DETERMINATION OF DENSITY AND HEIGHT OF SMALL GRAIN WITH ULTRASONIC SENSING

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DETERMINATION OF DENSITY AND HEIGHT OF

SMALL GRAIN WITH ULTRASONIC SENSING

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PREFACE

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Sincere thanks is extended to Oklahoma State University Agricultural Engineering Department and its head Dr. Thompson for financial assistance through a research assistantship.

My wife deserves my deepest appreciation for the constant support, moral encouragement, and understanding.

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CHAPTER I

INTRODUCTION

Every year in the U.S.A. millions of hectares are harvested with combines. Harvest is busy time for combine operators and they are concerned about losses, but they are more concerned in getting their grain harvested on schedule. Operators attempt to control combines to obtain maximum efficiency. It becomes apparent that the efficiency attained by a combine depends on the skill of the individual operator.

In combines, forward speed causes increased throughput, thereby increasing the thresher loss exponentially. On the other hand when forward speed is lower than optimum, field capacity of the machine is low, thereby increasing operating cost of the machine, and also the harvesting time is delayed. The operator must balance maximizing field capacity and minimizing thresher losses. Header losses also occur in form of heads missed by the cutter bar. Often the heads missed at the cutter bar are heads that have turned down and are below the normal cutting level. These heads are not easily seen from operators position. Header losses are significant because they are generally in form of entire heads. To overcome header loss, it is desirable to determine the height of crop so that header height can be controlled automatically to pick up all possible heads without any significant loss. Also to run the combine efficiently it is essential to optimize the throughput by controlling the speed of combine automatically.

Scope of Study of Automatic Forward Speed Control

With the availability of automation and electronics it would be possible to incorporate some device to control the forward speed, and header height of combine automatically. The advantage of automatic control over manual control would be :

1. Reduction of threshing loss.
2. Reduction of header losses.
3. Lower mental load on the operator.
4. Uniform feed would result in less jamming, less breakage of grain etc.
5. Lower fuel consumption per hectare harvested.
6. Optimization of wear on the machine.
7. Higher average throughput resulting in more timely harvest.

It is estimated that overall benefit of automatic forward speed control would reduce the combine harvesting loss by 6-7% (Downs et al 1985). Additional savings could also be in form of reduced summer tillage or chemical use. For example in a 3000 Kg per Hectare crop reducing losses by

2% would save about 60 kg/Ha.

In view of the above, scientists all over the world are conducting research to develop suitable forward speed control systems. All the control systems so far developed measure the feedback signal, throughput, after the crop has been picked up by combine. Yet, speed adjustments need to be made before or at the time crop is cut. To avoid any time delay the throughput signal must be determined before the crop is cut by combine.

Required Parameters of Automatic Speed Control

The relation between forward speed and other parameters of combine are given below:

$$FR = del\ H * D * W * FS \qquad (1)$$

FR = feed rate in Kg/sec.

del H = crop height - header height in meters.

D = density of crop in Kg/cubic meter

W = width of cut in meters.

FS = forward speed in meters/sec.

If crop height, density and desired feed rate are known then the forward speed can be evaluated. Considering the importance of determining crop height, and density this research project will evaluate ultrasonic sensing in determining both parameters.

CHAPTER II

OBJECTIVES

The objective of this research project was to evaluate the performance of an ultrasonic sensor in determining crop density and heights in wheat. The following factors were investigated to determine sensor performance:

1. Performