Date after Planting) and the calendar day in table 9, was calculated according to DD15.5. In-season soil moisture measurements were then assigned to growth stages based on their day of measurement. Average moisture-content values for each growth stage were then used to study correlations with fiber quality parameters. Also presented in table 9 are the total amount of precipitation and irrigation occurring in each stage. Weather data were available in the form of daily summary (including maximum air temperature, minimum air temperature, precipitation, etc) from the USDA – ARS (Agricultural Research Service) Minilab Weather Station located at the IMPACT Center. The irrigation record was provided by the IMPACT Center farm manager (personal communication with Vince Saladino, Department of Soil & Crop Sciences, Texas A&M University).

Table 9. DAP, calendar day, precipitation, and irrigation of five plant development stages in study site in 2005 and 2006.

Plant development stage	DAP ¶	Calendar day	Precipitation (mm)	Irrigation (mm)	Moisture measurement §
		Year 2005			
Germination & emergence	1 – 7	16 – 22 Apr.	1	0	—
Vegetative	8 – 54	23 Apr. – 8 Jun.	79	38	M1
Squaring & flowering	55 – 75	9 – 29 Jun.	0	63	M2, M3, M4
Boll enlargement	76 – 107	30 Jun. – 31 Jul.	89	63	M5, M6, M7, M8
Maturation	108 – 137	1 – 29 Aug.	41	0	M9, M10, M11, M12
		Year 2006			
Germination & emergence	1 – 6	5 – 11 Apr.	0	n/a	—
Vegetative	7 – 50	12 Apr. – 23 May	86	n/a	—
Squaring & flowering	51 – 74	24 May – 17 Jun.	41	n/a	M1, M2
Boll enlargement	75 – 108	18 Jun. – 21 Jul.	87	n/a	M3, M4
Maturation	109 – 123	22 Jul. – 5 Aug.	21	n/a	M5

¶ Date after Planting.
§ — means no measurement; Mi means the ith soil moisture measurement in each year (i equals 1 to 12 in 2005, and 1 to 5 in 2006).

The results of correlation analysis between fiber quality parameters and soil moisture at each plant development stage are presented in table 10 and table 11. In 2005, length, uniformity, strength, and Rd were positively correlated with soil moisture at all stages in the irrigated area. The only fiber quality parameter that showed a negative correlation with soil moisture was +b. Micronaire was found to be positively correlated with soil moisture only during the vegetative stage. No significant correlation was found between micronaire and soil moisture at the other stages. Elongation was positively correlated with soil moisture content at most stages expect for the vegetative stage.

During 2005 in the dry area, however, a completely different picture was found. Length, uniformity, strength, and +b were not correlated with soil moisture at any stage. Micronaire was negatively correlated with soil moisture at the boll enlargement and maturation stage. Elongation was positively correlated with soil moisture at the squaring and fruiting stage. Rd was negatively correlated with soil moisture at the vegetative stage.

Table 10. Pearson's correlation coefficients between fiber quality parameters and soil moisture at different plant development stages in 2005.

Plant development stage	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b
			Irrigated area (n = 40)				
Germination & emergence	—	—	—	—	—	—	—
Vegetative	0.37*	0.44*	0.35*	0.36*	ns	0.40*	-0.37*
Squaring & fruiting	ns	0.66**	0.61**	0.39*	0.42*	0.37*	-0.47**
Boll enlargement	ns	0.74**	0.74**	0.50**	0.33*	0.48**	-0.65**
Maturation	ns	0.76**	0.73**	0.55**	0.37*	0.46**	-0.58**
			Dry area (n = 36)				
Germination & emergence	—	—	—	—	—	—	—
Vegetative	ns	ns	ns	ns	ns	-0.38*	ns
Squaring & fruiting	ns	ns	ns	ns	0.44**	ns	ns
Boll enlargement	-0.41*	ns	ns	ns	ns	ns	ns
Maturation	-0.36*	ns	ns	ns	ns	ns	ns

— No measurement.
ns Not Significant.
* Significant at the 0.05 level.
** Significant at the 0.01 level.

Table 11. Pearson's correlation coefficients between fiber quality parameters and soil moisture content at different plant development stages in 2006 (n = 66).

Plant development stage	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b
Germination & emergence	—	—	—	—	—	—	—
Vegetative	—	—	—	—	—	—	—
Squaring & Fruiting	ns	0.58 **	0.52 **	ns	-0.37 **	0.27 *	-0.34 **
Boll enlargement	0.28 *	0.85 **	0.67 **	0.50 **	-0.60 **	0.36 **	-0.62 **
Maturation	0.28 *	0.78 **	0.58 **	0.56 **	-0.58 **	0.45 **	-0.54 **

— No measurement.
ns Not Significant.
* Significant at the 0.05 level.
** Significant at the 0.01 level.

In 2006, the correlation structure between fiber quality parameters and in-season soil moisture was quite similar to that of the irrigated area in 2005. Length, uniformity, and Rd were positively correlated, while elongation and +b were negatively correlated with soil moisture at all stages. No significant correlation was found between either micronaire and soil moisture or strength and soil moisture at the squaring and fruiting stage, but both relationships showed some correlation at the boll enlargement and maturation stages.

As expected, different levels of correlation with in-season soil moisture were observed between the various fiber quality parameters, and the correlations were also dependent on plant development stage. Generally speaking, soil moisture late in the season (e.g., the boll enlargement and maturation stage) had much higher correlation coefficients than early in the season. For example, length in irrigated 2005 cotton had the lowest correlation coefficient (0.44) at the vegetative stage, but high coefficients of 0.74

and 0.76 were observed for the boll enlargement and maturation stages. Uniformity had a low coefficient of 0.35 at the vegetative stage but a high coefficient of 0.74 at the boll enlargement stage. With respect to strength, the correlation coefficient increased from 0.36 at the vegetative stage to 0.55 at the maturation stage. The same correlation patterns were also found for most fiber parameters in 2006. Most strikingly, the correlation coefficient for length increased from 0.58 at the squaring and fruiting stage to 0.85 at the boll enlargement stage. Strength was found not to be correlated with soil moisture at the squaring and fruiting stage but a significant correlation was found at both the boll enlargement (r = 0.50) and maturation (r = 0.56) stages.

These findings provide supportive evidence for the hypothesis that soil moisture at different growing stages has different impacts on post-harvest fiber quality. More importantly, they suggest that soil moisture late in the season would be more crucial than early in the season, and this stands to reason. Physiologically speaking, cotton fibers are a product of plant reproductive growth, which occurs mainly during the late season stages of boll enlargement and maturation. The positive correlations with length, uniformity, and strength suggests that ample soil moisture at these later stages is conducive to cotton reproductive growth (such as the elongation process of the fiber primary wall) and thus gives rise to higher quality in the relevant fiber parameters upon harvest. On the other hand, soil moisture early in the season would largely contribute to vegetative growth (such as building a large plant framework) and would have less impact on the post harvest fiber quality. It can be seen in table 9 that no precipitation occurred at the squaring and flowering stage in 2005, and so no water at all was received for the cotton in the dry area during that period. This may explain the lack of correlation between most fiber parameters and soil moisture in dryland cotton in 2005 (table 10). Severe water stress may have caused the vegetative growth to be delayed (generally small cotton plants were observation in the dryland area in 2005), and the late season soil moisture replenished by precipitation may have been utilized largely for the vegetative growth.

Compared to other fiber parameters such as length and uniformity, micronaire exhibited weak correlations with soil moisture. This finding was somewhat unexpected because it is understood that micronaire within a given variety reflects fiber maturity and should respond readily to soil moisture, since adequate water is required by the plant to synthesize and deposit cellulose inside the fiber. One possible explanation is that micronaire's response to soil moisture may be more complex than for the other fiber parameters. If so, analysis with a simple linear relationship would not be adequate to describe the relationship.

Figure 12 is a scatter plot of micronaire versus soil moisture content during the boll enlargement ($r = 0.28$, table 11) and maturation stages ($r = 0.28$, table 11) in 2006. As evidenced by the trend lines, a non-linear relationship is present: micronaire tended to be high in the low moisture range, decreased gradually towards the moderate moisture range, and tended to increase again in the high moisture range. Upon cursory review it would appear that lighter soils exhibit a negative relationship between soil moisture and micronaire, while heavy soils exhibit a positive relationship between them. In consideration of this possibility, grid soil texture data for the IMPACT Center, collected by the USDA – NRCS Bryan Service Center (Bryan, Texas), were used to divide the samples into two categories (heavy soils and light soils). Grid soil texture data were on a regular grid (a total of 325 points at an average interval of 60 m). The soil texture at each sampling location was reported for up to five soil horizons. Regarding surface textures in the *D1* area, the data suggested three general types: clay, silty clay, and silty clay loam. A soil texture designation for the sample locations was derived with the nearest neighborhood method; i.e., the soil texture for a soil-moisture and cotton sample location was assigned the same soil texture as its nearest neighbor point in the USDA – NRCS soil texture data grid. Samples assigned clay and silty clay (clay content > 40%) were designated as heavy soils, and the samples assigned silty clay loam (clay content between 25 to 40%) were regarded as light soils. Correlation analysis between micronaire and soil moisture was run separately within both categories and the results are given in the figure 13. Upon dividing the samples according to light versus heavy soil texture, definite linear relationships between micronaire and soil moisture were observed. In the light soils, correlation coefficients were -0.53 and -0.4 at the boll enlargement and maturation stages, respectively. In the heavy soils, correlation coefficients were 0.74 and 0.64. These results seem to fall in line with the previously mentioned possibility that lighter soils exhibit a negative relationship between soil moisture and micronaire, while heavy soils exhibit a positive relationship between them.

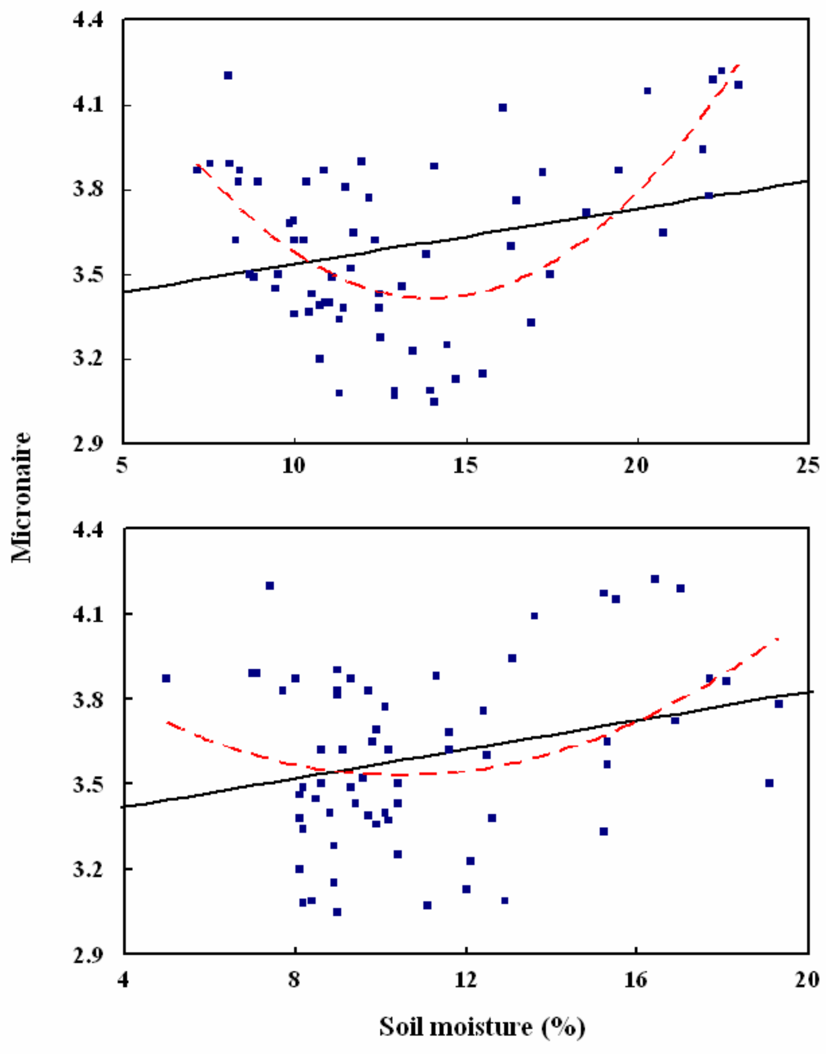


Figure 12. Scatter plot of micronaire versus soil moisture (■), linear regression line (▬▬), and trend line (▬ ▬) at boll enlargement (top) and maturation (bottom) stage in dry area in 2006 (n = 66).

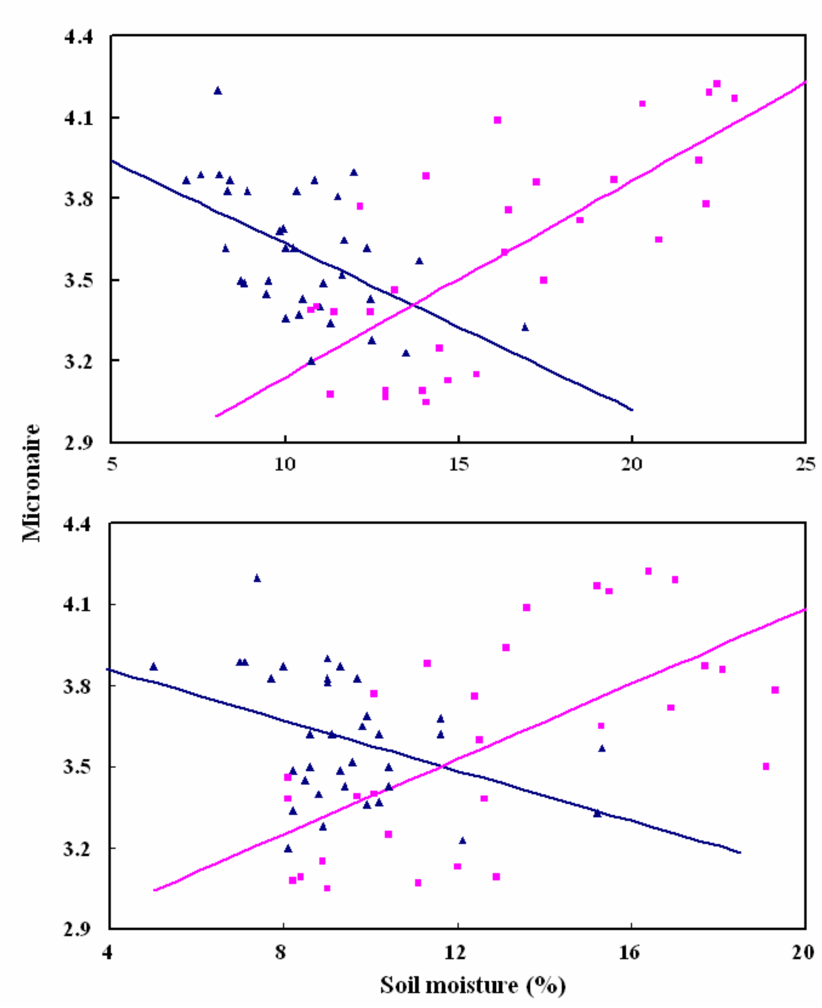


Figure 13. Scatter plot of micronaire versus soil moisture [heavy soils (■) and light soils (▲)] and linear regression line [heavy soils (—) and light soils (—)] at boll enlargement (top) and maturation (bottom) stage in dry area in 2006.

However, a detailed consideration of the literature points to a deeper answer. In studies undertaken at various geographic locations (Pettigrew, 2004a; Pettigrew, 2004b; Booker et al., 2006), a common conclusion drawn is that "reduced water application has an effect to increase micronaire (or bulk fiber maturation)". Some researchers

(Pettigrew, 2004a; Booker et al., 2006) have further proposed a reason for this phenomenon: “in substantial moisture deficits, cotton plants may only retain bolls at the lower fruiting branches and inner fruiting sites at each branch. Due to reduced photosynthate needs, cotton plants are able to carry these bolls into full maturation”.

These concepts appear to more satisfactorily explain the paradoxical relationship between micronaire and soil moisture in figure 12: (1) In the soils with low moisture content, cotton plants may have experienced severe boll abscission such that only bolls from lower and inner fruiting sites were retained and harvested. Due to reduced photosynthate requirements, these bolls could have been brought to full maturation (and thus high micronaire) even with very limited moisture supplies. (2) In soils with moderate moisture content (the depressed part of the scatter plot), cotton plants may have been able to retain some bolls at upper and outer fruiting sites. However, the higher soil moisture may not have been adequate for the rapid increase of water needs in the cotton plants to support extra bolls, giving rise to partially mature fibers and lowering of the overall bulk fiber micronaire. This phenomenon might be especially true if the textural composition of soils is considered. As mentioned previously, soils in the *D1* area are mainly categorized as clay, silty clay, and silty clay loam. These heavy soils tend to have high field capacity (FC, the amount of water remaining in a soil after a soaked wetting and when gravitational drainage is negligible) and high permanent wilting point (PWP, where water is entrapped so tightly in soil pores that it is no longer extractable by plants). Therefore, moisture contents in the high (moisture available over a long period of time) and low (moisture not available and likely to cause bolls to drop) ranges may have a greater positive effect on the fiber quality of cotton plants in these soils.

Based on the foregoing explanation, one should generally expect that if soil moisture content is low during boll enlargement, yield will be low and quality will depend on the availability of moisture in the fiber maturation stage: high moisture at this point will provide high fiber maturity and low moisture will provide low fiber maturity. On the other hand, if soil moisture content is high during boll enlargement, yield should tend to be high and quality will again depend on the availability of moisture in the fiber maturation stage: high moisture at this point will provide high fiber maturity and low moisture will provide low fiber maturity. With respect to yield, the foregoing expectations agree well with field observations: cotton plants grown in dryer soils (most of them were near field boundaries and some other relatively sandy areas) were usually smaller and shorter, and only retained 3 or 4 bolls per plant for hand-picking. On the other hand, cotton plants in the moister areas (such as the north-central area) had a much taller and larger vegetative framework, and many retained more than 20 bolls for hand-picking. With respect to fiber quality, it was deemed worthwhile to test what effect moisture content during fiber maturation had on micronaire, assuming that adequate moisture was available during boll enlargement. Therefore, the following analysis was conducted: (1) The 66 sample locations were divided into two equal-size categories of soil moisture during boll enlargement. (2) Of the 33 samples that fell into the higher-moisture category, these were divided into two roughly equal categories of soil moisture during fiber maturation. (3) These two categories were compared in terms of micronaire values. The results of this test fit the expectation given above, that higher moisture during fiber maturation will provide higher fiber maturity and lower moisture will provide lower fiber maturity. The lower-moisture category had micronaire values ranging from 3.1 to 3.9 with an average of 3.3, while the higher-moisture category had values ranging from 3.3 to 4.9 with an average of 3.9. A t-test indicated that the two categories were statistically different in terms of their micronaire values. Therefore, it is reasonably clear that the relationship between fiber maturity and soil moisture content depends less on soil type and more on the timing of moisture availability.

Discussion of Other Concerns

Hand- versus Mechanical-harvested Cotton Samples

It must be noted that there were several limitations in this study. First of all, the results of this experiment were based on hand-picked cotton samples. The samples were not stored in a module, and were processed with laboratory scale gins that have different machine sequences from a commercial gin with respect to seed cotton cleaning and lint cleaning. In other words, cotton in this study did not go through a commercial processing line that could substantially degrade fiber quality and reduce its value. Thus it is important to realize that the exploratory statistical summary (such as mean and CV) of the fiber parameters, the contour maps, and loan price maps only reflect fiber quality at the field level before harvest. Readers should be cautious in making comparisons between fiber quality data from commercial production and those presented in this study. For example, in 2005 the *D1* area had cotton with superior fiber quality such that the entire area would receive premiums from 4 to 7¢/lb. In practice however, this high level of premiums is questionable because mechanical harvesting and ginning fibers would likely degrade fiber quality somewhat.

Sample Spatial Correlation and Correlation Analysis

A fundamental assumption for correlation analysis is that samples should be independently distributed. In this study, nevertheless, appreciable spatial dependence was observed for all fiber parameters under investigation. This spatial dependence violates the assumption of independence, thus making the correlation coefficients suboptimal. In the other words, the estimated slope b_1 and intercept b_0 of a simple linear regression are not the maximum likelihood estimate of the population slope and intercept. It is important to point out that this problem persists in almost all field level studies where spatial dependence is likely to be observed. In soil sciences, some researchers (Odeh et al., 1994; Odeh et al., 1995; Hengl et al., 2004; McBratney et al., 2003) demonstrated how to account for spatial correlation in a linear regression analysis. Unfortunately in many agricultural disciplines this aspect has not been adequately considered.

An example analysis to account for spatial correlation was conducted with soil moisture data from the *D1* area at the boll enlargement stage in 2006. The method employed follows Hengl et al. (2003 and 2004). Firstly, semivariance analysis was performed on residuals from correlation analysis. If no spatial dependence were found in the residuals, Pearson's Correlation [OLS (ordinary least squares) estimation of population correlation] could be considered sufficient in describing the linear relationship between fiber quality and soil moisture (tables 10 and 11). However if apparent spatial dependence were found, Pearson's Correlation would tend to overestimate the true correlation, and the covariance structure in the residuals would need to be used to adjust the overestimation in a GLS (general least squares) sense.

Figure 14 presents the sample variograms and fitted models of residuals of each fiber parameter regressed against soil moisture at the boll enlargement stage in the *D1* area in 2006. To facilitate comparison, sample variograms of the original fiber parameters (as in figure 7) are also presented. Regression residuals for length, uniformity, strength, and Rd showed pure nugget effects (the percent nugget greater than 75%). Regression residuals for elongation and +b still showed spatial dependence, but to a much lesser extent [for elongation, the percent nugget was 33% (table 6) and 70% (0.056/0.080) for the original variable and residuals, respectively; and for +b 8% (table 6) and 35% (0.057/0.163)]. All these fiber parameters were found to be strongly correlated with soil moisture in correlation analysis. An explanation was that semivariance of the original variables occurring at larger lag distances was systematic and could be completely (in the case of length, uniformity, strength, and Rd) or partially (in the case of elongation and +b) removed by soil moisture [fitting an external drift, Hengl et al. (2004)], resulting in much smaller semivariance in residuals. On the other hand, residuals of micronaire exhibited almost the same level of semivariance at all lag distances as the original variable. Because of the low correlation, soil moisture as an external drift was not helpful in accounting for variance in micronaire.

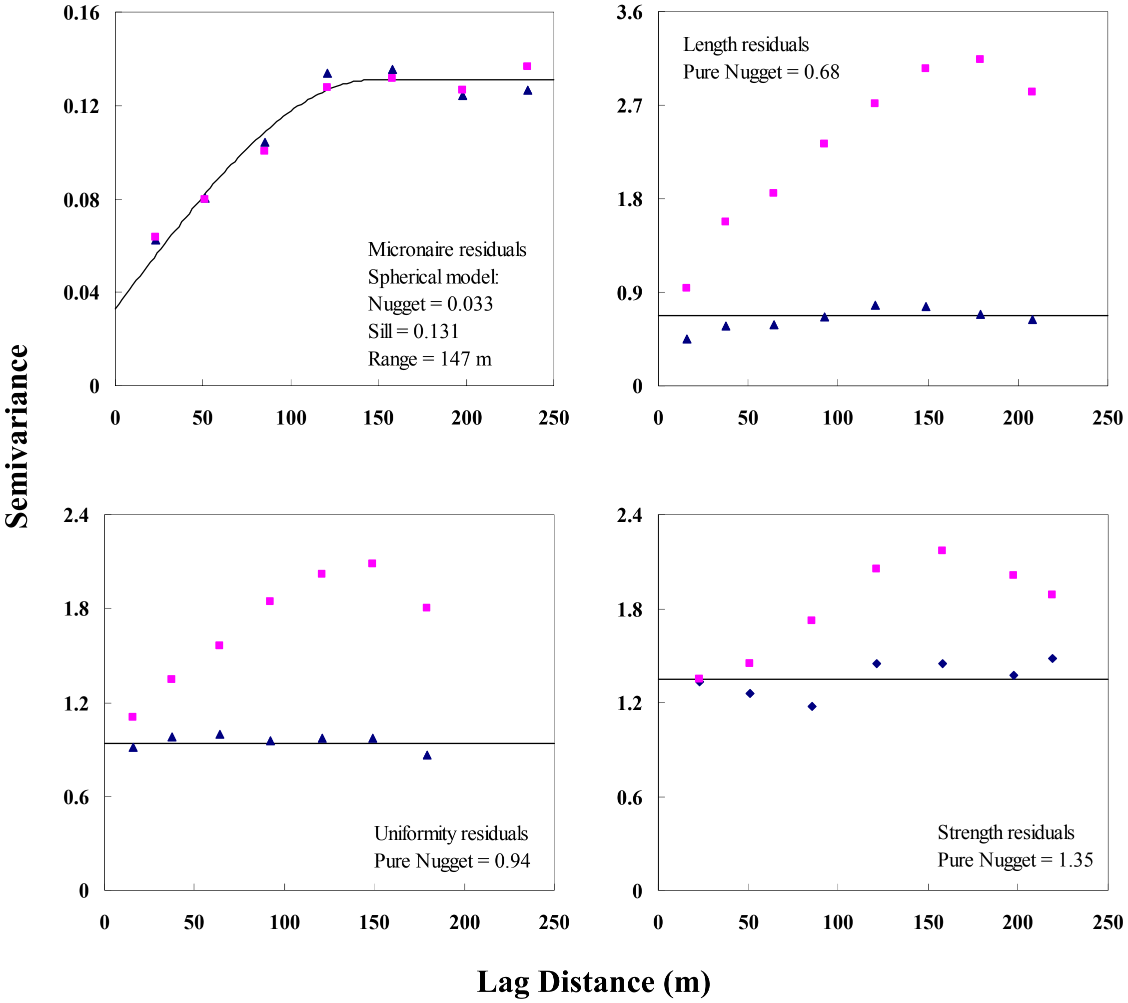


Figure 14. Sample variograms (▲) and fitted models (—) of residuals of regression between fiber parameters and soil moisture, and corresponding sample variograms of original variables (■).

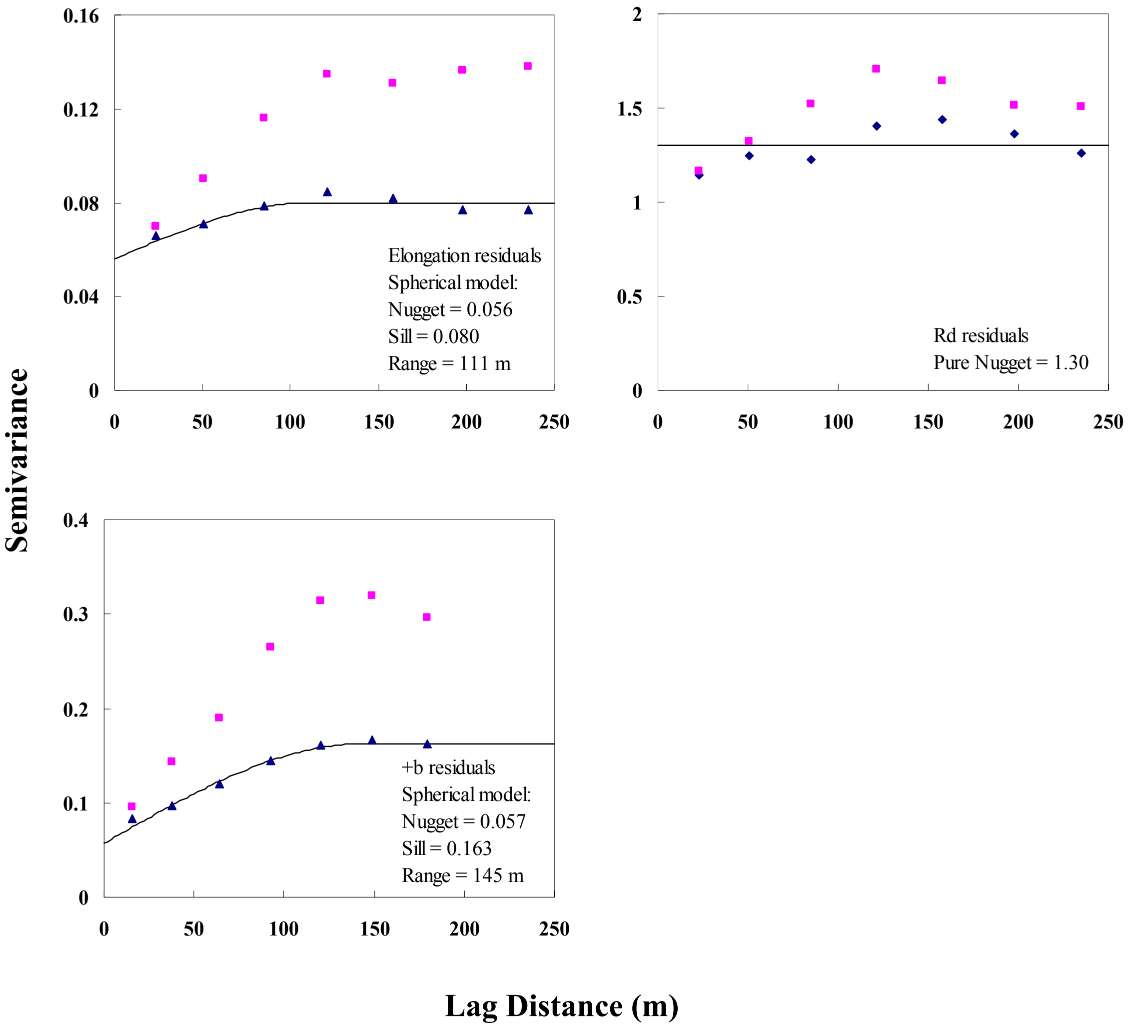


Figure 14. Continued.

Table 12 compares the parameters of the linear regression model for micronaire, elongation, and +b with and without the spatial correlation in residuals being accounted for. Relationships between the dependent and independent variables were somewhat different in the different models, as indicated by the regression coefficients b_0 and b_1. However, the true correlation (in the spatial model) was only slightly overestimated with the non-spatial model. On the other hand, the reduction in r could also have important influence on management decisions employed by farmers and researchers if overestimation passed certain critical lines (such as the 0.01 or 0.05 significant level). In other words, management decisions need to be made on the basis of models that are, in actuality, based on significant relationships. If a model appears to be significant at, say, the 5% level when spatial correlation is not considered, but is proven not to be significant when spatial correlation is considered, that model should not be used in making management decisions.

Table 12. Parameters of linear regression model for micronaire, elongation, and +b with and without considering spatial correlation in regression residuals.

	Non-spatial model			Spatial model		
	b_0	b_1	R	b_0	b_1	R
Micronaire	3.33	0.021	0.28	3.44	0.013	0.25
Elongation (%)	5.98	-0.047	-0.60	5.90	-0.041	-0.59
+b	10.8	-0.070	-0.62	10.5	-0.055	-0.60

¶ Non-spatial model means OLS regression as given in table 7; and spatial model means GLS regression. b_0 and b_1 represent the intercept and slope of the regression line, respectively.

Surface versus Subsurface Soil Moisture

In this study, soil moisture content was measured at the surface level with a nominal measurement depth of 30 mm. Late in the season, the cotton tap root can grow as deep as one to several meters, depending upon the surrounding soil conditions (Longenecker and Erie, 1968). Thus it would be more desirable if subsurface soil moisture were measured and related to fiber quality parameters. Sensors like neutron probes are commercially available for measuring soil moisture at different horizons. To use a neutron probe, a hollow column must be bored at each sampling location, taking a measurement is time-consuming, and safety considerations must be taken into account because of the use of a radioactive emitter. The difficulty involved in using a neutron probe would be inappropriate for a precision agriculture study in which soil moisture data are required at high temporal and spatial resolution. One benefit of measuring surface soil moisture is that it can be measured quickly and exhaustively over a wide area. With modern remote sensing technology (such as near infrared, thermal, and radar imaging), surface soil moisture can potentially be assessed over a wide scene within seconds. In this sense, surface soil moisture would be more desirable.

Since soil moisture in the root zone should explain more about plant growth than surface soil moisture, the latter affords a less than ideal amount of information. To tackle this problem for a similar study in the future, a two-stage sampling strategy is suggested. The first stage would involve exhaustive sampling of surface soil moisture with a Theta Probe or other appropriate method, possibly to include remotely-sensing. The second stage would involve selecting a subset of sampling points and measuring subsurface soil moisture at various horizons (sparse sampling), such as with a neutron probe. The relationship between surface and subsurface soil moisture at several locations could be established (such as with linear regression), and this relationship could be extended to the entire area for predicting the subsurface soil moisture at different horizons. Many statistical methods, such as kriging and co-kriging, could be employed for this purpose.

The predicted subsurface soil moisture could then be used instead of surface soil moisture to relate to post-harvest fiber quality.

Along these lines, a concurrent research project was conducted on the IMPACT Center in 2006 by Dr. Cristine Morgan and her graduate students (Department of Crop and Soil Sciences, Texas A&M University). They measured weekly moisture content along the soil profile (every 0.2 m to a depth of 1.2 m) using a neutron probe at eight locations in the *D1* area. These data afforded additional insight into the relationship between surface and subsurface soil moisture. Table 13 presents the surface and subsurface soil moisture at the eight locations, and figure 15 is a scatter plot between the ThetaProbe and neutron probe measurement at 1.0 m (the highest r value over all depths). Although significant correlations exist, discrepancies between the two sets of measurements are also evident. It appears that soil textures play a dominant role in relating surface soil moisture to subsurface soil moisture. It is known that points 4 and 7 in figure 15 are from the central portion of the field and have higher clay percentages than other points. Had these two points been removed, the positive correlation would disappear. Because soil textures tend to vary greatly horizontally within a field but tend to be similar along the vertical profile, it should be feasible to estimate subsurface soil moisture from surface soil moisture, and such an estimation might be enhanced by including data on the variation in soil texture.

Table 13. Surface and subsurface soil moisture measured at eight common locations in *D1* area in 2006. ¶

Point	ECa (dS/m)	Soil moisture (%)						
		Surface (ThetaProbe)	Subsurface (Neutron Probe)					
			0.2 m	0.4 m	0.6 m	0.8 m	1.0 m	1.2 m
1	58	6.8	20	14	10	10	11	14
2	92	8.9	11	10	8	12	12	12
3	81	9.3	9	4	5	7	14	12
4	108	16.7	24	20	28	23	26	27
5	59	9.2	9	5	6	5	5	7
6	79	8.3	13	8	7	13	9	12
7	118	10.9	23	25	3	15	18	26
8	83	7.5	10	7	10	9	9	13
Correlation coefficient *r*			0.61	0.59	0.79	0.83	0.88	0.79

¶ Surface soil moisture was measured with the ThetaProbe. Readings were taken at five random locations within 0.3 m radius around each neutron probe sampling pit. Five readings were averaged and rounded to the nearest tenth representing surface soil moisture at each neutron probe location. Both ThetaProbe and Neutron Probe measurements were taken on 17 Jul 2006.

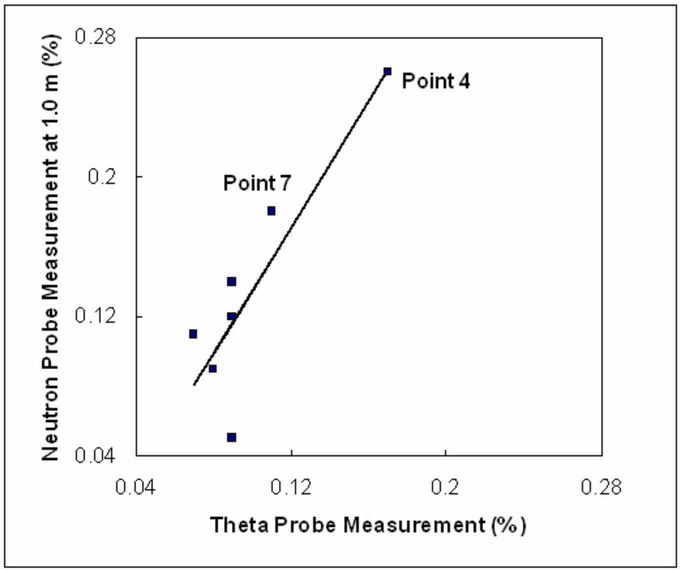


Figure 15. Scatter plot of Theta Probe Measurement versus neutron probe measurement at depth of 1.0 m for eight common points in *D1* area.

CHAPTER III

A WIRELESS GPS SYSTEM FOR AUTOMATED FIBER QUALITY MAPPING

PROBLEM STATEMENT

Producing fiber quality maps by means of manual sampling and spatial interpolation, as discussed in Chapter III, has two major disadvantages. First of all, it is very time-consuming and labor-prohibitive. The time and cost to collect enough fiber samples for characterizing an entire field would increase geometrically in large cotton fields. Secondly, the accuracy of maps is dependent on the validity of the statistical model (e.g., stationarity and omni-directional spatial structure), which is usually derived from a limited number of samples and subsequently difficult to validate. Lastly, fiber quality maps resulted from manual sampling may not reflect the actual quality of cotton fibers at the classing office because of the differences between hand-picked cotton that is ginned in a laboratory setting and mechanically harvested cotton that is ginned in a commercial gin. Machine harvested fibers usually contain more foreign matter than hand harvested samples, and there are differences in ginning that have been discussed previously. Calhoun et al. (1996) compared fiber quality data from hand- versus machine-harvested samples and found that some intrinsic fiber quality parameters (such as length and micronaire) were significantly affected by the harvesting method alone.

These shortcomings could be overcome if an automated, onboard fiber quality mapping system were developed, similar to the principle of a cotton yield monitor that is used for real-time cotton yield mapping (Wilkerson et al., 2001; Thomasson and Sui, 2003). Unfortunately, there are some technical difficulties that prevent direct use of this principle for real-time fiber quality mapping. Unlike the lint yield which is quantified by a simple index such as kg/ha, fiber quality consists of a collection of parameters that are quantified by different indices. Existing equipment for fiber quality measurement (e.g., HVI and AFIS) are laboratory-based and quantify the fiber quality of only ginned samples. No studies have been conducted on real-time, *in situ* fiber quality sensors (such as an onboard HVI line) which are capable of measuring individual fiber quality parameters of seed cotton upon harvest. Indeed, real-time fiber quality mapping is not foreseeable in the near future, because a very elaborate system comprising a sampling device, an onboard gin, and fiber quality sensors would be required. However, since fiber quality is measured for every bale of cotton produced in the U.S., it is conceivable to trace bale-level fiber-quality data back to the field location from which the bale came.

The Cotton Program at USDA – AMS has developed a standard data format [known as Universal Classification Data Format (USDA, 2005)] for classifying every bale of cotton produced and classed in the U.S. The format includes a five-digit module number, a unique 12-digit bale number (comprising a five-digit gin code and a seven-digit Permanent Bale Identification), fiber quality data, a five-digit number indicating premium or discount values, etc. (table 14). Farmers can easily obtain the fiber quality data via telecommunication or Internet (USDA, 2001; USDA, 2005). Thus if it were possible to develop a system to record the location information of each harvesting unit (such as baskets, bales, or modules) in the field, fiber quality data at the classing office could then be related to the location information so that fiber quality mapping would be possible, and the need for a real-time fiber quality sensor could be circumvented. Contrary to other mapping systems where target variables (such as lint yields) are measured real-time *in situ*, this system would involve an indirect method because fiber quality data would be obtained indirectly from the classing office some time after ginning.

Table 14. Universal Classification Data Format developed by Cotton Program in USDA-AMS.

Field Name	Column
Gin Code Number	01-05
Gin Bale Number	06-12
Date Classed	13-20
Module, Trailer, or Single Bale	21
Module/Trailer Number	22-26
Bales in Module/Trailer	27-28
Official Color Grade	29-30
Fiber Staple Length (32nds of an inch)	31-32
Micronaire	33-34
Strength (g/tex)	35-37
Leaf Grade	38
Extraneous Matter	39-40
Remarks	41-42
Instrument Color Grade	43-44
Color Quadrant	45
Color Rd	46-48
Color +b	49-51
Non-Lint Content (Trash Percent Surface)	52-53
Fiber Length (100ths of an inch)	54-56
Length Uniformity Index (percent)	57-59
Upland or Pima	60
Record Type	61
Record Status	62
CCC Loan Premiums and Discounts	63-67

Generally three types of field vehicles are used in cotton harvest: harvesters, boll buggies, and module builders. A harvester (picker or stripper) travels across the field and seed cotton is stored in its basket. When the basket is full, the harvester dumps the basket into a module builder directly, or a boll buggy basket which will later be dumped into a module builder when it is full. A completed module is stored on site and then hauled to the gin where it may be store temporarily but is ultimately disintegrated, ginned, and pressed into several bales. This system of collection, transport, storage, and processing has three important implications for a potential automated fiber quality mapping system.

1. As far as location information is concerned, the harvester's basket would be the smallest resolvable unit. That is to say, the location information can be collected and geographical boundaries can be delineated for each harvested basket, but no further division can be made within each basket unit, because once the cotton is accumulated in the basket, the location of individual portions cannot be resolved.
2. As far as fiber quality information is concerned, the module would be the smallest resolvable unit. Although fiber quality information is available at the bale level (table 14), it is impossible to relate a bale to the location information of an individual basket, as several baskets are mixed together in a module that is subsequently disintegrated into several bales. In other words, bale level fiber quality information must be averaged across an entire module.

3. In order to relate the basket-based location information to the module-level fiber quality information, a hardware and software system to trace each basket of seed cotton from harvester to boll buggy to module builder is needed.

The first two implications determine the achievable resolution of fiber quality maps when using the indirect method proposed. A basket unit roughly corresponds to a geographic region of 0.4 ha (1.0 ac.), assuming a yield of 1100 kg/ha (around 2.0 bale/ac.) and two bales per basket unit. This is in strong contrast to a conventional yield map with meter-level resolution generated by a cotton yield monitor (Thomasson and Sui, 2003; Sui et al., 2004). However, the current cotton pricing system maintained by USDA is based upon bulk fiber quality at the bale level, so high resolution fiber quality maps would not be justified anyway, as large portions of the in-field variation would be averaged. Moreover, indirect maps may also take into account the effects of harvesting routes which result in particular fiber segregation patterns. For these reasons, module level fiber quality maps have practical advantages in terms of differentiating between modules' fiber quality levels and calculating farmers' profit margins.

The third implication suggests wireless communication technology as a means to send tracking messages. The major advantage of wireless is that the mobility of field vehicles (harvesters, boll buggies, and module builders) would not be limited by wires and cables if electronic components needing to communicate with one another for basket tracking were distributed on various vehicles.

LITERATURE REVIEW

Fiber Quality Information System

Commercial systems are available to utilize fiber quality information at the classing offices to aid in textile processing and cotton production. Over the past 25 years, Cotton Incorporated has developed EFS® (Engineered Fiber Selection), which serves as a fiber quality information system between gins and textile mills. Through the use of USDA-AMS HVI data, it provides authoritative fiber management and analysis information and electronic communication among mills, ginners, producers, and merchants. EFS consists of a group of programs (such as GINNet, MILLNet, and QRNet 32) which allows cotton handlers to make accurate inventory, evaluation, and handling decisions from ginning to spinning. With these programs, users can also profitably apply the unique, natural properties of various types of cotton groups and categories to their growing, ginning, spinning, and processing techniques to produce statistically uniform cotton mixes which are best suited for a specified end product. Currently, the EFS® system is used by nearly all cotton spinning mills in the U.S. and a total of 29 mills in Europe, Canada, Mexico, and Asia.

Field-level Information System

Commercial systems are also available to utilize spatial information in cotton production. Mapshots Inc. (Cumming, Ga.) developed EASi Suite, a generic recordkeeping and information system providing SSCM solutions for agricultural crops. Recently, EASi Suite has incorporated special features that allow some level of data automation between gins and farms. These features include: PDA support for module identity entry and EASi Suite synchronization, gin notification for module pickup, notification of module weights into EASi Suite upon module pickup, notification of bale identification and weights into EASi Suite upon ginning, and notification of bale fiber quality into EASi Suite upon bale classification. Finally, EASi Suite is able to present these data in tables and charts and allows farmers to better understand the yield and quality of their cotton.

Automated Fiber Quality Mapping System

The only study available in the literature that has attempted some level of automation for on-farm fiber quality mapping is that of Sassenrath et al. (2005). The principal component of the reported system was a sampling device that could be turned on and off every 10 s, and when turned on it diverted seed cotton from the picker's conveyor chute to sample bags during mechanical harvesting. The geographic information of each sampled bag was recorded by a GPS receiver. Seed-cotton samples were later ginned with a small-scale research gin and classed. The discounts or premiums of each sample were determined by the fiber quality parameters. Spatially registered maps demonstrating variability of micronaire and lint discounts were then developed. The spatial resolution of the maps was 18 by 18 m, equivalent to 0.0324 ha. One advantage of the system was that cotton samples were mechanically harvested. However, the system still involved substantial human intervention (such as manually turning on and off the sampling device and laboratory seed-cotton ginning) and thus was not appropriate for large-scale applications.

Wireless Communication Technology in Agriculture

Wireless communication technology has been widely deployed in many aspects of agricultural production. Gomide et al. (2001) conceptualized an automated data acquisition and control mobile laboratory network for crop production and spatial variability studies in the Brazilian center-west region. The system could collect soil and crop data with a data collection vehicle via a wireless local area network (WLAN). Lee et al. (2002) prototyped a Bluetooth wireless communication system that could be used for corn silage mapping. Moisture content of corn silage was measured by the moisture sensor and transmitted wirelessly to a host computer mounted on a trailer. It was expected that the moisture measurement would be used to calibrate the yield data to dry basis in real-time. Hamrita and Hoffacker (2005) developed a prototype system that used the Radio Frequency Identification (RFID) technology to monitor soil temperature wirelessly. Soil temperature was sensed by a thermometer Integrated Circuit, and an embedded Motorola 68HC11 microcontroller was used to measure and send the signals to the RFID tag (transmitting unit). A receiving unit (interrogator) then collected the measurements from the RFID tags and transmitted them to a data processing PC. Although the system was limited in transmission range (less than one meter), it still has potential in precision farming applications where interrogators can be mounted on equipment regularly passing over the field (such as center pivot booms).

Wireless communication technology has also been employed in cotton production. McKinion et al. (2004) used WLAN on a 700-ha cotton farm in Noxubee County, Mississippi to integrate farm data with bale fiber quality information from two nearby gins. The system was reported to be helpful to both gin operators and farm managers in terms of serving their clients. Vellidis et al. (2005) developed and tested a prototype sensor array for measuring soil moisture and temperature in a cotton field at Tifton, Georgia. The system allowed for a large number of sensors to be installed and provided data wirelessly to a central receiver. The data could be used to realize Variable Rate Irrigation (VRI) for cotton production.

Wang et al. (2006) reviewed the recent development of wireless sensors for use in the agriculture and food industries. They pointed out that although deployment of wireless technology is still in the beginning stages, several scenarios have been attempted: (1) environmental monitoring, (2) precision agriculture, (3) machine and process control, (4) building and facility automation, and (5) traceability systems. Obvious advantages of wireless technology include increased system mobility and reduction and simplification in wiring and harnesses. On the other hand, many issues (such as system reliability, maintenance, security, etc.) remain to be addressed before the technology can be fully adopted in agricultural settings.

OBJECTIVES

The objective of this portion of the research was to develop an automated, GPS and wireless based system to: (1) record the location information of each harvested basket of seed cotton, and (2) trace the basket from the harvester to the boll buggy and the module builder. When used in conjunction with fiber quality information produced at the classing offices, the system can be used to enable indirect fiber quality mapping at the module level.

SYSTEM DESIGN AND FABRICATION

Design Criteria

As with most equipment designed for precision agriculture, the proposed system should be as fully automated as possible. The benefits of the added information obtained by using the system must not be eclipsed by high requirements for labor and investment. Cotton harvesting is very busy, and large acreages of cotton should be harvested as quickly as possible to reduce the risk of bad weather and quality degradation. In harvest operations workers usually concentrate on other business such as harvester-driving. Automation implies that the system needs very little human intervention. Upon installation, it should run automatically with a minimum of human oversight, which would keep the cost of operation low. In addition, automation implies that the system should be easy to operate when human interaction is required. Operators should be able to operate the system with little requirement for training.

Another design criterion is expandability. Individual cotton farms vary greatly in size, available equipment, and management practice. Therefore different numbers and types of field vehicles may be used during harvest. Expandability requires that the architecture of the system should be based on a general scenario, i.e., addition or deletion of field vehicles would not significantly cause the alteration of the system framework, hardware components, and software design.

Principles for Harvester Basket Tracing

The proposed wireless GPS system is composed of several functional subsystems, with each subsystem being mounted on a field vehicle. Each subsystem is composed of a grouping of electronic components that together execute functional requirements such as receiving GPS signals and transmitting wireless messages. The functional subsystems communicate with each other wirelessly to trace the harvested basket from one vehicle to another.

The system would be quite simple in the "basic scenario" where only one harvester and one module builder are used. In this situation, a basket dump would occur from only the harvester to the module builder. Two functional subsystems (referred to as harvester subsystem and module builder subsystem, to be mounted on the harvester and module builder, respectively) are needed. The principle of basket tracing is simple and can be described as follows.

The harvester subsystem successively receives the location information of the current basket from a GPS receiver and records it into a log file as the harvester travels across the field. When the basket is full and a dump occurs, the module builder subsystem transmits a wireless message that contains the current module number to the harvester subsystem. Upon receiving the module number, the harvester subsystem attaches this information to the log file and closes it. One cycle of basket tracing is thus completed. The harvester subsystem then opens a new log file to record the location information for a new basket. When the current module builder is full and a new module is started, the module builder subsystem generates a new module number. Thus each log file stored in the harvester subsystem represents a certain harvested basket, with the file content indicating the location information of that basket and the module into which it is dumped.

According to the above description, two major functions of the harvester subsystem are:

- To receive GPS signals and record the location information into log files;
- To receive and log the wireless message containing the module number from the module builder subsystem.

Two major functions of the module builder subsystem are:

- To transmit wireless messages containing the current module number;
- To update the module number when a new module is started.

The complexity of the system is increased when one boll buggy is added (the "simple scenario": one harvester, one boll buggy, and one module builder). In this situation, three dump types exist: (1) from the harvester to the module builder: (2) from the harvester to the boll buggy, and (3) from the boll buggy to the module builder. In this case a boll buggy subsystem is mounted on the boll buggy. If a basket is dumped directly from the harvester to the module builder, the same tracing actions are taken as in the basic scenario. If a basket is dumped into the module builder through the boll buggy, a temporary boll buggy number is employed as a link to trace a harvester basket to the module builder. Assuming the log file for the current basket is File #1 and the basket is dumped into the boll buggy, then a wireless message containing a boll buggy number is transmitted by the boll buggy subsystem. Upon receiving the boll buggy number, the harvester subsystem attaches it to File #1 and leaves the log file open. It is worth noting that multiple harvester baskets could be dumped into the boll buggy basket before it is dumped into the module builder. Thus, several log files could be maintained unclosed when a new log file is opened for the current harvester basket. When the boll buggy basket is dumped into the module builder, the module builder subsystem transmits a wireless message containing the current module number to the harvester subsystem. When the module number is received, the harvester subsystem attaches it to all of the unclosed log files and then close them. At the same time, a new boll buggy number is generated, representing a new boll buggy basket.

Two major functions of the boll buggy subsystem are:

- To transmit wireless messages containing the boll buggy number;
- To update the boll buggy number when the boll buggy basket dumps into the module builder.

Because of the addition of a boll buggy, an additional function of the harvester subsystem is:

- To receive and log the wireless message containing the boll buggy number from the boll buggy subsystem.

The proposed system would be much more elaborate if multiple harvesters, boll buggies, and module builders were involved (“complex scenario”). For the sake of simplicity, discussion of the tracing mechanism will be based on a hypothetical situation having two harvesters (referred to as H1 and H2), two boll buggies (referred to as B1 and B2), and two module builders (referred to as M1 and M2). Figure 16 illustrates 12 possibilities in which dumps could occur between different vehicles. Compared to the simple scenario, the following facts need to be considered in the tracing mechanism for the complex scenario:

- H1 (or H2) could dump two consecutive baskets into B1 and B2, respectively;
- B1 (or B2) could contain baskets from both H1 and H2.

For sake of discussion, it will be assumed that H1 dumps two baskets represented by two open log files, #1 and #2, into B1 and B2, respectively. Furthermore, H2 dumps two baskets represented by two open log files, #3 and #4, into B1 and B2, respectively. Thus File #1 in H1 and File #3 in H2 receive the same boll buggy number (from B1), and File #2 in H1 and File #4 in H2 receive the same boll buggy number (from B2). It should be noted that the boll buggy numbers used by B1 and B2 must be different from each other. When B1 is dumped into M1 and the wireless message is transmitted from M1, it is important to ensure that both H1 and H2 can receive the message (because both H1 and H2 have baskets dumped into M1 through B1). Different from the simple scenario, the wireless message in this scenario should contain not only the current module number for M1, but also the current boll buggy number for B1. Then, instead of simply attaching the message to the open files, the harvester subsystem would compare this boll buggy number with the one previously attached to the open log files, and only attach the associated module number to the files in which a match of the boll buggy number are found. In other words, H1 will attach the module number to only File #1 (where a match of the boll buggy number of B1 is found) and leave File #2 intact; H2 will attach the module number to only File #3 and leave File #4 intact. By this means all of the baskets from both harvesters can be linked to the appropriate module number via the boll buggy number.

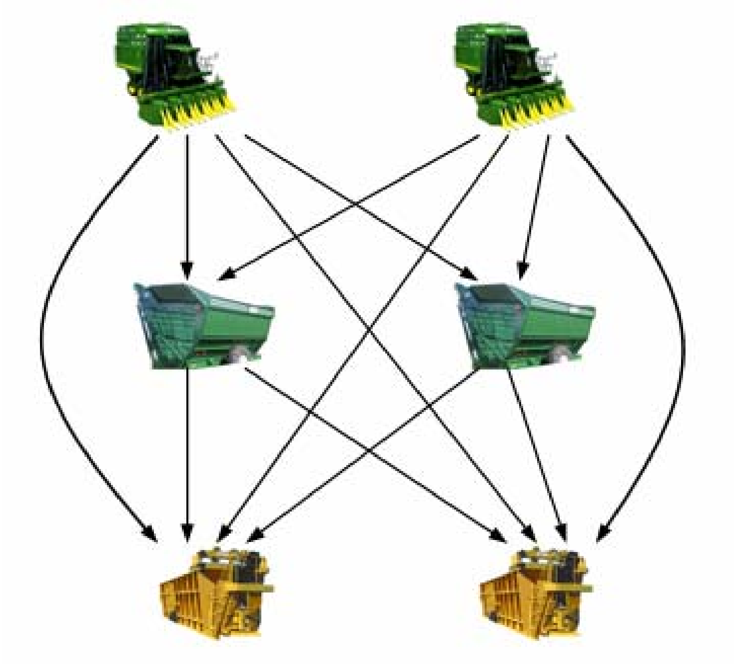


Figure 16. Twelve possible dump types between vehicles in a hypothetical harvesting scenario with two harvesters, two boll buggies, and two module builders.

Basic Hardware Requirements

Based on the foregoing discussion, the basic hardware requirements of for the harvester subsystem are identified as follows:

- A GPS receiver to record the location information from GPS satellites;
- A wireless transceiver to communicate wirelessly with other subsystems;

- A central processing unit to provide high-speed data processing and control;
- Non-volatile memory to log location information and boll buggy/module numbers;
- Supporting electronics for the I/O (input/output) purposes.

The boll buggy subsystem and module builder subsystem are very similar in terms of their functionality. Hence most of the same hardware components are required. These include:

- A wireless transceiver to communicate with other subsystem;
- A central processing unit to perform high-speed data processing and controlling;
- Supporting electronics for the I/O purposes.

FIRST VERSION PROTOTYPE SYSTEM

Due to logistical and budgetary concerns, the first version of a prototype system was based upon the basic scenario. It consisted of two functional subsystems, a harvester subsystem and a module builder subsystem.

Hardware Description and Assembly

A G30L-RS232 GPS receiver (LAIPAC Technology, Inc., Richmond Hill, Ontario, Canada; figure 17-a) was chosen because of its compact size (about half the size of a computer mouse) and full positioning capabilities, which make it readily adaptable to system prototyping. With WAAS correction, its position accuracy is 25 ft (about 8.0 m). This receiver is adequate for this application considering that the resolution of the eventual fiber quality maps would likely be at the 1.0-ac. level (around 65 by 65 m). The highest GPS signal update rate is 1.0 Hz. Because the harvester usually travels at a speed lower than 8.0 km/h (about 5.0 mi./h), this signal update rate is sufficient to produce enough points to delineate the areas of each harvester basket fairly precisely. The signals are output via an RS232 serial port with a baud rate of 4800 bps (bits per second). Output messages of the GPS receiver are in the NMEA (National Marine Electronic Association) 0183 protocol (Trimble, 2006). More specifically, it outputs five GPS sentences (GPGGA, GPRMC, GPGSA, GPGLL, and GPVTG) in a comma delimited format. Only the GPRMC is used in this system to extract the location information (other sentences are ignored). Figure 18 shows the structure of a GPRMC sentence and the meaning of each field (Trimble, 2006).

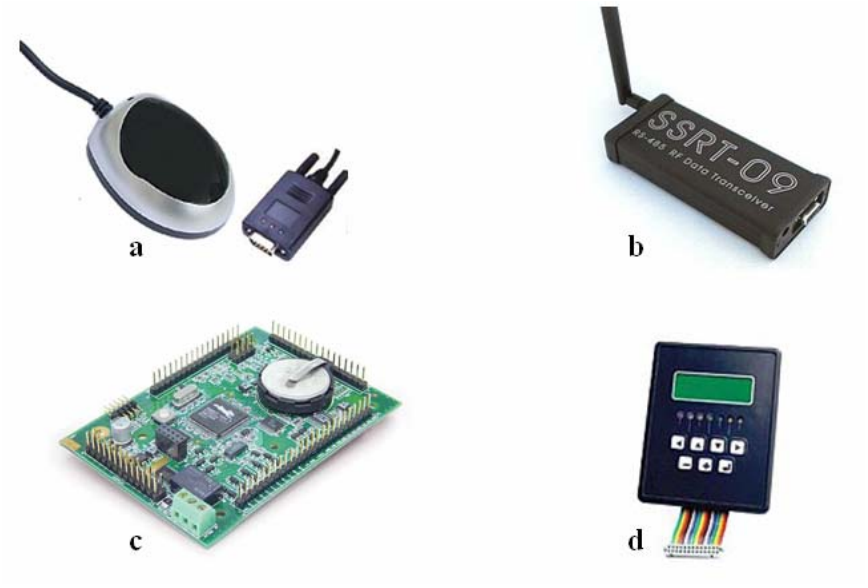


Figure 17. Major hardware components selected for prototype system: a. G30L-RS232 GPS receiver, b. SSRT-09-RS232 transceiver, c. 3500Fox single board computer, and d. keypad/display unit.

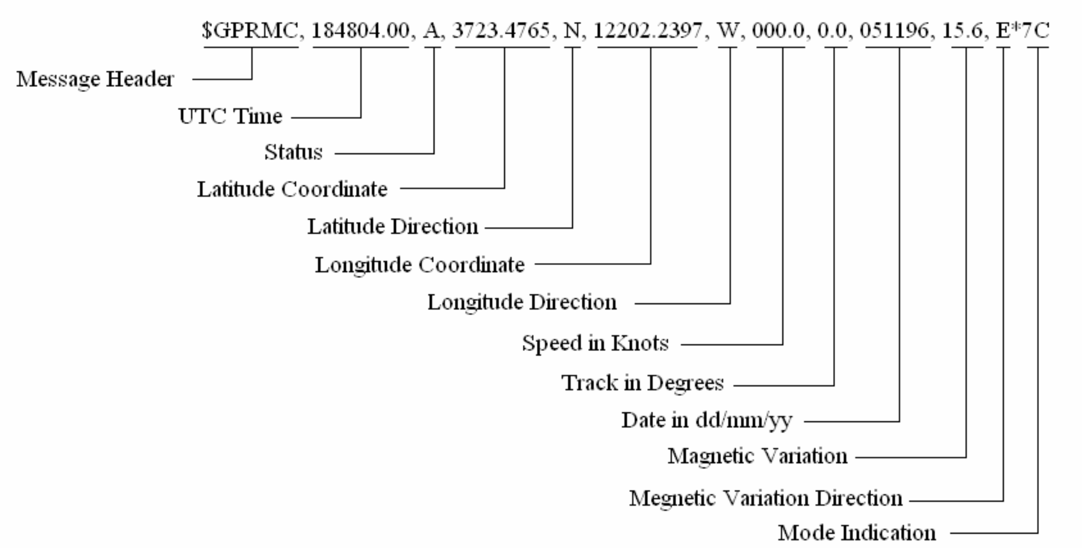


Figure 18. Structure of GPRMC sentence and meaning of each field.

A pair of SSRT-09-RS232 spread spectrum radio data transceivers (ABACOM Technologies, Inc., Ontario, Canada; figure 17-b) was used for wireless communication between the harvester subsystem and module builder subsystem. Each transceiver has a nominal 5.0-km (around 3.0-mi.) transmission range in the open, which is adequate for fairly large cotton fields. In the case of extremely large fields, optional high-gain antennas with a 32-km (20-mi.) transmission range are also available. Wireless messages are carried on the 900-kHz radio frequency, and the highest data transfer rate between the transceiver pair is 19,200 bps. In this application, the data transfer rate was set at 4,800 bps to be consistent with that of the GPS receiver. This rate is adequate because, as will be discussed in the following sections, the volume of data needing to be transmitted in this application is small (less than 200 bits per transfer). Signals being communicated are input to (or output from) the wireless transceiver via an RS232 serial port.

Two single board computers [SBC (model 3500Fox, Rabbit Semiconductor, Davis, Cal.; figure 17-c)] were used as the central processing units for both subsystems. Compared to other low level microcontrollers, the SBC includes all the necessary peripheral circuitry (e.g., oscillator, startup delay circuit) needed by the microcontroller so that it can automatically commence operation when power is supplied. Each SCB was mounted in a 3500Fox prototyping board (Rabbit Semiconductor, Davis, Cal.), greatly facilitating the connection of external electronics to the SBC's I/O ports. The SBC has a 7.4-MHz microprocessor with 512 kB (kilobytes) of Static Random Access Memory (SRAM) and two 256-kB flash memory boards. The first flash memory board was used for the control program, and the second was used as non-volatile memory for log file storage. In the case of extremely large fields needing an extra large number of log files, a portion of SRAM can be also used for data storage because of the onboard backup battery. The SBC features three RS232 serial ports (referred to as Ports B, C, and E), which were used to connect the GPS receiver and wireless transceiver to the SBC. The baud rate for serial communication on the SBC was set at 4,800 bps to match that of the GPS receiver and wireless transceivers.

A keypad/display unit (also manufactured by Rabbit Semiconductor, Davis, Cal.) having a seven-key keypad, six indicator outputs, and a 122 by 31 dot LCD (Liquid Crystal Display) was used (figure 17-d). It was connected to the SBC via a 20-pin ribbon cable. In addition to providing necessary I/O functions, the keypad/display unit facilitated system prototyping and debugging, as actual switch actions can be simulated by keypad pressing, and intermediate results (such as the GPS information) can be shown on the LCD. Detailed technical specifications for the G30L-RS232 GPS receiver, SSRT-09-RS232 transceiver, and 3500Fox SBC are presented in table 15. Figure 19 is a schematic of the harvester subsystem and the module builder subsystem.

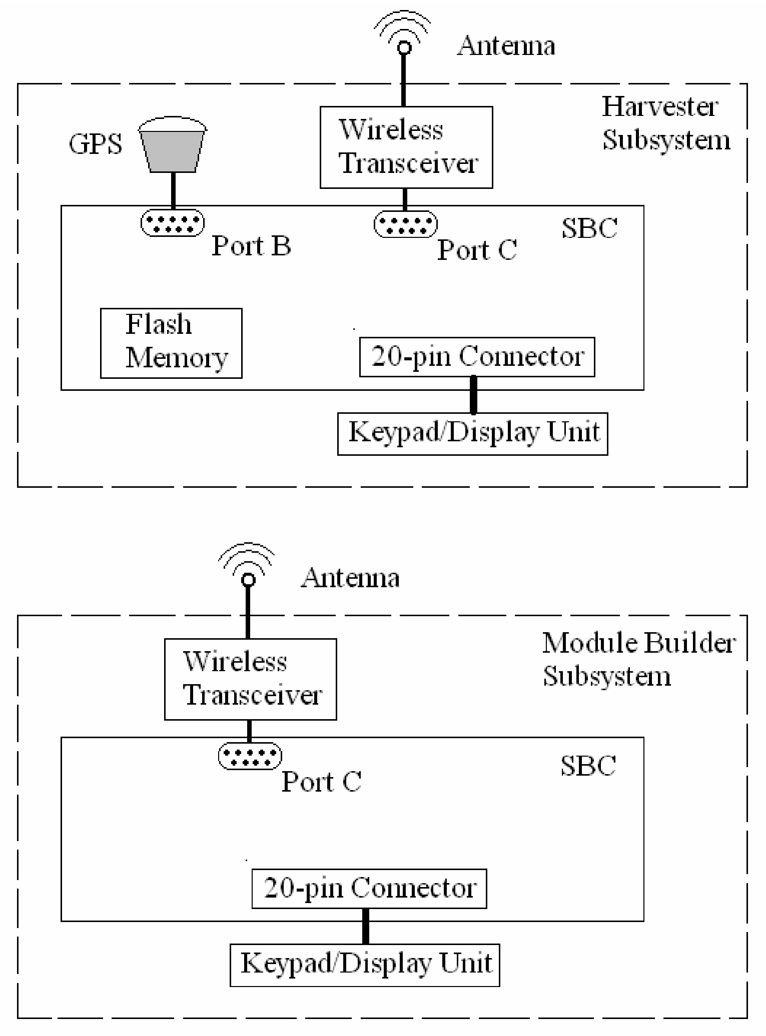


Figure 19. Schematic of functional subsystems of first version prototype system.

Table 15. Technical specifications of GPS receiver, wireless transceiver, and SBC selected for first version prototype system.

Hardware	Technical Specifications
GPS receiver	Position accuracy: 8.0-m circular error probable without selective availability Message protocol: NMEA-0183 version 2.2 Update rate: 1.0 Hz Cable connections: DB-9 serial connector Serial communication rate: 4,800 bps Input Voltage: 5.0 V DC Time to first fix: 45, 38, and 8 s for cold start, warm start, and hot start, respectively
Transceiver	Transmission range: up to 5 km (three miles) in open field and 600 m (1800 ft) in building; 32 km (20 miles) with optional gain antennas Cable connections: DB-9 serial connector Data transfer: half duplex with a pre-modulated 4,800 bps (maximum 19,200 bps) Power consumption: 7.5-15 V DC, 170 mA transmit mode, and 80 mA receive mode Carrier radio: High noise immunity spread spectrum architecture, 900 MHz FM Network capability: Point-to-point and point-to-multipoint radio frequency networks
SBC	Microprocessor: 7.4 MHz Memory: 512 kilobytes SRAM and 512 kilobytes flash memory (2 × 256 kilobytes) Serial ports: three regular RS232 (3 wires: RX, TX, and GND) Serial communication rate: programmed to 4,800 bps, around 1M bps maximum Power consumption: 3-30 V DC, 20 mA maximum Backup battery: three V lithium coin type Digital I/O: 16 inputs and 10 outputs (eight sink and two source) Operating Temperature: -40°C to +70°C

All of the hardware components, together with other supporting electronics (including wires, fuses, ON/OFF switches, cooling fans, voltage regulators, and connectors) were compactly assembled into two plastic box enclosures (Newark InOne, Chicago, Ill.). Figure 20 is a snapshot of the consolidated units (the top one being the harvester subsystem and the bottom one being the module builder subsystem). Users are allowed to input commands for a specific action via the keypad, and the status of the program is displayed on the LCD. Figure 21 shows the layout and wiring of the electronic components in the box enclosure for both subsystems.

Figure 20. Consolidated units of harvester subsystem (top) and model builder subsystem (bottom) in first version prototype system.

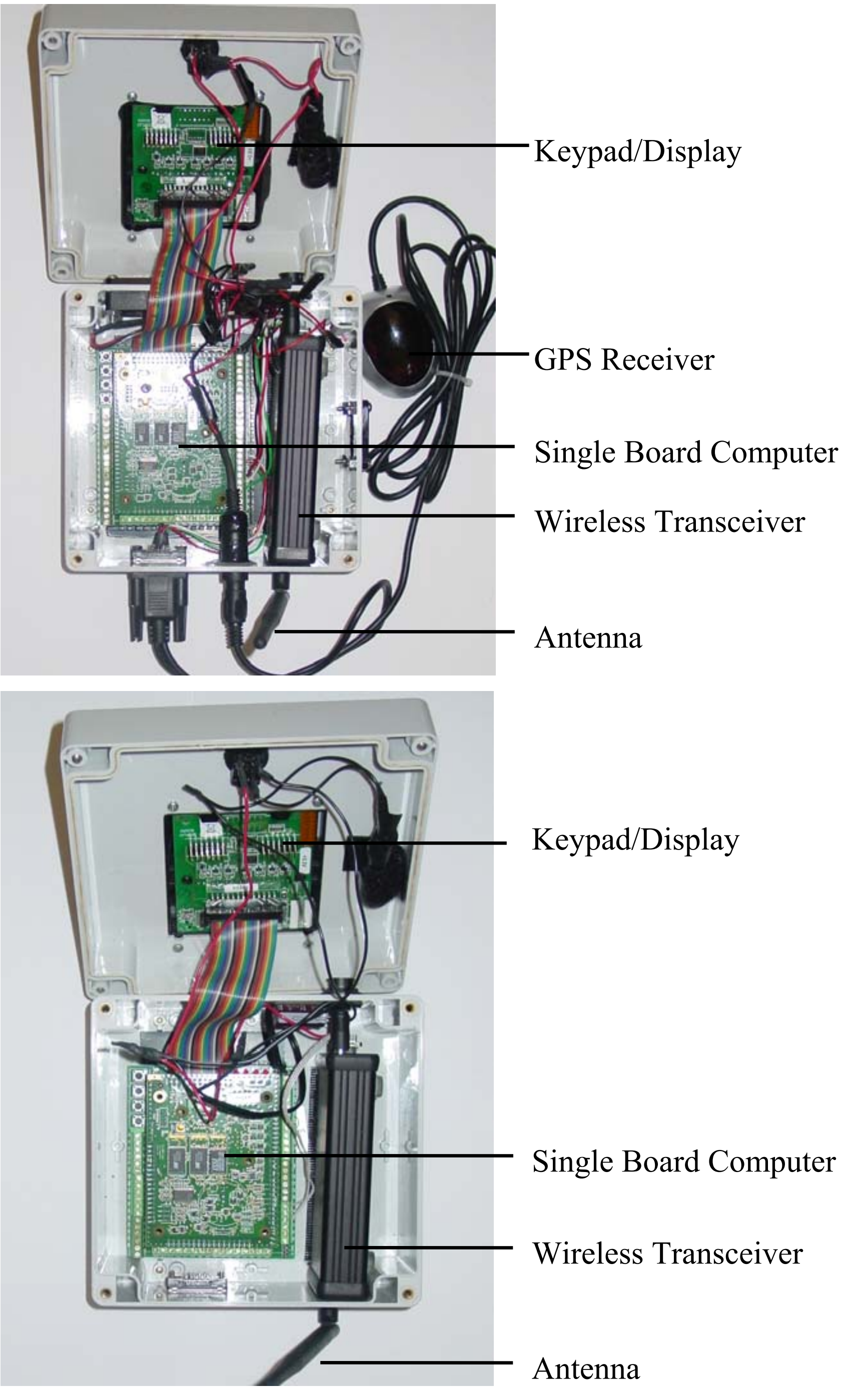


Figure 21. Layout and wiring of electronic components in box enclosure for harvester subsystem (top) and module builder subsystem (bottom) in first version prototype system.

Software Development

Boll Buggy Number & Module Number

As can be seen in the section on the principles of basket tracing, boll buggy numbers and module numbers play a key role. The boll buggy number serves as a link between a harvester basket and a module; and the module number is used to identify each physical module built. It is required that the boll buggy numbers be unique throughout the harvesting season. This is especially important in the complex scenario when multiple boll buggies are used, because tracing errors could occur if the same boll buggy numbers were used by different boll buggies. Figure 22 shows the structure of wireless messages that contain boll buggy numbers and module numbers designed for the prototype system.

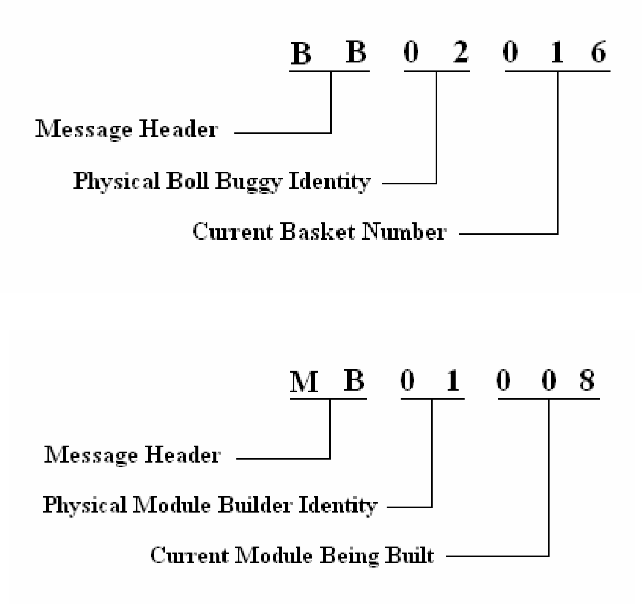


Figure 22. Structure of wireless messages containing boll buggy number (top) and module number (bottom) in first version prototype system.

All wireless messages are seven digits in length and have three fields. The first field (the first and second digit) is the message header that notifies the harvester subsystem whether the upcoming message is from a boll buggy subsystem (“BB”) or a module builder subsystem (“MB”).

The second field (the third and fourth digit) identifies the actual boll buggy or module builder that transmits the message. This field can be assigned to identify each vehicle in the system initialization. It allows a maximum of 99 (01-99) boll buggies and 99 module builders under operation in the system. The third field (the fifth, six, and seventh digits) constitutes a number that represents the current boll buggy basket or module being assembled in a particular boll buggy or module builder. Each time a boll buggy basket is dumped or a module is built, this field is incremented by 1, allowing a maximum of 999 (001-999) baskets or modules for each boll buggy or module builder, respectively.

The combination of the second and the third fields guarantees unique boll buggy numbers and module numbers throughout the harvest season. For example, in figure 22 the first wireless message indicates that it is from boll buggy #2 and the dumped basket is its 16th basket during harvest. The second wireless message indicates that it is from module builder # 1 and the current module is the 8th module it built during harvest.

The structure for boll buggy number and module number reflects the expandability design criterion. In the basic scenario in which only a harvester and a module builder are used (on which the first version prototype system is based), the boll buggy number is unnecessary. Since there is only one module builder, the second field in the module builder message is always the same, namely “01”.

In some cases, growers would like to use their own numbering system for harvested modules, and those numbers would be used by the ginners and classing offices for fiber quality data entry (table 14, personal communication with Mr. Rickey Bearden, cotton producer, Plains, Texas). Thus, extra effort could be incurred to match the module numbers generated by default (as in figure 22) with those determined by growers. To solve this problem, a subroutine was added into the module builder subsystem so that users can toggle between default and custom number systems for the modules built. If the custom number system is selected, users can input module numbers via the keypad.

Structure of Log File

Log files are physically stored in the harvester subsystems’ flash memory, and each log file corresponds to a harvester basket. Log files are designed to contain three sections: (1) a latitude longitude section, (2) an optional boll buggy number section, and (3) a module number section (figure 23). Latitude and longitude are extracted from the GPRMC sentence in the GPS signal. The boll buggy number section will not appear if the harvester basket dumps directly into a module builder.

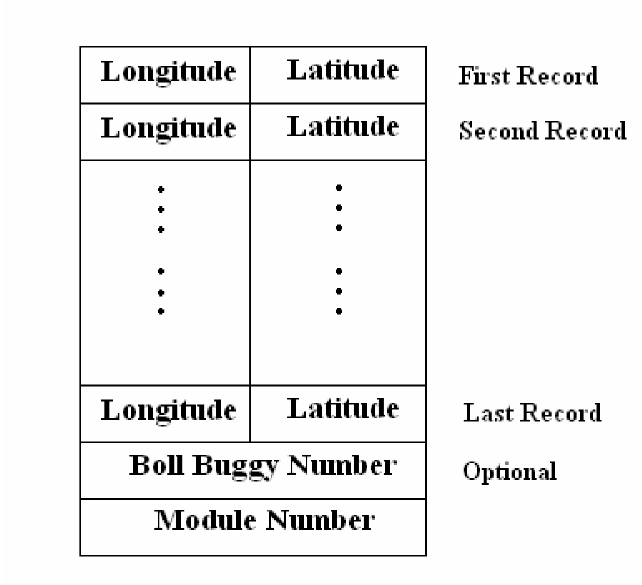


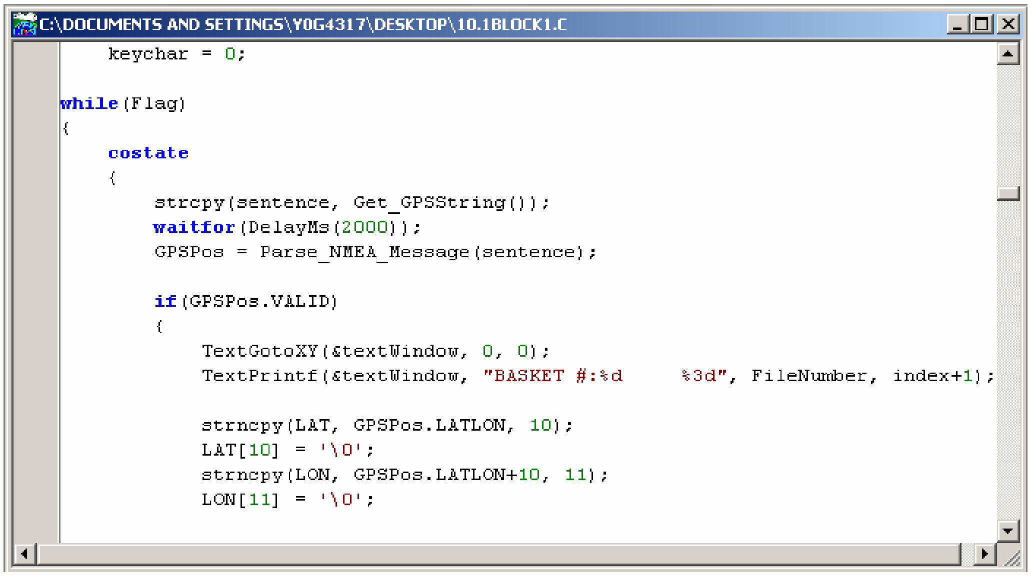
Figure 23. Structure of log file in first version prototype system.

Log files stored in each harvester subsystem are to be downloaded into GIS at the end of the season. Field areas associated with each basket (encompassing all of the GPS points) can therefore be delineated, and the corresponding module is indicated by the module number in the log file.

Programs

System control programs were written in Dynamic C® (Z-World Inc., Davis, Cal.) version 9.0, an integrated, industry-proven development system specifically designed for Rabbit family microprocessors (Rabbit Semiconductor, Davis, Cal.). As its name indicates, Dynamic C® is a C compiler which can handle standard C statements (operators, macros, functions, etc). It also includes many extended functions (such as co-functions, co-statements, and multi-tasking) and custom-developed libraries (such as the

GPS library and Serial Flash library) which make it more appropriate for embedded, real-time, industrial applications. Dynamic C® also features a built-in, full-function text editor, allowing developers to input program source code (figure 24). It also provides tools for compiling and debugging the program. The compiled program is downloaded from a PC to the SBC's first flash memory via the SBC's programming port.



```
    keychar = 0;

while(Flag)
{
    costate
    {
        strcpy(sentence, Get_GPSString());
        waitfor(DelayMs(2000));
        GPSPos = Parse_NMEA_Message(sentence);

        if(GPSPos.VALID)
        {
            TextGotoXY(&textWindow, 0, 0);
            TextPrintf(&textWindow, "BASKET #:%d     %3d", FileNumber, index+1);

            strncpy(LAT, GPSPos.LATLON, 10);
            LAT[10] = '\0';
            strncpy(LON, GPSPos.LATLON+10, 11);
            LON[11] = '\0';
```

Figure 24. Programming interface of Dynamic C®.

Two programs were written, one to control the harvester subsystem and one to control the module builder subsystem. The principal tasks of the harvester program included (1) GPS signal processing, (2) file operation, and (3) wireless signal processing. The principal task of the module builder program was wireless signal processing. In addition, both programs included many auxiliary tasks (such as a display subroutine, system initialization, etc.) to make the subsystems fully functional. Detailed flowcharts of both programs are shown in figures 25 and 26.

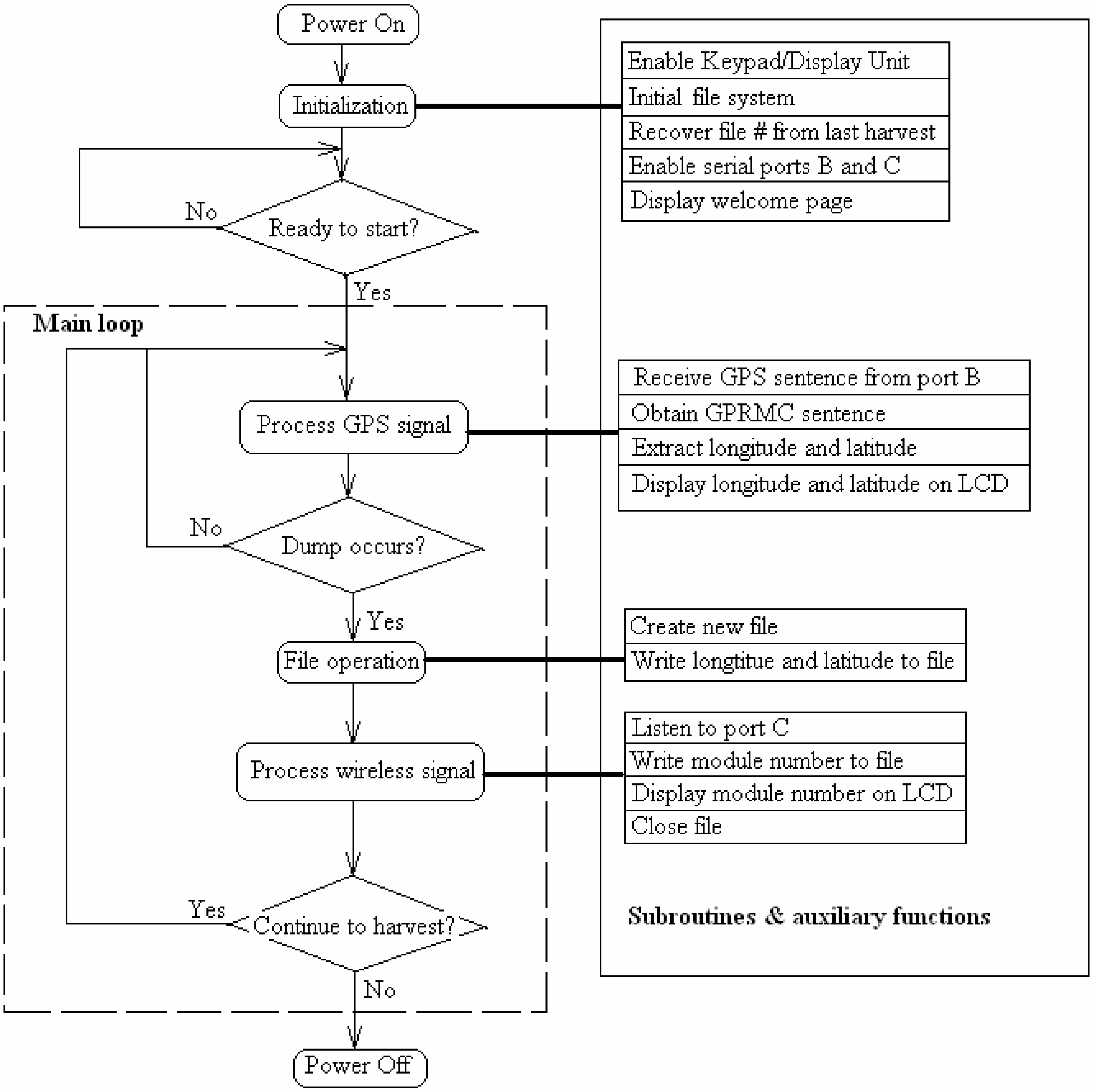


Figure 25. Flowchart of program in harvester subsystem in first version prototype system.

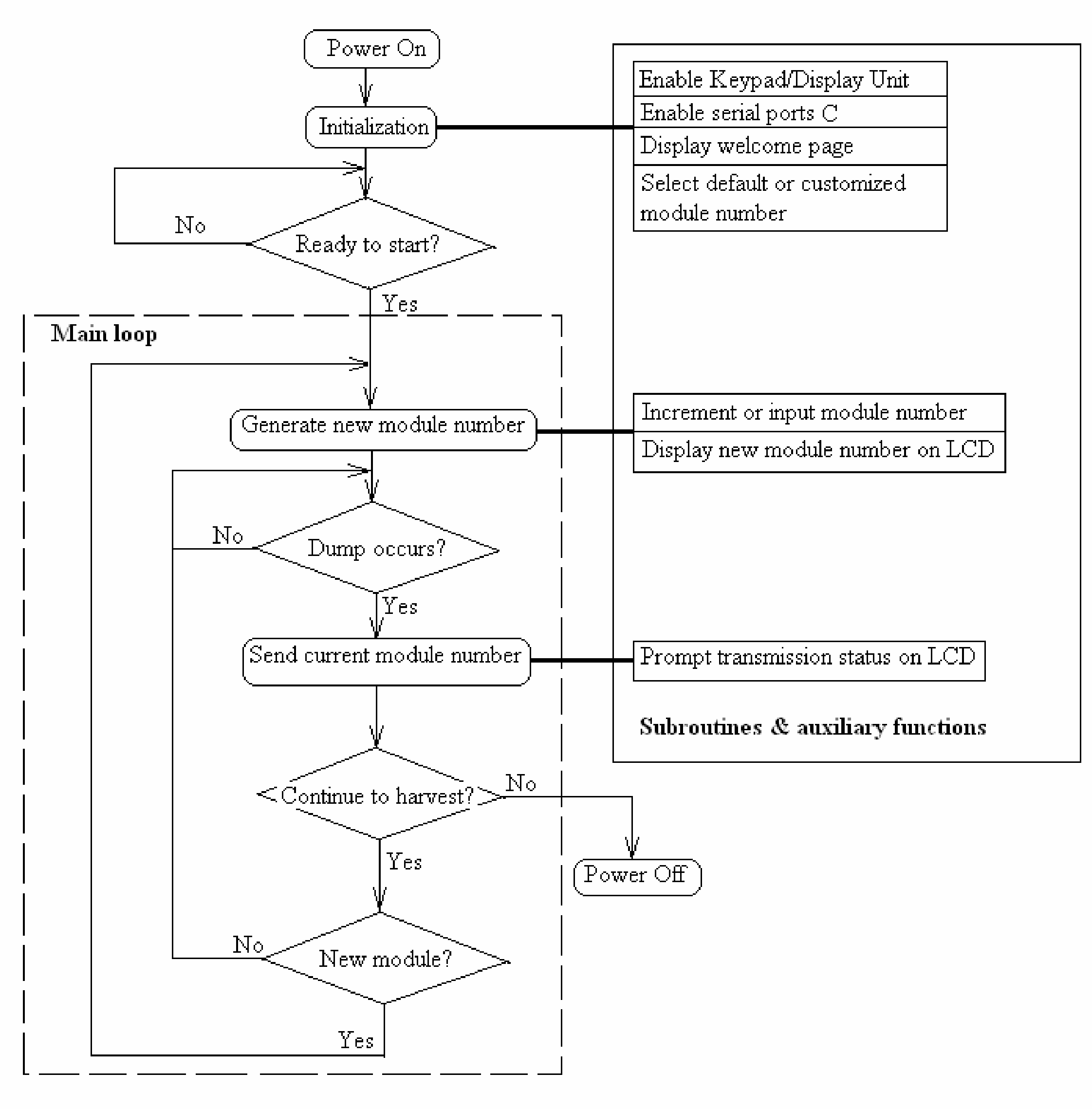


Figure 26. Flowchart of program in module builder subsystem in first version prototype system.

Field Test

On 7 November 2006, the first version prototype system was tested on a cotton farm in Yoakum County (latitude 33.182178° N, longitude 102.648785° W), about 17 km east of Plains, Texas. The harvester subsystem was mounted on a John Deere 7460 six-row cotton stripper, and the module builder subsystem was mounted on a Bush Hog Husky module builder. Power was supplied to both subsystems by two rechargeable 12-V automotive batteries. Both subsystems were light and small and could be easily secured in or on the vehicles' cabs. To better receive the GPS signals, the GPS receiver in the harvester subsystem was mounted on the top of the stripper cab. The GPS signal sampling interval was set at 6.0 s. Custom numbering for harvested modules was used; i.e., module numbers were input via the keypad by the operator.

After system installation, an initial test was run to examine the transmission capability between the wireless transceiver pair. The result showed that transmission errors consistently occurred over a distance of more than 70 m. It was inferred that the vehicles' steel frames were partially blocking wireless signals and thus impairing the transmission range. To solve the problem, the module builder subsystem was moved from the inside to the top of the cab. After this change, a much larger transmission range of about 0.5 mi. was achieved without transmission errors.

The system was run continuously for 6.5 h (from 2:00 to 8:30 pm), during which time a total of 30 stripper baskets were harvested and five complete modules built. No hardware malfunction occurred during the test, but the GPS receiver experienced occasional signal loss, which led to some missing points during the test.

The log files were downloaded, and recorded points were mapped in a GIS (ArcGIS version 9.1, ESRI, Redlands, Cal.), as shown in figure 27. It can be seen that GPS performance was satisfactory, with no points exhibiting unacceptable positioning errors. The stripper's harvesting route (along the cotton rows) is clearly visible in the figure, and the area boundary of each module was readily defined (different color schemes in figure 27). Also presented in figure 27 is an inset that includes a close-up of a portion of the test area. The average distance between points was around 10 m (along the row direction). The dashed-line rectangle in the inset corresponds to the area where the GPS receiver lost fix and no points were recorded.

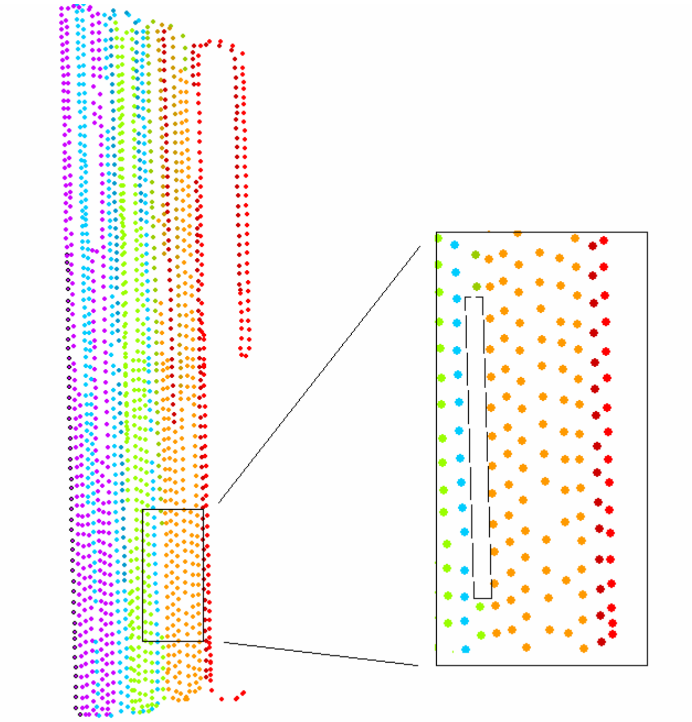


Figure 27. Map of all recorded points during field test (left) and close-up of a portion of test area (inset at right); the dash-line rectangle in the inset indicates where the GPS receiver lost signal.

The harvested modules were ginned, classed and the bale-level fiber quality data (Table A-5, Appendix A) were obtained via fax. A total of 48 bales were pressed from these modules. Table 16 lists the mean and CV of the fiber parameters from bale-level fiber quality data for each module. Clearly, different degrees of variability existed within each module, as evidenced by their CVs. For example, module "00101" was fairly uniform in terms of micronaire, length, uniformity, Rd, +b, and loan price. On the other hand, it was quite non-uniform in terms of strength (highest CV). The differences of the means of the fiber parameters among individual modules were observed, too. In the following, ANOVA (analysis of variance) were performed to verify whether the differences were statistically significant or just a play of chance. This analysis was very important because the proposed wireless- and GPS-based fiber quality mapping system would have practical values only if significant fiber quality had been found.

Table 16. Mean and CV of bale level fiber parameters for five harvested modules in field test.

Module Number	Bales per Module		Bale level fiber parameters						
			Micronaire	Length (mm)	Strength (g/tex)	Uniformity (%)	Rd	+b	Loan Price (¢/lb)
00101	8	Mean	2.83	28.4	26.8	77.4	82.4	7.86	50.52
		CV (%)	1.6	1.0	4.7	0.6	0.6	1.8	0.9
00201	10	Mean	2.89	28.4	26.8	77.3	81.4	8.05	50.32
		CV (%)	3.0	1.7	4.7	1.0	0.6	3.2	2.5
00301	10	Mean	2.95	28.3	26.9	77.6	80.7	8.14	51.52
		CV (%)	1.8	1.7	4.3	1.2	0.8	3.8	3.7
00401	10	Mean	3.02	28.7	27.1	77.6	80.1	7.90	51.43
		CV (%)	2.6	2.1	3.2	0.8	0.9	3.4	3.5
00501	10	Mean	3.05	28.4	26.5	77.7	80.8	7.70	51.72
		CV (%)	3.5	1.0	4.3	0.7	0.8	2.7	4.0

The ANOVA table testing the equality of means (SAS Procedure ANOVA) for each fiber parameter is presented in table 17. Length, uniformity, strength, and loan rate had non-significant *F* values, which meant all five modules could be deemed equal for these properties. Micronaire, Rd, +b had significant *F* values (at the 0.01 level), indicating that significant differences did exist for these parameters at the module level. Because micronaire is a very important fiber parameter and plays a key role in many fiber quality studies, the practical importance of the proposed system is justifiable. Table 18 gives the results of pair-wise multiple comparison for micronaire, Rd, and +b, for which significant *F* values were found.

Table 17. Summary of ANOVA *F* test for equality of means among five harvested modules.

Source	Degree of Freedom	Sum of Squares	Mean Squares	*F* Value	Pr > *F*
		Micronaire			
Model	4	0.31	0.077	12.33	< 0.0001
Error	43	0.27	0.006		
Corrected Total	47	0.58			
		Length (mm)			
Model	4	0.63	0.16	0.77	0.55
Error	43	8.81	0.20		
Corrected Total	47	9.44			
		Uniformity (%)			
Model	4	1.09	0.27	0.56	0.69
Error	43	20.8	0.48		
Corrected Total	47	21.9			
		Strength (g/tex)			
Model	4	1.92	0.48	0.37	0.83
Error	43	55.4	1.29		
Corrected Total	47	57.3			
		Rd			
Model	4	26.1	6.53	16.6	< 0.0001
Error	43	16.9	0.39		
Corrected Total	47	43.0			
		+b			
Model	4	1.16	0.29	4.78	0.0028
Error	43	2.61	0.06		
Corrected Total	47	3.77			

Table 17. Continued.

Source	Degree of Freedom	Sum of Squares	Mean Squares	*F* Value	Pr > *F*
		Loan rate (¢/lb)			
Model	4	15.6	3.91	1.44	0.24
Error	43	116.3	2.70		
Corrected Total	47	131.9			

Table 18. Pair-wise multiple comparison of means of micronaire, Rd, and +b among five harvested modules.

Micronaire				Rd			+b			
Module	Mean	Group		Module	Mean	Group	Module	Mean	Group	
00501	3.05	A		00101	82.4	A	00301	8.14	A	
		A							A	
00401	3.02	A	B	00201	81.4	B	00201	8.05	A	B
			B							B
00301	2.95	C	B	00501	80.8	C	00401	7.90	C	B
		C				C			C	B
00201	2.89	C	D	00301	80.7	C	00101	7.86	C	B
			D						C	
00101	2.83	`	D	00401	80.1	D	00501	7.70	C	

Now that both the location information and fiber quality information are available, they can be integrated in GIS for developing different fiber quality maps at the module level. Figure 28 shows such maps for micronaire and loan rate, superimposed on a remote sensing image of the field. The basket boundaries (indicated by solid lines) were delineated from the GPS points (figure 27) and the area covered by each module (indicated by different color schemes) was resulted from basket tracking.

As expected, the smallest resolvable unit was a harvester basket. With respect to fiber quality information, a module was the smallest unit since different baskets in the same module had the same fiber quality information (which is again, obtained by averaging the bale-level fiber quality data for that module). Also baskets in the same module were not necessarily geographically continuous, which was determined by the route of the stripper during harvest. It is interesting to point out that from the micronaire map, a general trend of the micronaire value in the field (increase from east to west) could be identified. Since there was no other reason apparent for this trend, the author is inclined to attribute it to the in-field variability of micronaire, which is subsequently attributed to environmental factors such as soil properties and elevation. In this sense, the module-level micronaire map can be regarded as an aggregated high resolution micronaire map (such as those in figures 8 and 9), and may be useful in determining the spatial distribution of fiber quality in the field and its environmental causes.

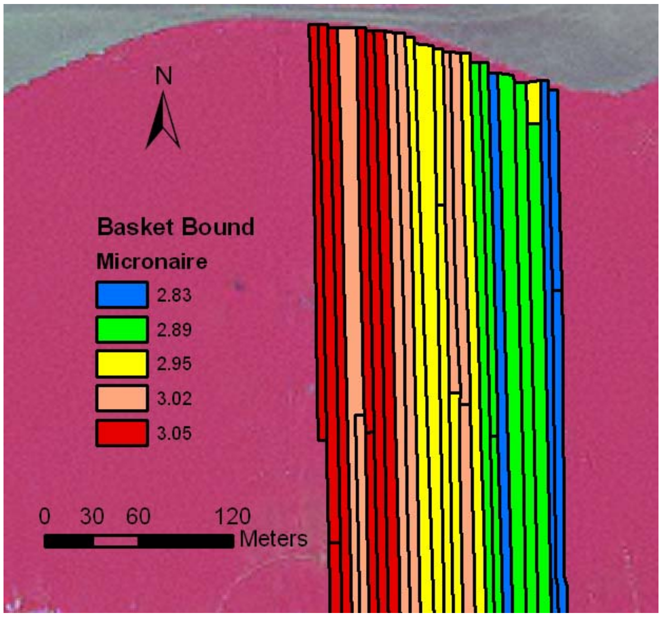


Figure 28. Module level fiber quality maps of micronaire and loan rate, superimposed on remote-sensing image of test field.

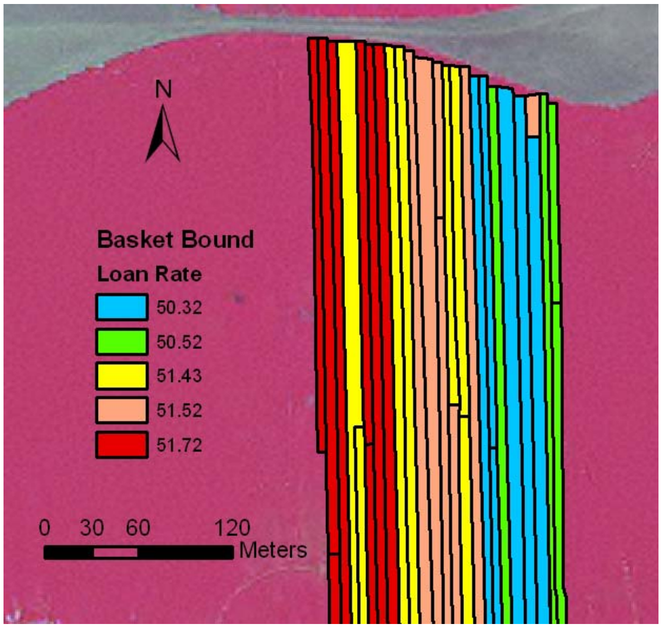


Figure 28. Continued.

Because the first version prototype system didn't contain a boll buggy subsystem, all dumped stripper baskets were manually tracked to the module builder through the boll buggy. This was possible because there was only one boll buggy used during harvest, and dumps occurring between vehicles were quite simple. Testing an automatic tracking mechanism with an included boll buggy subsystem would be done later with a second version prototype system.

During the field test two people were required to operate the subsystems, one person on the harvester and one on the module builder. Operators had to be aware of the moment when a dump occurred so that they could manually trigger the wireless transmission of module numbers. Thus, with the first version prototype, extra labor (one person per vehicle) was needed to operate the subsystems, and the “automation” design criterion was not met.

At this point it was still important to show that wireless transmission could be triggered automatically, and so a second version prototype had to be built and tested. In the new prototype, a request for the module builder number would be sent wirelessly from the harvester subsystem to the module builder subsystem when a dump occurred between them. When the module builder subsystem would receive this request, transmission of the current module number to the harvester subsystem would be triggered automatically, and thus no extra labor would be required.

Another automation shortcoming of the first prototype version was that when the module number was ready for transmission, the operators had to make sure that the harvester subsystem was in the “process wireless signal” mode (see figure 25). As can be seen in the flowchart, the main loop in the program was in a sequential structure. That is to say, if the program was in the “process GPS signal” mode, the harvester subsystem would not respond to wireless messages, making the system inefficient (i.e., wireless transmission would be delayed until the harvester subsystem is ready) and potentially causing tracking errors (i.e., a sent wireless message could be ignored).

SECOND VERSION PROTOTYPE SYSTEM

Modifications and Improvements

Based on the shortcomings of the first version prototype system, hardware and software modifications were made for the second version. In regard to hardware, a boll buggy subsystem was built and included. Its major electronic components included single board computer, a wireless transceiver, and a keypad/display unit. The overall layout of the subsystem was similar to that of the module builder subsystem (figure 19). In regard to software, a different tracking mechanism was employed. In the first version, a set of unique boll buggy number were used as a bridge linking harvester baskets to modules. In the second version, unique file numbers were used and a different protocol for wireless message transmission was applied. A detailed explanation of the new design is given in the following paragraphs.

A hypothetical harvest scenario having two harvesters (referred to as H1 and H2) must be considered again. Firstly then, two permanent numbers are assigned to each harvester (e.g., “01” and “02”) to distinguish them. Each basket harvested by one harvester is assigned a three-digit file number, from “001” to “999”. Thus, the tenth basket harvested by harvester 01 is represented by “01010”, and the sixteenth basket harvested by harvester “02” is represented by “02016”. This can be extended to more general cases having more than two harvesters under operation. The idea is that each basket of an individual harvester (and subsequently the corresponding geographic area in the field) would be identified by a unique file number.

When a harvester basket is full and a dump occurs between the harvester and a module builder, a wireless message is to be transmitted from the harvester to the module builder. The message contains two segments: a message header and the file number of that basket. The message header is a four-digit string “HTOM” (meaning Harvester TO Module builder). A message “HTOM, 02035” means that the 35th basket of Harvester 02 has been dumped into the module builder. On the module builder side, the message is received and parsed, the file number is extracted, and an echo message is transmitted back to the harvester. The echo message has three segments: a message header (a four-digit string “MTOH, meaning Module builder TO Harvester), the extracted file number in the received message, and the current module number. For example, an echo message “MTOH, 02035, 00023” means the 35th basket of Harvester 02 was dumped into the module 00023. When Harvester 02 receives the echo message, it attaches the module number to File 35. This echo design allows transmission of module numbers to be an automatic process, with no personnel needed at the module builder side to operate the module builder subsystem.

If a dump occurs between the harvester and a boll buggy, again a wireless message with the same structure is transmitted from the harvester to the boll buggy. The message header, however, is replaced by “HTOB” (meaning Harvester TO Boll buggy, to distinguish it from messages intended for a module builder). At the boll buggy side, this message is received and parsed, the file number extracted, and these data are stored it in memory.

In production a boll buggy can hold two or more harvester baskets. Thus when it is full, the boll buggy subsystem would have two or more file numbers stored in its memory. Suppose only two file numbers are stored in a boll buggy subsystem memory (for example, “01120” – the 120th basket of Harvester 01, and “02035” – the 35th basket of Harvester 02). When the boll buggy dumps into the module builder, a wireless message is transmitted. An example message is “BTOM, 01120 02035”. The message header “BTOM” means Boll buggy TO Module builder. Again, the module builder subsystem will echo this message to the associated harvester subsystem by sending a new message in the form “MTOH, 01120 02035, 00023”. When Harvester 01 receives this message, it extracts 01120 and attaches module number “00023” to its file #120. The file number “02035” would be ignored by Harvester 01, as this file is from Harvester 02 and should only be processed by Harvester 02.

In summary, the new tracking mechanism uses unique file numbers composed of a two-digit harvester number and a three-digit basket number relative to each harvester. Three types of comma delimited wireless messages are employed as shown in figure 29. It should be noted that the change of the tracking mechanism did not change the rest of the software design (such as the structure of log files).

Several other improvements were also made in software. Firstly, a Dynamic C program to be run on the boll buggy subsystem was developed. Secondly, the program in the module builder subsystem was improved such that it can send echo messages upon receiving a message from harvesters or boll buggy subsystems. Thirdly, and very importantly, the main loop of the program in the harvester subsystem was modified from a sequential structure to a parallel structure. In other words, the modified version can process GPS data and at the same time “listen” to the serial port for wireless communications.

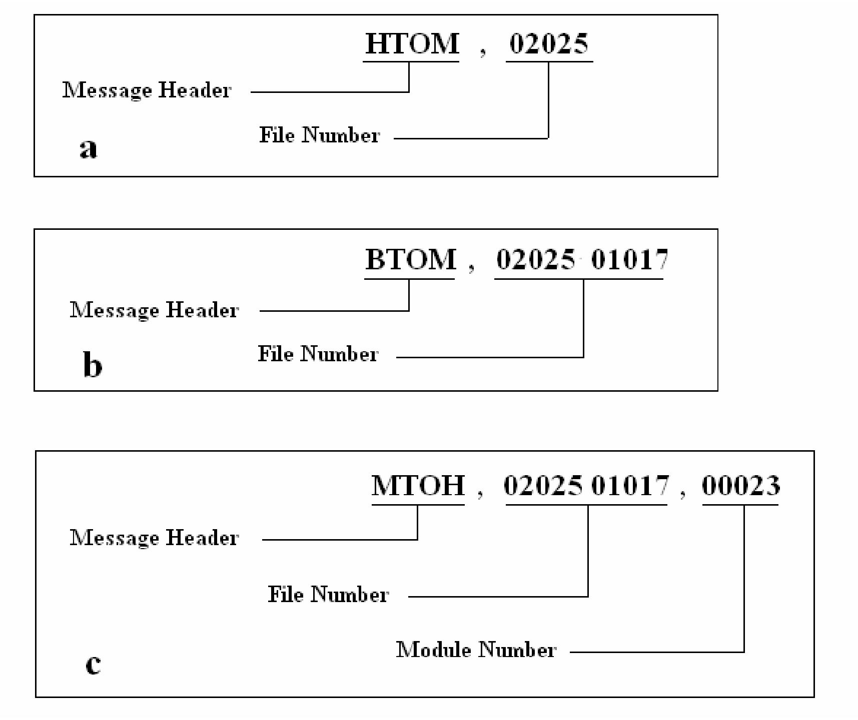


Figure 29. Wireless message structure in second version prototype system: a. from harvester intended to module builder, b. from boll buggy intended to module builder, and c. from module builder intended to harvester.

Parking Lot Field Test

On 11 February 2007, the second version prototype system was tested in a campus parking lot at Texas A&M University. The harvester and boll buggy subsystems were temporarily mounted on two vehicles imitating the harvester and boll buggy. The module builder subsystem was placed at a fixed location. The vehicles traveled at a speed of 5.6 km/h (around 3.5 mi./h). The test was predominantly focused on whether the shortcomings of the first version prototype system had been properly addressed.

Another important objective was to evaluate the accuracy of the wireless communication and associated software, so as to see if any tracking errors would occur with the modified tracking mechanism and program. A hypothetical harvesting scenario with predetermined harvesting routes and basket dumps (figure 30) was followed in an effort to identify any tracking errors. This type of test was necessary because, in real situations where the harvesting route or basket dump is not known *a priori*, such an evaluation would be very difficult. In this case system operation and resulting log files were completely predictable, and accuracy of system operation was thus easy to determine. In addition, the accuracy of the GPS receiver was evaluated as in the first field test. The system was tested for two hours, from 10:00 A.M. to 12:00 noon. Meanwhile a total of 25 hypothetical harvester baskets were collected and six hypothetical cotton modules were built. While it would take many more than 25 harvester baskets to actually produce 6 modules, it was not necessary to maintain the numerical relationship between harvester baskets and modules for the purposes of this test.

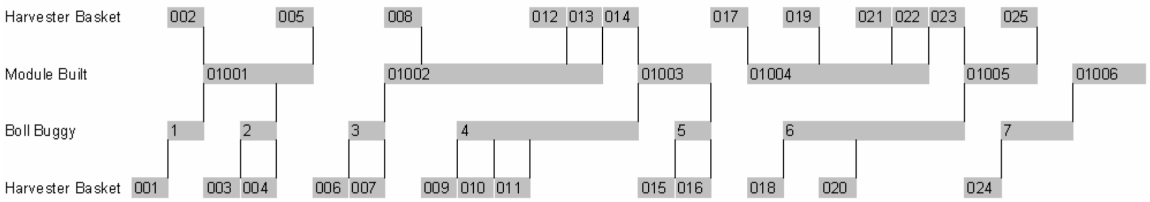


Figure 30. Predetermined basket dump scheme in parking lot test.

The following is a brief explanation of the basket dump scheme. The top and bottom lines in figure 30 show 25 hypothetical harvester baskets. The top line indicates those being directly dumped into the module builder, while the bottom line indicates those being dumped into the boll buggy then the module builder. Taking the first five baskets as an example; baskets 001, 003, and 004 were first dumped into the boll buggy and then dumped into the module builder; and baskets 002 and 005 were dumped into the module builder directly.

The resultant map developed from this test of the system is shown in figure 31. With respect to GPS, all of the points were recorded with a satisfactory accuracy (not shown in figure 31). The basket boundaries, which were drawn to encompass all of the points for each individual basket, were quite regular and agreed well with the predetermined vehicle routes. During the test, the module builder subsystem was run without human intervention, and all of the wireless messages were echoed successfully. The harvester subsystem performed well in terms of its multi-tasking capability; i.e., it processed GPS signals and wireless messages simultaneously. The only tracking error that occurred was in basket “001”, where its log file did not contain a module number. This was apparently caused by the fact that the simulated harvester was so far away from the “module builder” that the echo message containing the module number was too weak to be detected. Compared to the test of the first version prototype in an open cotton field, the parking lot had many trees surrounding it. Thus, it was not surprising that the wireless transmission range would be impaired somewhat.

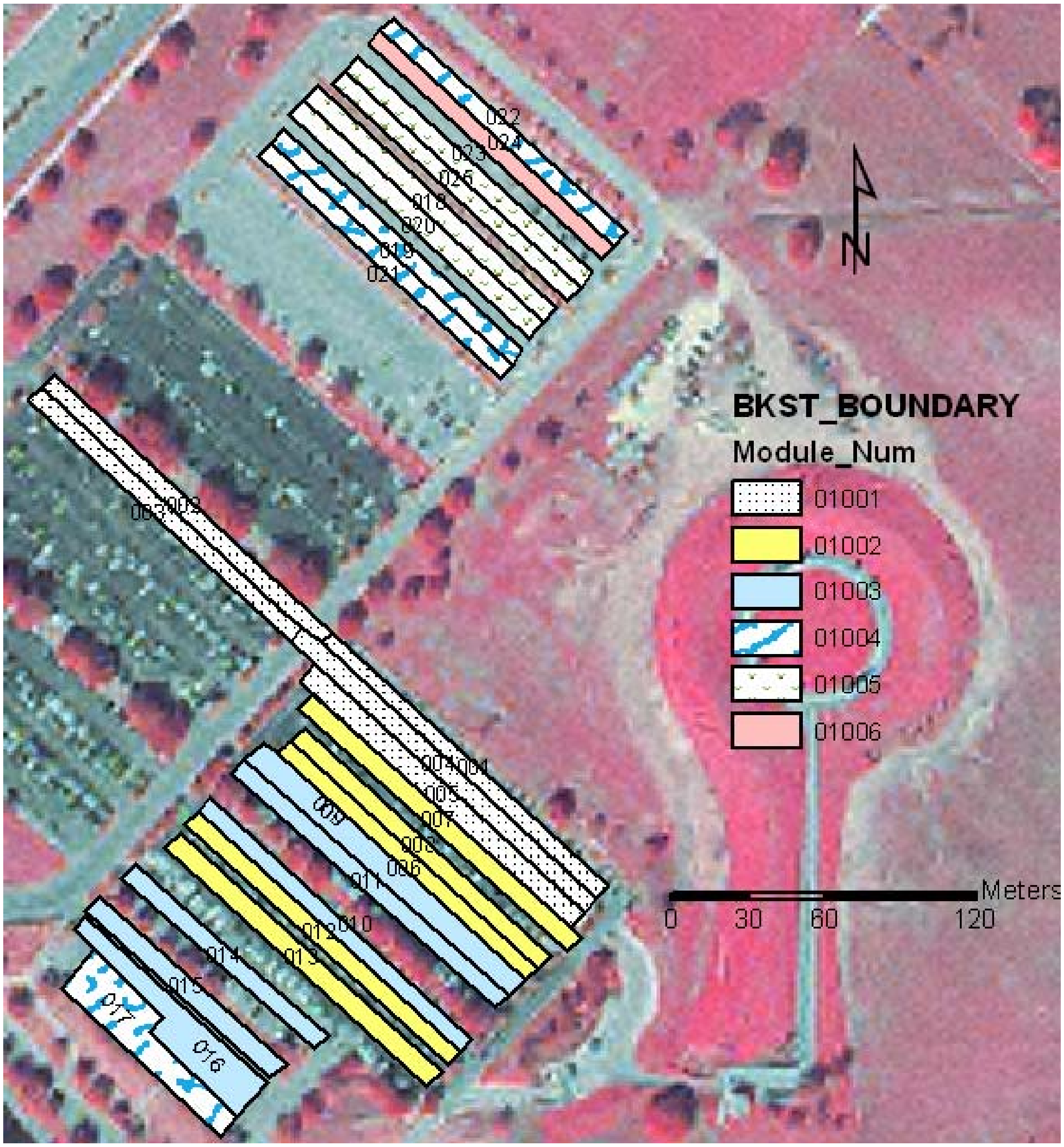


Figure 31. Remote sensing image of test parking lot, basket boundaries delineated from recorded points, areas covered by different modules, and their corresponding module numbers.

Suggestions for Future Development

At the GPS sampling interval of 6.0 s, point data recorded during the field test (covering around 12.5 ha, figure 27) used around 25% of the flash memory in the SBC (or 64 kb). If the system were used on a farm larger than 50 ha, which is quite common in cotton production, additional memory would be needed because the SBC's 256 kb flash memory limit would be exceeded. Rabbit Semiconductor (Davis, Cal.) provides optional 16 Mb external flash memory compatible with the 3500Fox SBC. With the optional memory the system would be adequate for a farm of 3200 ha. There are also two methods from a software standpoint which could reduce the GPS memory requirements if the harvest area were very large. Firstly, as can be seen in figure 27, recorded points were denser than required to define basket boundaries. Therefore, it is likely that a GPS sampling interval of 15 s or even more would be adequate. Secondly, current GIS software (such as SSToolbox) has the capability to calculate the trajectory of the harvester with sparsely collected location information (converting points to polygons). This feature can be integrated into system's software so that polygons can be calculated from GPS points. Once polygons are generated to represent individual baskets, GPS points are no longer needed and the memory requirement could be minimized.

In its second version, the prototype system needs operators at both the harvester and boll buggy to manually trigger wireless messages when dumps occur. No operator is needed at the module builder. In an actual production situation, if the subsystems are mounted in vehicle cabs, the harvester and boll buggy drivers could operate the system and send the wireless message when needed. However, as drivers concentrate on vehicle operations, they might inadvertently skip pressing the button. Moreover, placement of the subsystem in vehicle cabs may substantially weaken the wireless signal strength and impair transmission range, as evidenced in both field tests.

Thus future improvements are needed to place the antenna of the wireless transceiver on the top of the vehicle cab, and the wireless message transmission should be triggered by a particular event. One solution is to mount contact switches (connected to the subsystems) on the basket-lift arm of the harvester and boll buggy, such that each time the arm is lifted for a basket dump, the contact switch is triggered (similar to the button press in the prototype systems), and a wireless message is sent automatically. This modification would make the system fully automated; i.e., no operator would be needed.

The prototype was tested with one harvester, one boll buggy, and one module builder. A problem would arise if this system were used in a multi-vehicle scenario is that the wireless message is transmitted in a broadcast manner. That is, if a wireless message from a harvester were intended for Boll Buggy “01”, all other boll buggies in the system would also detect this message. However, in the message protocol there is no mechanism that can distinguish Boll Buggy “01” from all other boll buggies. Thus a tracking error would occur if other boll buggies also record this wireless message. Because the distance of two vehicles, between which a dump occurs, would be small, it is conceivable to include a GPS receiver in each subsystem and use the proximity information to select an appropriate target vehicle. More specifically, if the harvester dumps into Boll Buggy “01”, the distance between the two would be much shorter than with any other boll buggies in the field. Thus by setting an appropriate threshold (e.g., 10 m), other boll buggies could filter out the unintended messages from the harvester. In this case, a wireless message would contain the current latitude (LAT) and longitude (LON) information. For example, a harvester message could be designed as “HTOB, 02035, LAT LON”. When the boll buggy received this message, it would first extract the position information, compare it to its own position, and accept the message for processing only if the calculated distance met the proximity condition. The same strategy also applies for dumps between harvesters and module builders, and between boll buggies and module builders.

Regarding communication among system components, a more advanced and viable option would be to use CAN-Bus (Controller-Area-Network Bus) communications technology – an industry-proven and widely adopted technology originally designed for use in automobiles, but now in common application on farm machinery. Several advantages are foreseeable if CAN-Bus communications could be successfully adapted to the wireless GPS fiber quality mapping system. Firstly, the data transfer and communication would be especially robust even in electromagnetically noisy environments. Secondly, the communication protocol defines CAN identifiers, nodes, and message priorities, which minimize data transmission errors. It should be noted that transmission error could be a problem in the wireless GPS system if many field vehicles were involved in a very intensive harvesting operation. Currently, CAN has been widely applied in many precision agriculture applications, and a good review is provided in De Baerdemaeker et al. (2001).

OTHER CONCERNS ABOUT WIRELESS GPS FIBER QUALITY MAPPING SYSTEM

Comparison of Proposed System to Existing Fiber Quality Information Technologies

In cotton production, commercial systems that integrate the fiber quality information at gins and classing offices into farmers' field databases are commercially available. An example of such a system is EASi Suite crop management software developed by Mapshots Inc. (Cumming, Ga.). A unique aspect of this system is fiber quality record keeping, which allows a farmer to better understand the quality of his cotton and make informed management decisions, taking the farm as a whole. To the best of the author's knowledge, no existing system is capable of any level of fiber quality information integration in a spatial context. The innovative point of the proposed system is that it associates each harvested module with location information, such that the fiber quality information can be associated with a specific area in the field. For cotton farmers, this is a good starting point for addressing the fiber quality issue site-specially. As will be seen in the side benefits section, the proposed system also gives rise to some other interesting research topics.

Compatibility with Technology Advancement in Cotton Production

The harvester subsystem is quite similar to a cotton yield monitor in terms of hardware components and functionalities. Both of them have (1) a GPS receiver to provide the location information of the harvester and (2) a high-speed microcontroller to process data. It is thus possible to combine them into an integrated system that can record the yield information and process the wireless messages at the same time. When working with the other subsystems at the boll buggy and module builder, this integrated system would be able to simultaneously accomplish yield mapping and module level fiber quality mapping. The cotton yield monitor has already become a fairly well accepted technology and is mounted on a significant number of harvesters. This fact might make it easier for farmers to accept the proposed system and facilitate its commercialization.

The proposed system is based on a traditional harvest mode involving harvesters, boll buggies, and module builders. Recent literature (Parvin, 2004) and news releases (Farm Press Western, 2005; Farm Press Delta, 2006), nonetheless, indicate that cotton harvesters with an on-board module builder have been at the prototype and field testing stages and may appear in the market in the next few years. As a result, boll buggies and module builders would no longer be needed in future harvesting. The small module, to be built onboard the harvester, is about half the size of the regular module. The new technology has important implications for the GPS and wireless based fiber quality mapping system. First of all, wireless communication would be unnecessary as no boll buggies and module builders would be used. As for the resultant fiber quality maps, the spatial resolution for a module would be doubled, which is an obvious advantage. However, the individual basket boundaries as shown in figures 28 and 31 would also be eliminated.

Costs and Marketability

The approximate cost to build the prototype wireless and GPS based fiber quality mapping system was around \$2,400 (table 19) for three subsystems, or roughly \$800 dollars per vehicle. It is common for a large farm to use more than six vehicles during harvest. In these situations, the material costs would be approximately \$5,000, based on the current purchasing scenario.

Table 19. Approximate cost of proposed wireless GPS fiber quality mapping system with one harvester, one boll buggy, and one module builder subsystem.

Hardware components	Unit Price (\$)	Quantity	Subtotal (\$)
3500Fox SBC	200	3	600
Prototyping board	100	3	300
LCD & keypad	100	3	300
ABACOM wireless transceiver	300	3	900
LAIPAC GPS receiver	100	1	100
Miscellaneous	200		200
Total (\$)			2400

The cost of the proposed system could be reduced in several ways. The 3500Fox SBC and prototyping board were designed for more complicated industrial applications. They were selected to minimize the requirements for peripheral circuitry and connections with external electronics. At the production level, these could be replaced with low-level microcontrollers (MCU) at a much lower price. A good example would be the Motorola 68HC11 E-series microcontrollers (Freescale Semiconductor). These microcontrollers have adequate processing power and I/O capabilities and would be adequate for the boll buggy and module builder subsystems. The price of the 68HC11 microcontroller is less than $10. This replacement would reduce the cost by around 300 dollars for each boll buggy and module builder subsystem. Moreover, the keypad/display unit in the boll buggy and module builder subsystem would also be unnecessary as it was used in the prototype systems mainly for debugging purposes.

The cost could be further reduced if the harvester subsystem were integrated with a yield monitor. Since commercial yield monitor systems have already been equipped with a powerful processing unit, GPS receiver, and display/keypad unit, the additional investment needed for the integrated system would be merely for a wireless transceiver.

With these cost reductions, not to mention reductions through production efficiencies, it is possible that the entire system cost would be as low as $1,100 ($300 × 3 for three wireless transceivers plus $200 for miscellaneous), averaging around $350 per vehicle. Thus for a fairly large farm with six vehicles, the investment for such a system might be as low as $2,000.

Other Side Benefits

Conventionally, research on fiber quality has started with the selection of appropriate bales from the mill warehouse (Chewning, 1995), such that blended fibers would meet the quality demand of a particular end-product. When significant defects occur in yarns and fabrics, textile processors attribute these defects to post-harvest events such as storage, handling, ginning, and bale selection. It is currently impractical to relate fabric defects to cotton fiber quality in the field before harvest, because the fiber quality information chain terminates at the gin. For example, if sticky fibers are found in the textile mill, the current technology allows processors to find out only which farm the cotton is from via permanent bale identification (PBI). This level of knowledge may not be adequate, because a farm can cover thousands of hectares and it is impossible to identify where an insect infestation might have occurred. With the proposed system, however, it becomes possible to narrow down the suspected areas to several hectares. Intensive field scouting could be implemented to identify the agronomic or environmental causes (such as a high insect density) of sticky fibers. In this sense, the proposed wireless and GPS based system would connect the fiber quality information chain between gins and farmers in a spatial context, provide a proactive response to the fiber traceability issue, and be a fundamental step to future studies for fiber quality purposes.

With the rapid development of agricultural technologies, it is natural to anticipate that field sensors for *in situ* fiber quality measurement would be invented in the near future (Sui et al., 2007). It is probable that onboard sensors would directly measure harvested seed-cotton or fiber from an onboard gin. No matter which method is used, there are two major reasons that could cause the *in situ* measurement to substantially deviate from the bale-level fiber quality data in the classing offices. Firstly, an onboard gin would not have a full sequence of seed-cotton and lint cleaning stages similar to a commercial gin. Therefore, fiber samples in the field would likely have higher staple length and uniformity but lower color and leaf grade. Secondly, field sensors usually have relatively poor measurement accuracy and repeatability. For example, if a fiber quality sensor were based on optics and spectroscopy, measurements might vary with ambient light intensity. In any event, field measurements would likely be substantially different from the laboratory measurements by the HVI line. Because the proposed wireless and GPS based system uses laboratory fiber quality measurement (HVI) for fiber quality mapping, it could be used as a *post facto* calibration tool for the future real-time fiber quality sensors, such that field measurements could be directly related to fiber quality measurements associated with the official classing system.

CHAPTER IV

CONCLUSIONS AND SUMMARY

The overarching goal of this dissertation was to address several fundamental aspects of applying SSCM for cotton fiber quality management. In the first part, a two-year study was conducted on a research farm to explore the spatial variability of cotton fiber quality and relate it to in-season soil moisture content. The major conclusions are as follows.

- Exploratory data analysis revealed that in-field variability of fiber quality existed. However, the reported degree of variability, as reflected in CVs for individual fiber parameters, was generally low for the field of study (the highest CV = 9.48%) and usually smaller than that of lint yields and soil properties.
- Semivariance analysis revealed that all fiber parameters in both years were spatially dependent. In 2005, length, uniformity, strength, and Rd exhibited a strong level of spatial dependence (percent nugget smaller than 25%); and micronaire, elongation, and +b showed a moderate level (percent nugget between 25 and 75%). In 2006, micronaire, length, and +b showed a strong level of spatial dependence, while uniformity, strength, elongation, and Rd showed a moderate level.
- Consistent over two years, the contour maps of length, uniformity, and

strength showed a similar spatial pattern, meaning they were positively correlated (r among these fiber parameters reached 0.79). Rd and +b showed an opposite spatial pattern, indicating they were negatively correlated with one another (r reached -0.69). In both years, micronaire exhibited a distinct spatial pattern compared to the other fiber parameters.

- In 2006, a similar spatial pattern was observed between soil apparent electrical conductivity and most fiber parameters (except for micronaire). However, no such relationship was found in 2005.
- The fiber quality induced loan price varied as much as 9 ¢/lb in the dry area in 2006. This fact has important economic implications for cotton producers and would tend to justify an SSCM system that can involve both lint yields and fiber quality in cotton production.
- In the irrigated area in 2005 and dry area in 2006, soil moisture was correlated positively with length, uniformity, strength, and Rd, and negatively with +b at almost all plant development stages. On the other hand, the only significant correlations found in the dry area in 2005 were micronaire at the boll enlargement and maturation stages, elongation at the squaring and fruiting stage, and Rd at the vegetative stage.
- The degree of correlation between soil moisture and most fiber parameters varied at different plant development stages. Generally speaking, the correlation coefficients in the early season (vegetative and squaring and fruiting stages) were low and increased considerably in the late season (boll

enlargement and maturation stages).

- A non-linear relationship was found between micronaire and soil moisture in the dry area in 2006. This was attributed to cotton plant's physiological responses (specifically boll abscission and retention patterns) to different soil water availability levels.

In the second part, a wireless GPS system was developed to accomplish automated module-level fiber quality mapping. Due to the characteristics of cotton harvesting, the system was composed of three functional subsystems distributed among the different field vehicles. In the overall system design, detailed descriptions were given on how to trace each harvested basket from a harvester to a boll buggy and a module builder. Automation and expandability were two important criteria considered in the design. Essential hardware components (including a GPS receiver, wireless transceivers, and central processing units) for the system were identified, purchased, and assembled. Software was designed and developed in C language, with the primary functions of GPS signal processing and wireless communication among subsystems. The first version of the prototype system containing harvester and module builder subsystems was field tested in a cotton field during harvest. The purposes were to evaluate the accuracy of the GPS receiver, wireless transmission range, and overall system performance. It was found that the fiber quality maps developed with the system can be used to readily differentiate some fiber parameters (including micronaire, Rd, +b, and also loan value) at the module level, indicating the competence of the system in fiber quality mapping and its potential for site-specific fiber quality management. A general trend of micronaire (increasing from east to west) was discernible. Shortcomings of the first version prototype – lack of a boll buggy subsystem, sequential structure of the subsystem program, and manual wireless transmission – were addressed in the second version prototype system. A subsequent field test of the second version prototype showed that the system performed satisfactorily. The test involved predefined harvesting routes and basket dump types. Overall the test showed that little basket tracking error occurred. In order to make the system fully functional at the production level, further modifications and development were suggested.

The original contributions of this body of work to the community of science are as follows: (1) in-field spatial variability of cotton fiber quality and monetary value were demonstrated in a way that indicates potential economic benefits for site-specific management related to cotton fiber quality; (2) the relationship between cotton fiber quality and soil moisture content at different plant development stages was quantified in a way that indicates potential benefits for considering fiber quality in the development of irrigation strategies, particularly late in the growing season (i.e., during boll enlargement and maturation); and (3) a unique new system of hardware and software was developed to automatically provide fiber quality maps

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APPENDIX A

IN-SEASON SOIL MOISTURE CONTENT AND HVI FIBER QUALITY DATASETS

Table A-1. In-season soil moisture content in 2005.¶

Sample #	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
	--%--											
Irrigated area												
1	14.8	15.5	10.4	—	—	31.4	27.9	19.5	10.9	38.0	27.2	—
2	13.7	11.8	9.2	—	—	24.1	21.2	11.4	8.5	29.8	21.4	—
3	13.4	12.4	9.6	—	—	23.5	22.0	14.0	10.0	31.3	21.0	—
4	16.0	8.1	9.4	—	—	21.5	20.6	13.9	8.4	30.0	18.5	—
5	19.7	14.4	13.0	—	—	27.7	34.2	28.5	26.8	35.9	32.5	—
6	19.5	13.6	13.0	—	—	36.5	33.8	28.0	17.8	37.1	28.1	—
7	17.1	8.4	10.8	—	—	17.4	18.2	10.7	9.6	23.7	18.4	—
8	12.4	12.7	11.0	—	—	27.8	27.1	15.1	12.8	31.0	21.5	—
9	15.1	13.5	12.5	—	—	27.7	26.0	18.2	12.7	33.7	23.4	—
10	17.2	13.5	13.6	—	—	33.5	33.1	23.3	12.3	39.3	28.2	—
11	18.9	12.9	14.3	—	—	31.0	27.8	13.7	15.5	37.6	24.4	—
12	14.2	15.9	14.0	—	—	32.7	26.4	19.2	13.2	39.3	26.3	—
13	16.8	10.2	13.3	—	—	32.5	29.6	18.6	15.0	38.2	27.6	—
14	17.8	9.0	13.6	—	—	22.9	18.4	11.5	9.8	29.1	16.5	—
15	18.4	12.1	15.2	—	—	34.7	31.8	24.8	12.0	36.8	25.0	—
16	17.1	11.9	15.0	—	—	27.4	23.1	17.3	12.9	34.4	22.6	—
17	18.5	8.1	14.5	—	—	22.7	18.7	11.6	7.9	28.1	13.9	—
18	13.6	10.4	14.0	—	—	27.0	23.9	12.9	11.8	34.4	23.9	—
19	12.0	10.7	13.9	—	—	29.8	17.8	17.9	13.7	37.3	21.8	—
20	12.6	12.6	15.1	—	—	29.0	17.8	18.2	15.8	39.3	24.8	—
21	16.0	9.6	15.5	—	—	32.7	39.2	22.3	22.3	36.8	32.1	—
22	13.9	9.0	15.0	—	—	36.3	35.8	23.0	17.9	38.1	32.2	—
23	20.6	14.5	19.4	—	—	39.4	35.5	21.0	13.9	39.9	31.8	—
24	17.6	14.6	18.7	—	—	37.1	38.2	23.7	16.1	39.3	34.4	—
25	21.3	7.2	17.8	—	—	38.5	34.3	27.7	18.8	36.9	28.4	—
26	20.4	10.9	19.1	—	—	35.2	35.9	23.2	18.8	38.4	30.5	—
27	22.3	12.1	20.5	—	—	37.2	36.6	30.6	18.9	39.3	24.9	—
28	20.6	13.3	20.6	—	—	33.9	39.4	27.1	16.2	39.8	31.6	—
29	19.2	15.0	21.1	—	—	38.9	36.8	27.7	13.4	37.8	28.8	—
30	20.7	11.8	20.8	—	—	38.4	38.0	25.9	19.6	38.4	31.3	—
31	18.7	12.1	20.6	—	—	35.4	35.8	24.9	16.3	39.2	28.4	—
32	21.0	10.0	21.0	—	—	36.0	37.7	28.6	18.9	36.6	30.7	—
33	14.0	10.6	19.2	—	—	36.3	39.2	28.9	15.4	37.7	36.8	—

Table A-1, Continued

Sample #	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
	---					%					---	
34	16.2	9.6	19.9	—	—	39.9	36.7	25.8	21.7	39.3	35.9	—
35	17.3	9.8	20.7	—	—	39.2	36.7	28.3	18.2	36.3	33.8	—
36	19.9	9.8	21.9	—	—	33.3	29.7	24.9	10.1	37.4	30.4	—
37	22.0	7.8	22.3	—	—	33.9	30.9	21.5	14.6	35.7	27.6	—
38	22.6	12.0	24.2	—	—	34.7	30.8	21.5	15.9	39.2	26.3	—
39	21.3	14.0	24.8	—	—	31.2	35.2	16.8	13.3	38.9	31.6	—
40	20.3	8.5	22.9	—	—	27.0	33.8	18.5	9.7	37.5	32.3	—
						Dry area						
51	9.8	7.4	6.2	6.6	5.7	27.3	21.1	8.8	15.9	36.3	15.8	11.9
52	11.2	9.4	8.3	8.9	7.2	21.3	16.9	9.8	15.9	31.3	15.6	7.7
53	11.2	9.3	7.4	10.1	6.6	25.6	23.6	12.1	21.6	39.3	17.4	10.3
54	14.0	8.4	8.9	9.3	8.4	25.4	20.2	12.1	14.4	33.7	16.4	9.6
55	12.3	9.9	6.5	7.7	8.6	24.9	18	8.9	16.4	30.0	15.3	8.0
56	7.9	7.8	7.4	9.0	6.1	39.8	31.7	20.0	19.9	36.7	24.4	17.9
57	12.9	7.5	8.3	9.0	6.8	29.8	22.9	16.4	19.3	40.0	18.2	12.0
58	13.7	10.2	7.5	10.1	7.9	31.2	28.1	16.9	19.2	35.8	24.6	18.6
59	13.1	10.3	8.3	8.1	9.1	28.1	24.3	15.4	18.0	35.8	20.6	12.8
60	11.8	9.9	6.5	8.0	6.9	24.8	20.6	11.1	14.1	33.5	16.1	10.6
61	13.4	11.9	12.1	8.1	9.8	30.2	29.7	13.9	13.4	40.0	23.4	15.4
62	10.3	9.1	7.2	11.2	6.9	31.7	26.0	17.3	17.4	34.1	22.7	13.7
63	11.2	14.2	11.3	12.1	10.9	31.5	20.4	12.7	12.9	38.7	17.9	9.8
64	11	9.7	12.2	11.3	8.4	32.5	28.5	16.2	15.6	37.7	26.4	10.8
65	10.1	10.6	8.5	9.4	7.8	32.0	27.1	14.1	14.8	34.6	18.8	9.1
66	14.4	9.8	9.9	7.5	8.9	25.3	23.1	13.3	16.4	35.2	19.9	9.7
67	13.3	11.1	8.1	7.3	8.2	31.4	24.8	18.1	22.9	37.9	29.3	15.1
68	8.6	6.9	6.2	4.8	4.3	18.2	15.8	7.1	15.3	31.7	11.7	4.8
69	7.3	3.2	4.3	5.1	5.4	19.8	16.6	7.6	16.4	31.9	13.5	8.5
70	9.8	7.1	4.5	6.2	6.1	17.1	15.6	8.7	13.1	33.6	15.0	7.2
71	5.4	4.5	3.7	3.6	3.8	17.1	16.1	7.2	11.8	29.1	13.5	6.7
72	9.7	7.1	9.3	7.0	8.0	30.7	28.7	17.4	22.3	33.0	17.8	11.9
73	10.0	5.5	7.7	8.8	9.6	33.7	29.7	17.2	19.1	33.6	22.6	10.0
74	7.3	7.3	7.3	6.2	6.9	38.1	37.2	23	18.7	37.8	28.0	17.3
75	9.0	9.4	8.8	12.1	9.2	30.3	24.6	15.8	14.3	34.5	18.9	10.2
76	15.9	10.6	9.1	8.8	12	27.5	25.2	16.4	21.3	37.3	20.7	14.6
77	14.5	6.9	7.6	13.5	10.2	28.5	24.4	14.7	16.3	33.2	20.2	10.4
78	17.0	8.0	7.9	9.0	7.7	24.2	23.0	15.5	16.5	35.2	19.1	12.9
79	11.2	10.1	8.5	9.1	10.9	29.1	23.2	14.8	—	31.1	23.5	13.3
80	12.0	9.6	9.9	9.8	9.8	30.0	22.2	17.4	16.8	31.3	19.4	13.3
81	14.5	11.3	9.4	11.1	11.9	30.8	23.0	16.3	16.2	34.4	18.4	11.4
82	13.9	11.3	11.8	8.0	9.7	26.8	26.3	14.4	18.8	38.3	18.7	8.6
83	10.3	4.9	5.8	6.4	5.6	39.1	33.6	23.7	19.4	40.3	22.9	17.7
84	10.8	10.0	9.5	5.5	7.9	32.0	29.1	18.2	19.2	36.9	24.5	14.4
85	12.5	10.8	6.3	8.1	5.4	27.7	23.7	13.2	18.9	36.5	20.9	12.3
86	9.4	5.0	3.4	4.3	3.1	20.9	15.6	10.0	15.5	27.6	19.3	5.8

¶ The missing measurement in M4 and M5 in the irrigated area was due to concurrent irrigation and precipitation which caused the area too wet to enter; the missing measurement in M12 was due to the defoliant application, which made the area inaccessible on the sampling day.

Table A-2. In-season soil moisture content in 2006 (dry area, n = 66).

Sample #	M1	M2	M3	M4	M5
			%		
51	10.5	8.1	17.5	10.2	15.3
52	11.0	6.3	9.9	7.5	8.6
52-1	7.6	5.9	11	6.8	7.7
52-2	9.8	7.3	12.5	7.4	9.9
52-3	9.5	6.0	9.7	7.0	9.0
53	9.4	5.7	10.3	6.5	8.0
54	11.6	7.5	12.0	7.7	11.6
54-1	12.3	7.7	14.1	7.9	8.8
54-2	10.4	7.8	12.2	7.8	9.9
54-3	11.1	7.6	11.4	7.6	10.4
55	10.2	6.9	11.0	6.6	8.2
56	20.4	14.3	32.1	21.6	18.8
56-1	16.0	9.8	18.5	14.4	12.4
56-2	14.4	9.5	18.1	11.3	12
56-3	14.2	9.3	15.0	9.3	10.1
57	11.2	9.2	12.0	9.5	9.7
58	17.1	11.9	20.3	13.5	15.2
59	11.1	8.1	17.3	9.6	12.1
60	12.0	7.9	11.6	8.4	9.1
61	13.2	8.8	12.9	8.6	8.1
62	14.4	8.5	13.8	10.1	9.0
62-1	14.6	9.8	13.1	9.5	8.2
62-2	12.2	9.4	13.5	9.9	9.8
62-3	13.3	9.3	13.4	8.8	9.3
63	10.8	8.4	13.1	7.9	9.4
64	14.8	11.5	25.8	15.7	15.3
64-1	15.8	12.9	27.0	17.2	19.3
64-2	15.6	11.7	19.7	15.2	19.1
64-3	15.4	13.8	23.9	15.0	17.7
65	13.0	8.2	14.0	8.8	12.6
66	9.6	6.5	12.1	8.4	10.2
67	10.4	6.7	9.6	7.0	8.6
67-1	11.1	6.0	15.3	9.4	11.6
67-2	8.3	6.3	8.8	6.3	7.0
67-3	11.6	6.2	13.0	8.8	10.1
68	9.4	6.0	10.3	8.6	8.5
69	9.6	5.5	9.5	6.7	7.1
70	10.2	4.9	16.7	11.4	11.3
71	7.7	6.1	8.9	7.2	7.4
72	9.8	7.3	13.6	7.2	10.2
73	15.1	10.3	19.9	12.7	12.5
73-1	13.7	12.1	20.8	13.7	18.1
73-2	11.6	11.4	27.1	17.3	17
73-3	13.2	10.9	28.8	16.1	16.4
74	13.7	12.4	25.6	20.3	15.2
75	13.1	10.3	17.6	8.2	11.1
76	13.6	9.9	17.7	11.2	10.4
77	11.9	8.2	11.7	9.0	9.7

Table A-2, Continued

Sample #	M1	M2	M3	M4	M5
	----------	----------	%	----------	----------
77-1	11.6	11.4	14.2	8.4	8.2
77-2	13.0	9.7	13.7	9.3	9.0
77-3	14.8	10.5	15.5	9.5	8.9
78	14.7	9.6	14.5	10.4	10.4
79	15.0	9.9	13.4	9.9	9.6
80	14.0	11.5	17.2	9.1	8.1
80-1	14.1	11.0	15.9	9.9	8.4
80-2	14.8	9.9	18.4	9.5	12.9
80-3	15.5	9.1	20.2	10.8	8.9
81	11.9	10.9	17.6	10.5	9.0
82	15.2	10.2	14.8	10.1	8.1
83	11.3	11.7	25.7	18.1	13.1
83-1	9.6	11.1	22.7	17.9	15.5
83-2	14.2	11.3	20.4	16.6	16.9
83-3	11.4	10.6	18.4	13.8	13.6
84	9.4	12.7	19.6	15.8	13.9
85	8.6	7.6	13.9	7.8	9.3
86	10.8	5.0	9.7	4.6	5.0

Table A-3. HVI fiber quality data in 2005.

Sample #	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b	Loan rate (¢/lb)
Irrigated area								
1	4.5	28.2	83.5	30.6	5.2	80.6	8.9	58.35
2	3.5	27.4	81.8	27.5	4.9	80.0	8.9	55.20
3	4.1	27.9	81.9	29.6	4.8	79.5	8.8	58.00
4	4.1	26.4	82.3	27.4	5.8	77.9	10.1	51.45
5	4.4	29.2	84.5	28.7	5.9	78.7	8.9	59.25
6	4.5	26.7	83.8	28.4	5.7	79.4	8.5	52.70
7	4.6	27.2	82.4	27.8	4.5	79.0	9.3	54.85
8	4.3	27.9	82.5	27.9	4.8	79.3	8.9	57.80
9	4.3	27.4	83.2	28.1	5.2	78.7	9.5	55.10
10	4.5	29.2	84.5	29.5	5.0	80.3	9.0	59.50
11	4.5	28.7	83.8	29.0	5.0	79.6	9.1	59.15
12	4.0	27.7	83.5	27.9	5.5	78.5	9.5	55.40
13	4.3	29.0	83.7	29.5	5.0	80.3	8.8	59.40
14	4.6	27.4	82.9	28.8	4.6	80.8	9.2	55.45
15	4.6	27.9	84.6	29.3	5.0	80.7	9.0	58.00
16	4.4	29.0	84.2	30.2	4.5	79.8	8.7	59.40
17	4.1	27.4	82.9	27.8	4.7	78.1	9.7	55.30
18	4.4	27.7	84.4	30.2	5.3	79.2	9.1	55.80
19	4.0	27.9	83.5	30.4	5.3	79.6	9.3	58.35
20	4.6	29.0	84.4	30.1	5.1	79.4	9.2	59.40
21	4.6	29.2	84.4	28.7	5.1	80.8	9.1	59.15
22	4.5	29.5	84.8	29.4	4.9	80.0	8.8	59.40
23	4.5	29.5	84.9	30.5	5.3	80.1	8.8	59.85
24	4.0	29.0	83.9	29.6	5.6	80.4	9.0	59.60
25	4.5	29.5	83.8	29.6	5.0	79.8	8.6	59.55
26	4.4	29.7	83.9	30.2	4.8	80.5	8.9	59.55
27	4.3	30.0	85.1	29.4	5.3	80.3	8.4	59.40
28	4.5	29.7	84.6	30.3	5.4	80.4	8.8	59.65
29	4.3	30.2	84.8	30.0	5.5	80.8	8.7	59.65
30	4.4	30.0	84.4	31.5	5.0	80.5	9.0	59.75
31	4.3	29.2	84.1	29.7	4.9	79.5	8.6	59.40
32	4.3	29.5	83.9	30.9	4.9	80.8	8.5	59.75
33	4.4	29.2	84.3	30.3	4.9	79.9	8.8	59.40
34	4.3	30.2	85.7	30.1	5.1	80.5	8.6	59.75
35	4.4	30.0	84.2	29.5	5.1	80.7	8.3	59.55
36	4.4	29.0	84.2	30.4	5.2	80.4	9.1	59.40
37	4.5	29.0	83.9	29.7	4.9	80.9	8.9	59.40
38	4.5	29.7	85.4	31.7	5.4	80.4	8.7	59.85
39	4.2	29.2	84.0	30.7	5.2	81.7	8.6	59.80
40	4.6	27.9	82.2	30.1	5.0	80.0	9.0	57.80
Dry area								
51	4.6	29.0	83.4	33.4	3.6	79.3	8.8	59.55
52	4.7	30.2	83.5	33.3	3.9	79.0	8.3	59.80
53	4.6	27.9	83.6	31.8	3.7	80.7	8.6	58.35

Table A-3, Continued

Sample #	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b	Loan rate (¢/lb)
54	4.4	28.2	83.0	31.8	4.0	80.1	9.0	58.25
55	4.5	28.4	82.8	31.1	3.8	78.7	8.6	58.25
56	4.2	31.0	84.1	35.0	3.9	81.5	8.7	60.00
57	4.3	29.7	83.3	34.0	3.6	79.3	8.7	59.70
58	4.0	30.7	83.0	33.4	3.8	81.4	8.5	59.90
59	4.4	31.0	83.7	34.5	3.7	80.9	8.9	59.80
60	4.7	29.2	83.4	33.8	3.6	81.6	8.4	59.55
61	4.8	27.9	82.1	31.1	4.4	81.3	8.4	58.00
62	4.4	28.7	81.4	30.0	4.3	81.5	8.6	59.05
63	4.6	28.4	82.2	30.5	3.9	81.8	8.3	58.00
64	4.3	28.2	82.2	29.3	4.0	83.2	8.0	57.55
65	4.8	27.4	81.7	30.7	4.0	82.5	8.1	55.65
66	4.8	27.4	81.9	29.3	4.0	81.3	8.3	55.20
67	4.9	28.4	81.8	30.5	4.0	81.2	8.3	58.00
68	4.7	29.2	81.2	31.7	3.8	83.0	8.2	59.25
69	4.7	29.0	82.0	30.6	3.8	82.2	8.3	59.25
70	4.7	28.4	82.0	31.9	3.9	83.1	8.1	58.00
71	4.9	29.0	82.5	30.6	3.8	82.8	8.1	59.50
72	4.2	29.2	81.2	31.1	4.0	83.5	7.9	59.45
73	4.4	28.4	81.7	30.5	4.2	82.3	8.4	58.00
74	4.4	28.7	83.2	30.5	3.9	82.4	8.1	59.50
75	4.7	28.2	82.3	30.1	4.2	82.3	8.0	57.80
76	4.6	28.2	81.4	30.3	4.1	81.0	8.4	57.80
77	4.5	27.9	81.4	28.9	4.3	82.1	8.6	57.55
78	5.1	26.9	81.0	28.9	4.0	80.8	8.1	49.60
79	4.3	28.2	82.5	30.7	4.2	82.1	8.5	58.25
80	4.8	26.9	81.4	30.0	4.1	82.3	8.4	55.45
81	4.5	27.7	81.6	31.3	3.9	81.4	8.6	55.65
82	4.5	27.4	82.2	29.9	4.1	82.5	8.4	55.45
83	4.7	28.4	80.7	30.8	3.6	82.2	7.9	58.00
84	4.4	29.0	81.8	30.2	3.7	83.1	8.1	59.05
85	4.5	28.4	80.6	30.1	3.9	82.7	8.2	57.80
86	4.0	28.7	81.0	30.4	3.9	82.8	8.0	59.25

Table A-4. HVI fiber quality data in 2006 (dry area, n = 66).

Sample #	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b	Loan rate (¢/lb)
51	3.57	29.2	80.5	27.9	5.0	80.9	9.4	58.80
52	3.50	26.4	80.5	28.6	5.7	77.3	10.2	51.15
52-1	3.83	27.2	81.6	28.0	5.7	78.2	10.2	53.30
52-2	3.69	25.7	81.3	25.9	5.8	76.6	10.4	49.80
52-3	3.83	26.4	81.7	29.3	6.1	77.2	10.2	51.35
53	3.87	25.4	81.0	25.8	5.9	77.2	10.4	49.80
54	3.68	27.2	79.4	26.4	5.4	77.2	10.9	52.80
54-1	3.40	29.5	82.6	28.2	5.7	78.4	9.9	56.65
54-2	3.36	27.9	82.0	27.0	5.5	76.8	10.3	52.85
54-3	3.50	28.2	79.8	26.9	5.7	77.1	10.1	54.75
55	3.49	27.7	81.3	29.5	5.3	78.4	9.9	55.10
56	3.66	31.2	83.4	30.4	5.1	78.2	9.4	56.70
56-1	3.76	29.0	82.4	28.6	5.3	79.3	9.9	55.95
56-2	3.13	28.4	81.0	27.6	5.6	77.0	9.9	51.15
56-3	3.77	26.9	80.8	27.4	5.5	76.3	10.1	51.35
57	3.39	26.4	80.7	28.9	5.7	75.2	10.9	49.25
58	3.33	29.7	81.6	28.9	5.1	79.2	10.0	54.10
59	3.23	27.7	81.7	28.7	5.4	78.3	9.9	51.25
60	3.62	26.7	81.3	27.6	5.6	78.3	9.7	52.25
61	3.20	27.9	80.8	27.7	5.2	77.6	10.1	51.15
62	3.90	27.4	82.7	26.7	5.5	76.4	10.4	53.55
62-1	3.34	25.9	80.1	26.4	5.5	77.5	10.2	47.70
62-2	3.65	26.9	81.7	28.2	5.8	75.9	10.3	51.35
62-3	3.49	26.7	80.0	27.6	5.2	76.9	10.3	51.15
63	3.43	26.2	79.4	27.4	5.7	77.0	10.6	47.20
64	3.65	28.7	82.3	26.3	5.9	78.8	9.7	55.95
64-1	3.78	31.5	82.9	28.5	5.3	79.0	9.4	58.75
64-2	3.50	30.5	83.3	29.2	5.0	80.0	9.2	59.20
64-3	3.87	31.0	83.9	30.3	4.8	79.8	9.0	59.75
65	3.38	27.9	81.1	28.3	5.2	78.6	10.0	53.00
66	3.62	28.4	81.7	28.7	5.5	78.7	9.7	54.90
67	3.62	26.7	80.4	27.2	5.7	76.8	10.3	51.15
67-1	3.62	27.4	80.0	28.8	5.4	76.7	10.2	53.10
67-2	3.89	25.7	77.3	26.7	5.9	78.3	9.7	50.05
67-3	3.40	27.9	80.7	29.4	5.2	78.8	9.6	55.15
68	3.45	27.7	81.1	28.0	5.1	77.8	9.9	54.85
69	3.89	27.2	81.4	26.6	5.3	77.8	10.0	55.05
70	3.88	30.5	82.7	29.6	4.6	81.0	9.0	59.65
71	4.20	27.9	80.8	28.1	5.5	77.9	9.6	57.25
72	3.37	28.2	81.6	27.5	5.3	78.1	10.4	52.85
73	3.60	29.2	82.5	28.6	5.1	79.8	9.0	59.05
73-1	3.86	30.0	81.8	31.1	4.9	81.7	9.0	59.60
73-2	4.19	31.0	81.1	29.6	4.2	76.8	9.3	56.45
73-3	4.22	31.2	84.4	31.6	5.0	77.6	8.9	59.95
74	4.17	31.2	84.5	29.5	4.9	79.8	8.7	59.85
75	3.07	27.9	81.4	27.3	5.3	77.9	10.3	51.15
76	3.25	28.7	82.5	26.9	5.6	78.4	10.3	53.80
77	3.83	26.9	81.8	27.2	5.2	78.0	9.9	52.45
77-1	3.08	27.9	80.9	27.1	5.5	77.5	10.1	51.15

Table A-4, Continued

Sample #	Micronaire	Length (mm)	Uniformity (%)	Strength (g/tex)	Elongation (%)	Rd	+b	Loan rate (¢/lb)
77-2	3.81	27.4	81.8	29.0	5.7	77.7	10.4	53.30
77-3	3.28	28.4	82.7	28.4	5.4	77.9	9.8	55.40
78	3.43	28.7	82.8	28.9	5.7	79.0	9.8	54.10
79	3.52	28.2	81.8	26.7	5.3	80.1	9.0	57.55
80	3.46	28.4	81.9	28.4	5.3	79.2	9.8	54.90
80-1	3.09	27.9	81.4	25.8	5.2	78.5	10.0	51.30
80-2	3.09	29.0	81.5	27.8	5.2	78.5	10.3	51.85
80-3	3.15	28.7	81.6	26.3	5.0	78.7	9.5	54.55
81	3.05	28.7	81.8	27.4	5.4	77.2	10.3	51.85
82	3.38	27.4	79.8	27.4	5.5	77.5	9.5	51.20
83	3.94	30.7	82.2	29.2	4.9	77.6	9.2	59.15
83-1	4.15	31.0	83.7	30.1	4.9	78.4	9.0	59.75
83-2	3.72	30.0	83.4	30.3	4.7	79.8	9.2	59.65
83-3	4.09	28.4	82.6	30.6	5.0	79.8	9.8	57.95
84	4.87	27.7	81.8	26.2	5.6	79.3	9.7	54.85
85	3.87	26.9	79.7	28.7	5.5	78.3	10.0	51.35
86	3.87	27.2	79.0	27.9	5.6	78.5	9.5	54.55

Table A-5. Bale level fiber quality data from classing office for five complete modules built in field test of first version prototype of wireless GPS system.

Module Number	PBI ¶	HVI fiber parameter						
		Micronaire	Length (mm)	Strength (g/tex)	Uniformity (%)	Rd	+b	Loan Rate (¢/lb)
00101	4319567	2.8	28.2	26.2	77.9	83	7.8	51.25
	4319568	2.8	29.0	24.8	76.6	82	7.7	49.50
	4319569	2.8	28.2	27.5	77.6	83	8.0	50.60
	4319570	2.8	28.4	26.4	77.5	82	7.9	50.60
	4319571	2.8	28.7	28.4	77.6	82	7.8	50.60
	4319572	2.9	28.4	28.1	77.2	82	8.1	50.50
	4319573	2.8	28.2	27.5	76.9	82	7.9	50.50
	4319574	2.9	28.4	25.7	77.7	83	7.7	50.60
00201	4319575	2.8	29.0	28.9	76.8	82	8.1	50.65
	4319576	2.8	27.7	24.9	76.0	82	7.6	48.25
	4319577	2.9	28.4	25.6	77.3	81	7.8	50.50
	4319578	2.9	28.4	27.0	77.8	82	8.0	50.60
	4319579	2.8	28.2	27.0	78.0	81	8.3	50.60
	4319580	3.1	27.9	26.7	78.6	82	8.2	52.55
	4319581	2.9	29.2	28.7	78.1	81	8.3	50.75
	4319582	2.9	29.0	27.2	76.8	81	7.9	50.65
	4319583	2.9	28.2	26.6	77.1	81	8.4	48.10
	4319584	2.9	28.4	25.8	76.8	81	7.9	50.50
00301	4319585	2.9	27.4	25.2	76.1	81	7.8	48.25
	4319586	2.9	29.2	25.8	77.6	82	7.7	50.75
	4319587	3.0	28.2	25.7	76.5	81	7.9	53.45
	4319588	2.9	28.4	27.0	76.7	80	8.0	50.50
	4319589	2.9	28.2	28.0	77.2	81	8.2	50.50
	4319590	3.0	28.2	27.8	78.1	81	8.4	53.55
	4319591	2.9	28.2	25.7	78.7	80	8.1	50.70
	4319592	3.0	27.9	27.5	78.4	80	8.7	50.30
	4319593	3.0	28.7	28.1	77.9	80	8.2	53.55
	4319594	3.0	28.7	27.9	78.7	81	8.4	53.65
00401	4319595	2.9	28.2	27.3	77.6	81	8.1	50.60
	4319596	3.1	29.0	27.5	78.3	81	7.6	53.70
	4319597	2.9	29.2	26.1	77.2	81	7.6	48.35
	4319598	3.0	29.2	25.7	77.9	80	7.6	50.70
	4319599	3.1	28.2	25.9	77.2	79	7.7	50.40
	4319600	3.0	29.5	27.1	78.7	80	7.8	50.80
	4319601	3.1	27.9	27.2	76.5	79	8.1	50.20
	4319602	3.0	27.9	27.6	78.0	80	8.3	52.45
	4319603	3.1	28.4	28.2	77.7	80	8.2	53.55
	4319604	3.0	29.0	27.9	77.2	80	8.0	53.60

Table A-5, Continued

Module Number	PBI ¶	HVI Fiber Parameter						
		Micronaire	Length (mm)	Strength (g/tex)	Uniformity (%)	Rd	+b	Loan Rate (¢/lb)
00501	4319605	3.1	28.2	27.5	77.2	81	7.8	53.45
	4319606	3.0	28.2	27.8	78.1	81	7.9	51.15
	4319607	3.0	28.2	26.8	78.1	81	7.8	53.55
	4319608	2.9	28.7	26.3	77.6	81	7.8	48.20
	4319609	3.2	28.2	25.9	77.0	80	7.8	53.45
	4319610	3.1	28.4	24.8	78.2	80	7.7	52.40
	4319611	3.0	28.7	24.7	77.4	80	7.3	49.25
	4319612	3.2	28.7	28.0	78.6	81	7.6	53.65
	4319613	3.1	28.7	26.4	77.8	81	7.4	52.75
	4319614	2.9	27.9	26.3	77.2	82	7.9	49.40

¶ PBI: Permanent Bale Identification

APPENDIX B

SOURCE CODES OF PROGRAMS IN PROTOTYPE WIRELESS GPS FIBER QUALITY MAPPING SYSTEM

B-1. SOURCE CODE FOR HARVESTER SUBSYSTEM.

```
// HARVESTER SUBSYSTEM.C
// Wireless GPS system for fiber quality module mapping
// Run on harvester subsystem
// Copyrighted to Department of Biological and Agricultural Engineering
// Texas A&M University
// Developer: Yufeng Ge, J. Alex Thomasson, Ruixiu Sui

                                    //Start of source code
#class auto                         //Local variables stored on stack
#memmap xmem                        //Reduce root memory usage

#define FS_MAX_FILES 128            //Maximum # of files equal to 64
#use "FS2.LIB"                      //Use FS2 library

#define BINBUFSIZE 511              //B serial port in buffer size 511
#define BOUTBUFSIZE 31              //B serial port out buffer size 31
#define CINBUFSIZE 63               //C serial port in buffer size 15
#define COUTBUFSIZE 15              //C serial port out buffer size 15

                                    //Define a struct type POSITION
typedef struct                      //to store Latitude Longitude information
{
float Lat;                          //Latitude: **.******** degrees
float Lon;                          //Longitude: ***.******* degrees
}
POSITION;

#define PTNUM 127                   //Each file is 1K in size, thus the
                                    //maximum # of point is
                                    // |1k / sizeof(POSITION)|
#define MAX_SENTENCE 128            //Longest sentence received by
                                    //GPS would be 128 bytes
unsigned short k;                   //Variable to record existing file number
fontInfo fi6x8;                     //Handle of font info in LCD
windowFrame textWindow;             //Handle of window frame in LCD
```

```
POSITION Parse_NMEA_Message(char*);           //Subroutine to parse the "GPRMC" sentence
void SignOnPage1();                           //Subroutine to display Sign On page 1
void SignOnPage2(unsigned short);             //Subroutine to display Sign On page 2


void main()                                   //Start of the main function
{                                             //Variable Declaration
int rc;                                       //Variable to store result of file operation
char FileNumber;                              //Variable to store current file number

char keychar;                                 //Variable to store result of key press

short flag;                                   //Boolean variable for loop control
unsigned short CursorPos_Y;                   //Variable for cursor control in Sign On page 2
int index;
int n1, n2;
int i, j;
int lapse;

char PHSCL_HH[2];                             //String to store physical Harverst #: 01 - 99

static char sentence[MAX_SENTENCE];           //Temporary string to store received GPS sentence
static char buf[6];                           //Temporary variable

char RCVD_MSG[40];                            // Temporary string to store received wireless MSG
char SEND_MSG[10];                            // Temporary string to store wireless MSG to be sent

int RCVD_FileNumber;                          //Relative file number being received
char RCVD_BSKT[4];                            //Temporary char array to store received
                                              // basket #, the first three digits:
                                              // 001 - 999, the last digit: null terminator

int GPS_STATE;                                //Boolean to indicate GPS receiving and
                                              //not receiving
int CPU_STATE;                                //Boolean to indicate program status

File file, file1;                              //File handles for file operation

POSITION GPSPos;                              //Temporary variable to store parsed GPS
POSITION GPSPos1;                             //Temporary variable to store intended GPS
POSITION GPS[PTNUM];                          //POSITION type array to store the recorded
                                              //GPS point Latitude and Longitude

#if _BOARD_TYPE_ = = 0x1200 || _BOARD_TYPE_ = = 0x1201
   brdInit();                                 //board initialization, required for all applications
#endif

devPowerSet(DISPDEV, 1);                      //LCD initialization, required for all applications
dispInit();
keypadDef();                                   //Use Default keypad configuration

SignOnPage1();                                //Call subroutine to show Sign On page 1
fs_init(0, 0);                                //Initial file system for file operations
```

```
PHSCL_HH[0] = '0';                          //Actual physical Harvester #: 01, different physical
PHSCL_HH[1] = '1';                          //harvester numbers are assigned here

SEND_MSG[9] = '\0';                         //The null terminator for wireless MSG should be
RCVD_BSKT[3] = '\0';                        //defined explicitly

k = 1;                                      //Count how many files are currently stored in the
while( (rc = fopen_rd(&file, k)) = = 0)     //flash memory. This is necessary for return harvest
{
   fclose(&file);
   k++;
}
FileNumber = k;

LOOP1:

flag = 1;
CursorPos_Y = 1;
SignOnPage2(CursorPos_Y);                   //Call subroutine to show Sign On page 2

while(flag)                                 //Loop to test which button is pressed
{
   keyProcess();                            //Test the keyboard
   keychar = keyGet();
   if(keychar = = 'U')                      //If Up button is pressed
   {                                        //The highlight bar scroll up
      if(CursorPos_Y >1 )
      {
         CursorPos_Y --;
         SignOnPage2(CursorPos_Y);
      }
   }
   if(keychar = = 'D')                      //If Down button is pressed
   {                                        //The highlight bar scroll down
      if(CursorPos_Y < 3)
      {
         CursorPos_Y ++;
         SignOnPage2(CursorPos_Y);
      }
   }
   if(keychar = = 'R')                      //If the Enter button is pressed
   {
      flag = 0;                             //then jump out of this while structure
   }
}

if(CursorPos_Y = = 1)                       //If "download data" is selected
{                                           //Then downloads GPS data for all stored files
   for( i = 1; i < k; i++ )                 //Open the file from 1 to k, where k is the maximum
   {
      rc = fopen_rd(&file, i);              //Open file i for read operation
      rc = fseek(&file, 0, SEEK_SET);       //Set file pointer to beginning
```

```
      printf("\n File: %d", i);
      while(fread(&file, &buf, sizeof(POSITION))>0)//Read the file
      {
         printf("\n %9f,%9f", buf.Lat, buf.Lon);          //Print out the Lat, Lon information on the screen
      }

      rc = fseek(&file, -5, SEEK_END);                    //Set file pointer to -5 relative to file end
                                                          //Module number for each file is stored at the end of
                                                          //Each file
      fread(&file, buf, 5);                               //Read the module number into buf
      buf[5] = '\0';
      printf("\n %s", buf);
      rc = fclose(&file);                                 //Close file i
   }
   goto LOOP1;
}

if(CursorPos_Y = = 2)                                     //If “clear the memory” is selected
{
   fs_format(0, 0, 0);                                    //Format the current file system
                                                          //and clears all of the existing data
   FileNumber = 1;                                        //and sets the current file number as 1
   k = 1;
   goto LOOP1;
}


GPS_COLLECT:                                              //If “start collecting” is selected

   serBopen(4800);                                        //Open serial port B at rate 4800 bps
                                                          //port B is connected to GPS receiver
   serBrdFlush();                                         //Clear port B read buffer
   serCopen(4800);                                        //Open serial port C at rate 4800 bps
                                                          //port C is connected to wireless transceiver
   serCrdFlush();                                         //Clear port C read buffer
   flag = 1;                                              //Set loop control “true”
   index = 0;
   lapse = 0;
   GPS_STATE = 1;                                         //Initial state
   CPU_STATE = 0;

LOOP2:
   glBlankScreen();                                       //Clear LCD Screen
   TextGotoXY(&textWindow, 0, 0);
   TextPrintf(&textWindow, "Next Basket is #:%d", FileNumber);
                                                          //Print current file number on LCD
   TextGotoXY(&textWindow, 0, 1);
   TextPrintf(&textWindow, "Press E to Continue");

loopinit();                                               //Start the main loop
                                                          //improved design, the loop is in a parallel structure

while(flag)
```

```
{
   loophead();                                        //necessary of multitasking functions and statements

   costate                                            //Listening to serial port C
                                                      //and process wireless MSG
   {
      waitfor(DelayMs(2000));                         //inquire for wireless data every 2000 milliseconds

      wfd n2 = cof_serCread(RCVD_MSG, 40, 10);        //Read  characters from port C
                                                      //until a null terminator is received

      if (n2 > 0)                                     //If the read function returns successfully
      {                                               //The following code in this parenthesis is to parse
                                                      //the wireless MSG, which is from either boll buggy
                                                      //or module builder subsystem
         if(strncmp(RCVD_MSG, "MTOH", 4) = = 0)       //If the message is from Module Builder
         {                                            //Which means there might be more than one file
                                                      Numbers in the message
            j = (n2-4)/5-1;                           //Calculate how many files are there

            for (i = 0; i < j; i++)
            {
               if(strncmp(RCVD_MSG+4+5*i, PHSCL_HH, 2) = = 0)
                                                      //Determine if the file number is originated from this
                                                      //Physical harvester
               {
                  strncpy(RCVD_BSKT, RCVD_MSG+4+5*i+2, 3);
                                                      //Parse out the file number
                  TextGotoXY(&textWindow, i*5, 3);
                  TextPrintf(&textWindow, "%s", RCVD_BSKT);
                                                      //Display the file number on LCD
                  RCVD_FileNumber = atoi(RCVD_BSKT);
                                                      //Convert the file number from string form to the
                                                      //Digital form
                  rc = fopen_wr(&file1, RCVD_FileNumber);
                                                      //Open the file for write
                  rc = fseek(&file1, 0, SEEK_END);    //Set file pointer to the end of file
                  rc = fwrite(&file1, RCVD_MSG+n2-5, 5);
                                                      //Write the last 5 digits of the wireless MSG
                                                      //while is the corresponding module number to file
                  rc = fclose(&file1);                //Close the file
               }
            }
         }
         n2 = 0;
      }
   }

   costate                                            //Monitor serial port B and process the GPS signal
   {
      wfd n1 = cof_serBgets(sentence, 128, 10);       //Read characters from port B into string sentence
                                                      /until a null terminator is encountered/
      if(n1 != 0)                                     //if the read function returns successfully
```

```
  {
    if(lapse = = 65535)
      lapse = 0;
    lapse++;                              //lapse is used to control the GPS refresh rate
  }

  GPSPos1 = Parse_NMEA_Message(sentence); //Parse the received GPS and Store the
                                          // latitude, longitude information into GPSPos1

  if(GPSPos1.Lat != 88.888888)            //if the message is GPRMC sentence
      GPSPos = GPSPos1;                   //store the GPSPos1 into GPSPos for display and
                                          //recording

  if(CPU_STATE = = 1)
  {
    if(GPS_STATE = = 1)
    {
      if(( lapse%50) == 0)                // Set GPS signal refresh rate
      {
      TextGotoXY(&textWindow, 0, 0);
      TextPrintf(&textWindow, "BASKET #:%d     %3d", FileNumber, index+1);
                                          //Print the current file number on LCD
      TextGotoXY(&textWindow, 0, 1);
      TextPrintf(&textWindow, "LON: %9f W", GPSPos.Lon);
                                          //Print the current Longitude on LCD
      TextGotoXY(&textWindow, 0, 2);
      TextPrintf(&textWindow, "LAT: %9f N", GPSPos.Lat);
                                          //Print the current Latitude on LCD
      if(index = = 126)                   //if index exceeds 126
      {
        index = 0;                        //reset itself
      }
      GPS[index] = GPSPos;                //Store the GPSPos into GPS array for storage
      index++;
      }
    }
  }
}

Costate                                   //Store the GPS array to file
{                                         //and send the wireless MSG
  if(CPU_STATE = = 2)
  {
    glBlankScreen();

    TextGotoXY(&textWindow, 0, 0);
    TextPrintf(&textWindow, "Basket #:%d is Full", FileNumber);

    TextGotoXY(&textWindow, 0, 2);
    TextPrintf(&textWindow, "Store Data to File", FileNumber);

    rc = fcreate(&file, FileNumber);      //create the file with file number
    rc = fopen_wr(&file, FileNumber);     //Open the file for writing
```

```
      rc = fseek(&file, 0, SEEK_SET);             //set the file pointer to the beginning
      rc = fwrite(&file, GPS, index * sizeof(POSITION));
                                                  //write the GPS position into the file
      rc = fclose(&file);                         //close file

      if (keychar = = '+')                        //if the "H→B" button is pressed
      {
         strncpy(SEND_MSG, "HTOB", 4);            //Attach the message header "HTOB" in front of the
                                                  //wireless message
      }

      If (keychar = = 'E')                        //If the "H→M" button is pressed
      {
         strncpy(SEND_MSG, "HTOM", 4);            //Attach the message header "HTOM" in front of the
                                                  //wireless message
      }
                                                  //Construct the wireless message
      strncpy(SEND_MSG+4, PHSCL_HH, 2);           //Attach the 2-digit physical Harvester Number
      SEND_MSG[6] = floor(FileNumber / 100) + 48;
                                                  //Attach the 3-digit file number
      SEND_MSG[7] = floor((FileNumber % 100)/10 ) + 48;
      SEND_MSG[8] = (FileNumber % 10)+ 48;

      wfd cof_serCputs(SEND_MSG);                 //Write the wireless MSG into port C output buffer

      index = 0;                                  //Reset the index as 0
      FileNumber++;                               //Increment file number
      CPU_STATE = 0;
      goto LOOP2;                                 //go back to Loop 2
   }

}

costate
{
   waitfor(DelaySec(40));                         //Flush the read buffer of port B every 40 seconds
   serBrdFlush();
}

costate
{
   keyProcess();
   keychar = keyGet();                            //process the keyboard and get the key char

   if(CPU_STATE = = 0)
   {
      if( keychar = = 'R')                        //if Right button is pressed
      {
         CPU_STATE = 1;                           //Set the CPU and GPS State
         GPS_STATE = 1;
         glBlankScreen();                         //Clear the LCD screen
      }
   }
```

```
    if(CPU_STATE = = 1)
    {
      if( (keychar = = '+') || ( keychar = = 'E' ))
      {
        CPU_STATE = 2;
      }
      if( keychar = = '-')                      //if Pause button is pressed
      {
        if(GPS_STATE = = 1)                     //if current GPS state is 1
        {
          glBlankScreen();
          TextGotoXY(&textWindow, 0, 0);
          TextPrintf(&textWindow, "GPS Paused\n");
                                                //Print “GPS Paused” on LCD
          TextGotoXY(&textWindow, 0, 1);
          TextPrintf(&textWindow, "Press P/R Resume\n");
                                                //Print “Press P/R to Resume” on LCD
          GPS_STATE = 0;                        //Set the GPS State as 0
          continue;                             //Restart the loop
        }
        if (GPS_STATE = = 0)                    //if current GPS sate is 0
        {
          GPS_STATE = 1;                        //Set the GPS state as 1
          continue;                             //Restart the loop
        }
      }
    }

  }

}                                               //End of the main loop

}                                               //End of the main function


                                                //Start of the subroutines

void SignOnPage1()                              //Subroutine SignOnPage1
{
  glXFontInit(&fi6x8, 6, 8, 32, 127, Font6x8);  //Initialize the font information, font size 6×8
  TextWindowFrame(&textWindow, &fi6x8, 0, 0, 122, 32);
                                                //Initialize the LCD display widow, window size
                                                //122× 32
  TextGotoXY(&textWindow, 0, 0);
  TextPrintf(&textWindow, "Texas A&M Univ");    //Print welcome information
  TextGotoXY(&textWindow, 0, 1);
  TextPrintf(&textWindow, "Wireless GPS System");
  TextGotoXY(&textWindow, 0, 2);
  TextPrintf(&textWindow, "Harvester Block");
  TextGotoXY(&textWindow, 0, 3);
  TextPrintf(&textWindow, "Initialization...");
}
```

```
                                             //Subroutine to display sign on page 2, the input
                                             //argument indicates which selection item is current
                                             // and should be highlighted
void SignOnPage2(unsigned short CursorPos_Y)
{
   int number;                               //local variable store how many percents of the
                                             //memory have been used

   number = floor(k/1.28);                   //Calculate the percentage: k × 100 / 128
   glBlankScreen();
   TextGotoXY(&textWindow, 0, 0);
   TextPrintf(&textWindow, "-%2d%% of Memory Used-\n", number);
                                             //Display percentage of flash memory has been used

   glBlock(0, 8*CursorPos_Y, 122, 8);        //Select the intended line for highlight
   glSetBrushType(PIXXOR);                   //Set the paint mode as "exclusive OR" to highlight
                                             //the intended line
   TextGotoXY(&textWindow, 0, 1);            //Display the selection item on LCD display
   TextPrintf(&textWindow, "----Download Data----\n");
   TextGotoXY(&textWindow, 0, 2);
   TextPrintf(&textWindow, "----Clear Memory----\n");
   TextGotoXY(&textWindow, 0, 3);
   TextPrintf(&textWindow, "----Collect Data----");

   glSetBrushType(PIXBLACK);                 //Set the paint mode back to normal
}


                                             //Subroutine to parse the receive GPS signal store
                                             //sentence (starting address, the input argument), the
                                             //subroutine only parses the GPRMC sentence, and
                                             // ignores other types. The output argument is a
                                             //POSITION structure, which contains the extracted
                                             //Latitude and Longitude information

                                             //The received Latitude and Longitude is in the form
                                             //of "dd.mm.ssss"
                                              It is converted to "dd.dddddd" in the subroutine
POSITION Parse_NMEA_Message(char* sentence)
{
   int j;                                    //local variables for data operations
   POSITION Pos;
   char deg_buf[4];
   char min_buf[3];
   char sec_buf[5];
   float degree;
   float minute;
   float second;
                                             //If the subroutine can't parse the signal
                                             //successfully, or it is not a "GPRMC" sentence,
                                             //the latitude and longitude will be assigned
                                             //"88.8888"
   Pos.Lat = 88.888888;
   Pos.Lon = 88.888888;
```

```
    if(strncmp(sentence, "$GPRMC", 6) = = 0)         //determine if the sentence is “GPRMC”
    {

        for(j = 0; j < 5; j ++)
        {
            sentence = strchr(sentence, ',');         //Search the comma delimiter
                                                      //reminder all NMEA messages are comma delimited

            if(sentence = = NULL)
                return Pos;

            sentence++;

            if(j = = 2)                               //The segment after the third comma is latitude
            {
                strncpy(deg_buf, sentence, 2);        //extract 2-digit latitude degree
                deg_buf[2] = '\0';
                degree = (float) atoi(deg_buf);       //convert string to number
                strncpy(min_buf, sentence+2, 2);      //extract 2-digit latitude minute
                min_buf[2] = '\0';
                minute = (float) atoi(min_buf);       //convert string to number
                strncpy(sec_buf, sentence+5, 4);      //extract 4-digit latitude second
                sec_buf[4] = '\0';
                second = (float) atoi(sec_buf);       //convert string to number
                Pos.Lat = degree + minute/60 + second/600000;
                                                      //store latitude in the form “dd.dddddd”
            }

            if( j = = 4 )                             //The segment after the fifth comma in longitude
            {
                strncpy(deg_buf, sentence, 3);        //extract 3-digit longitude degree
                deg_buf[3] = '\0';
                degree = (float) atoi(deg_buf);       //convert string to number
                strncpy(min_buf, sentence+3, 2);      //extract 2-digit longitude minute
                min_buf[2] = '\0';
                minute = (float) atoi(min_buf);       //convert string to number
                strncpy(sec_buf, sentence+6, 4);      //extract 4-digit longitude second
                sec_buf[4] = '\0';
                second = (float) atoi(sec_buf);       //convert string to number
                Pos.Lon = degree + minute/60 + second/600000;
                                                      //store longitude in the form “dd.dddddd”
            }

        }
    }
    return Pos;
}
```

B-2. SOURCE CODE FOR MODULE BUILDER SUBSYSTEM.

```
// MODULE BUILDER SUBSYSTEM.C
// Wireless GPS system for fiber quality module mapping
// Run on module builder subsystem
// Copyrighted to Department of Biological and Agricultural Engineering
// Texas A&M University
// Developer: Yufeng Ge, J. Alex Thomasson, Ruixiu Sui


                                            //Start of source code
#class auto                                 //Local variable stored on stack
#memmap xmem                                //Reduced root memory usage, needed for large
                                            //project

#define CINBUFSIZE 31                       //Input buffer size of serial port C is 31
#define COUTBUFSIZE 31                      //Output buffer size of serial port C is 31

#use "FS2.LIB"                              //Use FS2 function library for file operation

fontInfo fi6x8;                             //Handle of font information in LCD
windowFrame textWindow;                     //Handle of text window information in LCD

void Input_Refresh(unsigned short, char*);  //Subroutine to refresh the screen for sign on page 3
void SignOnPage1();                         //Subroutine to display sign on page 1
void SignOnPage2(unsigned short);           //Subroutine to display sign on page 2
void SignOnPage3(unsigned short);           //Subroutine to display sign on page 3

void main()                                 //Start of the main function
{
char MB_NUM[6];                             //String to store module number in string form
int Module_Counter;                         //integer to store module number

char keychar;                               //Variable to store key press result
int result;
int CursorPos_Y;                            //Variable to store working mode,
                                            // default (2) or customized (3)
int CursorPos_Y1;                           //Variable to store working mode,
                                            //continuous numbering (2) or not (3)

char RCVD_MSG[40];                          //String to store received message
char SEND_MSG[40];                          //String to store sent message
char BSKT_DISP[6];

int i;                                      //Temporary variables
int j;
int n;
short flag;                                 //Boolean variable for loop control

int counter;                                //Variables for counting
short CursorPos_X;                          //Variable for cursor control at X direction
int Value;
```

```
File file;                                    //Handle for file operation
int rc;                                       //Variable store the result of file operation

#if _BOARD_TYPE_ == 0x1200 || _BOARD_TYPE_ == 0x1201
  brdInit();                                  //Board initialization, required for all applications
#endif

devPowerSet(DISPDEV, 1);                      //Set LCD power mode
dispInit();                                   //LCD/Keyboard initialization, required for all
                                              //applications
keypadDef();                                  //Use default key codes

glXFontInit(&fi6x8, 6, 8, 32, 127, Font6x8);  //LCD font initialization
                                              //The intended font size is 6×8
TextWindowFrame(&textWindow, &fi6x8, 0, 0, 122, 32);
                                              //LCD display window initialization
                                              //The intended window size is 122×32

SignOnPage1();                                //Display the first Sign On page
fs_init(0, 0);                                //Initialize the file system for file operations

CursorPos_Y = 2;
SignOnPage2(CursorPos_Y);                     //Display the second Sign On page
                                              //and low 2 is highlighted, and the current working
                                              //Mode is 2 (default numbering)
flag = 1;                                     //Set flag as 1, entering the loop, and jump out the
                                              //loop when flag is 0

BSKT_DISP[5] = '\0';                          //Add a null terminator explicit for proper display
MB_NUM[5] = '\0';

while(flag)                                   //Entering a loop
{
  keyProcess();                               //Process the keyboard
  keychar = keyGet();                         //Get the code of pressed key
  if(keychar = = 'U')                         //If the "up" button is pressed
  {
    if(CursorPos_Y = = 3 )                    //If row 3 is highlighted
    {
      CursorPos_Y--;                          //move the cursor to row 2
      SignOnPage2(CursorPos_Y);               //and highlight row 2
    }
  }
  if(keychar = = 'D')                         //If the "down" button is pressed
  {
    if(CursorPos_Y = = 2)                     //If row 2 is highlighted
    {
      CursorPos_Y++;                          //move the cursor to row 3
      SignOnPage2(CursorPos_Y);               //and highlight row 3
    }
  }
  if(keychar = = 'E')                         //If the "Enter" button is pressed
```

```
        {
            flag = 0;                                   //Jump out of this loop
        }
    }

    if(CursorPos_Y == 2)                                //If row 2 was selected in the previous page
    {                                                   //meaning a default numbering system
        flag = 1;

        CursorPos_Y1 = 2;                               //Highlight the row 2 in sign on page 3

        SignOnPage3(CursorPos_Y1);                      //Display sign on page 3

        while(flag)
        {
            keyProcess();                               //Process the keyboard
            keychar = keyGet();                         //Get the pressed key code
            if(keychar = = 'U')                         //If the "up" button is pressed
            {
                if(CursorPos_Y1 = = 3)                  //If row 3 is currently highlighted
                {
                    CursorPos_Y1--;                     //move the cursor to row 2
                    SignOnPage3(CursorPos_Y1);          //highlight row 2
                }
            }
            if(keychar = = 'D')                         //If the "down" button is pressed
            {
                if(CursorPos_Y1 = = 2)                  //If row 2 is currently highlighted
                {
                    CursorPos_Y1 ++;                    //move the cursor to row 3
                    SignOnPage3(CursorPos_Y1);          //highlight row 3
                }
            }
            if(keychar = = 'E')                         //If the "enter" button is pressed
            {
                flag = 0;                               //jump out of this loop
            }
        }
    }

    if(CursorPos_Y == 2 && CursorPos_Y1 == 2)           //If default numbering and continuous numbering
    {                                                   //The module number from the last harvesting
                                                        //practice will be recovered from file 1
        fopen_rd(&file, 1);                             //Open file 1 for reading operation
        fread(&file, MB_NUM, 5);                        //read the last module number into MB_NUM
        fclose(&file);                                  //Close the file
        Module_Counter = atoi(MB_NUM);                  //Convert the module number from string to number
    }

    if(CursorPos_Y == 2 && CursorPos_Y1 == 3)           //If default and new numbering
    {
        Module_Counter = 1;                             //Set the current module number as 1, its string form
```

```
                                              //is 00001
}

if(CursorPos_Y == 3)                          //If customized numbering is selected
{
   strncpy(MB_NUM, "00000", 5);               //Set MB_NUM as 00000, users are allowed to input
                                              //intended module number by themselves via
                                               //keyboard
}

serCopen(4800);                               //Open serial port C for wireless communication, the
                                              //baud rate is set as 4800 bps
serCrdFlush();                                //Flush the input buffer for port C

glBlankScreen();                              //Clear the LCD screen

CursorPos_X = 0;
Value = 0;
flag = 1;                                     //flag Boolean is true

LOOP1:

TextGotoXY(&textWindow, 0, 0);

if(CursorPos_Y == 2)                          //If the default numbering
{                                             //Convert the module number into string form for
                                              //display
   MB_NUM[0] = '0';                           //The first two digits denotes the physical module
                                              //identity, and here it is set as "01"
   MB_NUM[1] = '1';
   MB_NUM[2] = floor(Module_Counter / 100) + 48;
                                              //The last three digits is the module number
   MB_NUM[3] = floor((Module_Counter % 100)/10 ) + 48;
   MB_NUM[4] = (Module_Counter % 10)+ 48;
   TextPrintf(&textWindow, "Default Module #:");
}

if(CursorPos_Y == 3)
{
   TextPrintf(&textWindow, "Customized Module #:");
}

TextGotoXY(&textWindow, 0, 1);
TextPrintf(&textWindow, "%s", MB_NUM);        //Display the current module number in LCD

n = 0;

loopinit();                                   //Start of the main loop

while(flag)
{
    loophead();                               //Necessary for multitasking functions and
                                              //statements
```

```
costate
{
   keyProcess();                                //Process the keyboard
   keychar = keyGet();                          //Get the code for pressed key

   if(keychar != 0)                             //If some key is pressed
   {
      if(CursorPos_Y = = 3)                     //If the current mode is "customized"
      {                                         //Users input their intended module number from
                                                //here
         switch(keychar)
         {
         case 'L':                              //If "Left" button is pressed
            CursorPos_X = CursorPos_X -6;       //Move the cursor 6 pixels (one character wide)
                                                //to the left
            if(CursorPos_X < 0)                 //If cursor is already in the leftmost place
            {
               CursorPos_X = 0;                 //Then set cursor as 0
            }
            Input_Refresh(CursorPos_X, MB_NUM);
                                                //Call Input_Refresh subroutine to highlight the
                                                //current cursor position
            break;

         case 'R':                              //If "Right" button is pressed
            CursorPos_X = CursorPos_X +6;       //Move the cursor 6 pixels to the right
            if(CursorPos_X > 24)                //If cursor is already in the right most place
            {
               CursorPos_X = 24;                //The set cursor at the fifth character place
            }
            Input_Refresh(CursorPos_X, MB_NUM);
                                                //Call Input_Refresh subroutine to highlight the
                                                //current cursor position
            break;

         case 'U':                              //If "Up" button is pressed
            Value = MB_NUM[CursorPos_X/6] - 48;
                                                //Convert the highlighted character "0 – 9" (ASCII
                                                // Code) into number
            Value ++;                           //increment the number
            if(Value > 9)                       //If the value is greater than 9
               Value = 0;                       //Set the value as 0
            MB_NUM[CursorPos_X/6] = Value + 48;
                                                //Convert the value back to character (ASCII Code)
            Input_Refresh(CursorPos_X, MB_NUM);
                                                //Call Input_Refresh subroutine to highlight the
                                                //current cursor position
            break;

         case 'D':                              //If "Down" button is pressed
            Value = MB_NUM[CursorPos_X/6] - 48;
                                                //Convert the highlighted character "0 – 9" (ASCII
                                                // Code) into number
```

```
            Value --;                       //Decrement the number
            if(Value < 0)                   //If the value is smaller than 0
               Value = 9;                   //Set the value as 9
            MB_NUM[CursorPos_X/6] = Value + 48;
                                            //Convert the value back to character (ASCII Code)
            Input_Refresh(CursorPos_X, MB_NUM);
                                            //Call Input_Refresh subroutine to highlight the
                                            //current cursor position

            break;
         }

      }

      if(CursorPos_Y = = 2)                 //If the current mode is default numbering
      {
         if(keychar = = '+')                //Press the "+" button to increase the
         {                                  //module number
            Module_Counter ++;
            goto LOOP1;
         }
      }
   }
}


costate
{
   waitfor(DelayMs(2000));                  //Read serial port C for wireless message
                                            //every two seconds
   wfd n = cof_serCread(RCVD_MSG, 40, 20);  //Read the strings into RCVD_MSG until a null
                                            //terminator has been received

   if(n > 0)                                //If the read function returned successfully
   {
      if((strncmp(RCVD_MSG,"BTOM",4)==0)||(strncmp(RCVD_MSG,"HTOM",4) == 0))
                                            //Determine if the wireless message is valid, i.e.,
                                            //from a boll buggy or module builder with a leading
                                            //header of "BTOM" or "HTOM"
      {
         glBlankScreen();                   //Clear the LCD screen
         TextGotoXY(&textWindow, 0, 0);
         TextPrintf(&textWindow, "Module #: %s", MB_NUM);
                                            //Print the current module builder number in LCD
         TextGotoXY(&textWindow, 0, 1);
         TextPrintf(&textWindow, "Basket Dumped:");
                                            //Print the received file numbers from either
                                            //Boll Buggy or Module Builder in LCD
                                            //Note that there might be several file numbers
                                            //contained in one message from the boll buggy, as
                                            //several harvester baskets could be dumped into a
                                             //boll buggy before it is dumped into a module
                                            //builder and this can be calculated from the length
```

```
                                            // of the wireless message
        j = (n - 4) / 5;                    //Calculate how many file numbers are contained

        for(i = 0; i < j; i++ )
        {
          strncpy(BSKT_DISP, RCVD_MSG+ 4 + i*5, 5);
                                            //Copy the file number into string “BSKT_DISP”
          if(i < 3)
          {
            TextGotoXY(&textWindow, 7*i, 2);
            TextPrintf(&textWindow, "%s", BSKT_DISP);
                                            //Display the received file number in LCD
          }
          if(i >= 3)
          {
            TextGotoXY(&textWindow, 7*(i-3), 3);
            TextPrintf(&textWindow, "%s", BSKT_DISP);
          }
        }
                                            //The following code formulating the wireless
                                            //message to be sent
                                            //The message is intended for harvesters
                                            //and should include all file numbers received
                                            //previously
        strncpy(SEND_MSG, "MTOH", 4);       //Attach the message header, “MTOH”
        strncpy(SEND_MSG+4, RCVD_MSG+4, n-4);
                                            //Attach the file number
        strncpy(SEND_MSG+n, MB_NUM, 5);     //Attach the current module number
        strncpy(SEND_MSG+n+5, "\0", 1);     //Attach a null terminator explicitly
        serCputs(SEND_MSG);                 //Write the message into serial port C output buffer
        n = 0;                              //Set n to 0

                                            //The following code stores the current module
                                            //number into file 1, the stored module number will
                                            //Be recovered next time in a continuous harvesting
                                            //practice
        rc = fcreate(&file, 1);             //Create file with filename 1
        rc = fopen_wr(&file, 1);            //Open file 1 for write operation
        rc = fwrite(&file, MB_NUM, 5);      //Write MB_NUM, which contains 5-digit module
                                            //number
        rc = fclose(&file);                 //Close the file

      }
    }

  }

}                                           //end of the main loop

}                                           //end of the main function
```

```
void SignOnPage1()                              //Subroutine to display the first sign on page
{
   TextGotoXY(&textWindow, 0, 0);               //Move cursor to 0, 0
   TextPrintf(&textWindow, "Texas A&M Univ");   //Display "Texas A&M Univ."
   TextGotoXY(&textWindow, 0, 1);               //Move cursor to the next line
   TextPrintf(&textWindow, "Wireless GPS System");
                                                //Display "Wireless GPS System"
   TextGotoXY(&textWindow, 0, 2);               //Move cursor to the next line
   TextPrintf(&textWindow, "Module Builder Block");
                                                //Display "Module Builder Block"
   TextGotoXY(&textWindow, 0, 3);               //Move cursor to the next line
   TextPrintf(&textWindow, "Initialization...");   //Display "Initialization…"
}

                                                //Subroutine to display the second sign on page
                                                //And allow the user to select between the default
                                                //And continuous numbering mode
                                                //The input argument CursorPos_Y indicates
                                                //The line needs to be highlighted
void SignOnPage2(unsigned short CursorPos_Y)
{
   glBlankScreen();                             //clear the LCD screen

   TextGotoXY(&textWindow, 0, 0);               //Move cursor to 0, 0
   TextPrintf(&textWindow, "Which number system" );
                                                //Display "Which number system"
   TextGotoXY(&textWindow, 0, 1);               //Move cursor to the next line
   TextPrintf(&textWindow, "you like to use?"); //Display "you like to use?"
   glBlock(0, 8*CursorPos_Y, 122, 8);           //Black the rectangle area specified
   glSetBrushType(PIXXOR);                      //Set the brush type as "XOR", exclusive OR
   TextGotoXY(&textWindow, 0, 2);               //Move cursor to the next line
   TextPrintf(&textWindow, "     Default      ");  //Display "Default"
   TextGotoXY(&textWindow, 0, 3);               //Move cursor to the next line
   TextPrintf(&textWindow, "    Customized     "); //Display "Customized"
   glSetBrushType(PIXBLACK);                    //Set the brush type back to normal
}

                                                //Subroutine to display the third sign on page
                                                //If the default numbering is selected in the previous
                                                //sign on page, this page allows user to further select
                                                //between continuous and new numbering
                                                //Continuous numbering is for returned user and
                                                //recover the last module number from previous
                                                //harvest
                                                //The input argument CursorPos_Y indicates
                                                //The line needs to be highlighted
void SignOnPage3(unsigned short CursorPos_Y)
{
   glBlankScreen();                             //Clear the LCD screen

   TextGotoXY(&textWindow, 0, 0);               //Move cursor to 0, 0
   TextPrintf(&textWindow, "Continuous Numbering");
                                                //Display "Continuous Numbering"
```

```
   TextGotoXY(&textWindow, 0, 1);                  //Move cursor to the next line
   TextPrintf(&textWindow, "---from last time?--"); //Display "from last time?"
   TextGotoXY(&textWindow, 0, 2);                  //Move cursor to the next line
   glBlock(0, 8*CursorPos_Y, 122, 8);              //Black the specified rectangular area
   glSetBrushType(PIXXOR);                         //Set the brush type as exclusive OR
   TextGotoXY(&textWindow, 0, 2);                  //Move cursor to the next line
   TextPrintf(&textWindow, "---------Yes--------"); //Display "Yes"
   TextGotoXY(&textWindow, 0, 3);                  //Move cursor to the next line
   TextPrintf(&textWindow, "---------No--------");  //Display "No"
   glSetBrushType(PIXBLACK);                       //Set the brush type back to normal
}

                                                   //If the customized numbering is selected
                                                   //this subroutine allows the use to input their
                                                   //intended module number through keypad
                                                   //The input argument PosX indicates the cursor
                                                   //position, which should be highlighted
                                                   //The input argument s indicates the
                                                   //string (module number) to be displayed
void Input_Refresh(unsigned int PosX, char* s)
{
   glBlankScreen();                                //Clear the LCD display

   TextGotoXY(&textWindow, 0, 0);                  //Move cursor to 0, 0
   TextPrintf(&textWindow, "Customized Module #:");
                                                   //Display "Customized Module #"
   glBlock(PosX, 9, 6, 8);                         //Black the intended area
   TextGotoXY(&textWindow, 0, 1);                  //Move cursor to the next line
   glSetBrushType(PIXXOR);                         //Set the brush type to exclusive OR
   TextPrintf(&textWindow, "%s", s);               //Print string s
   glSetBrushType(PIXBLACK);                       //Set the brush type back to normal
}
```

B-3. SOURCE CODE FOR BOLL BUGGY SUBSYSTEM.

```
// BOLL BUGGY SUBSYSTEM.C
// Wireless GPS system for fiber quality module mapping
// Run on boll buggy subsystem
// Copyrighted to Department of Biological and Agricultural Engineering
// Texas A&M University
// Developer: Yufeng Ge, J. Alex Thomasson, Ruixiu Sui


                                        //Start of source code
#class auto                             //Local variable stored on stack
#memmap xmem                            //Reduce root memory usage, required for large
                                        //project

#define CINBUFSIZE 127                  //Set the input buffer size of serial port C 127
#define COUTBUFSIZE 127                 //Set the output buffer size of serial port C 127

fontInfo fi6x8;                         //Handle of font used in LCD
windowFrame textWindow;                 //Handle of display window in LCD

void SignOnPage1();                     //Subroutine to display the first sign on page

void main()                             //Start of the main function
{
int rc;
int i;                                  //i,k are local variables used in program
int k;
int n;                                  //local variable to store the result of serial port
                                        //reading
int flag;                               //Boolean variable for loop control
char keychar;                           //Local variable to store the keypad process result

char PHSCL_BB[2];                       //String to store the physical BB number
char BSKT_NUM[30];                      //String to store the received basket number
char temp[6];
char SEND_MSG[35];                      //String to store wireless MSG to be sent
char RCVD_MSG[10];                      //String to store received wireless MSG

#if _BOARD_TYPE_ == 0x1200 || _BOARD_TYPE_ == 0x1201
  brdInit();                            //Board initialization, required for all applications
#endif

devPowerSet(DISPDEV, 1);                //Set the LCD power mode
dispInit();                             //LCD/keypad initialization
keypadDef();                            //Use the default keypad return code

PHSCL_BB[0] = '0';                      //Assign the physical BB number 01
PHSCL_BB[1] = '1';
temp[5] = '\0';
SignOnPage1();                          //Display Sign On page 1
```

```
for(k = 0; k < 768; k++)                    //Empty loop to elapse time so that the sign on page
{                                           //can be seen
   for(i = 0; i < 256; i++)
   {
   ;
   }
}

flag = 1;                                   //Set the flag to true
i = 0;                                      //set i to 0
serCopen(4800);                             //open the serial port C at a baud rate of 4800 bps
glBlankScreen();                            //Clear the LCD screen

LOOP1:

TextGotoXY(&textWindow, 0, 0);              //Move the cursor to 0, 0
TextPrintf(&textWindow, "PHYSICAL BB ID: %c%c", PHSCL_BB[0], PHSCL_BB[1]);
                                            //Print out the physical Boll Buggy number
TextGotoXY(&textWindow, 0, 1);              //Move cursor to the next line
TextPrintf(&textWindow, "MSG Received From:");  //Print out "MSG Received From:"

loopinit();                                 //Start of main loop

while(flag)
{
   loophead();                              //Statement required for multitasking

   costate
   {
      waitfor(DelayMs(2000));               //Read serial port C for wireless MSG
                                            //every 2000 milliseconds
      wfd n = cof_serCread(RCVD_MSG, 40, 20);   //Read serial port and store the characters into
                                            //RCVD_MSG, until a null terminator is
                                            //encountered
      if( n > 0)                            //If the read function returns successfully
      {
         if(strncmp(RCVD_MSG, "HTOB", 4) = = 0)  //If the message received is from harvester
         {
            strncpy(temp, RCVD_MSG+4, 5);   //parse the message and copy the file number
                                            //into temp
            if(i < 3)
               TextGotoXY(&textWindow, i*7, 2);   //Move the cursor to a desired place

            if(i >= 3)
               TextGotoXY(&textWindow, (i-3)*7, 3);  //Move the cursor to a desired place

            TextPrintf(&textWindow, "%s", temp);  //print out the received file number
            strncpy(BSKT_NUM + i*5, temp, 5);     //Copy the file number into BSKT_NUM
            i++;                            //Increment i
         }
      }
   }
```

```
  costate
  {
    keyProcess();                             //Keypad process
    keychar = keyGet();                       //Get the key code for pressed key
    if((keychar = = 'E') && (i != 0))         //If the "enter" button is pressed and i is not 0
    {                                         //The following code construct and send the wireless
                                              //message
      strncpy(SEND_MSG, "BTOM", 4);           //Copy the message header "BTOM" into
                                              //SEND_MSG
      strncpy(SEND_MSG+4, BSKT_NUM, i*5);     //Copy the file numbers into SEND_MSG
      SEND_MSG[4+i*5] = '\0';                 //Put a null terminator explicitly
      serCputs(SEND_MSG);                     //write the SEND_MSG to the input buffer of serial
                                              //port C
      i = 0;                                  //Clear i
      glBlankScreen();                        //Clear the LCD screen
      goto LOOP1;
    }
  }
}                                             //End of the main loop
}                                             //End of the main function

void SignOnPage1()                            //Subroutine to display the first sign on page
{
  glXFontInit(&fi6x8, 6, 8, 32, 127, Font6x8);        //Set the font size as 6×8
  TextWindowFrame(&textWindow, &fi6x8, 0, 0, 122, 32);
                                              //Set the size of display window as 122 × 32
  TextGotoXY(&textWindow, 0, 0);              //Move the cursor to 0, 0
  TextPrintf(&textWindow, "Texas A&M Univ\n"); //Print "Texas A&M Univ."
  TextGotoXY(&textWindow, 0, 1);              //Move the cursor to the next line
  TextPrintf(&textWindow, "Wireless GPS System\n");
                                              //Print "Wireless GPS System"
  TextGotoXY(&textWindow, 0, 2);              //Move the cursor to the next line
  TextPrintf(&textWindow, "Boll Buggy Block\n"); //Print "Boll Buggy Block"
  TextGotoXY(&textWindow, 0, 3);              //Move the cursor to the next line
  TextPrintf(&textWindow, "Initialization...\n");     //Print "Initialization…"
}
```

VITA

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Ge, Y., C. L. S. Morgan, J. A. Thomasson, and T. Waiser. 2007. A new perspective to NIRS: a wavelet approach. *Trans. ASABE* 50(1): 303-311.

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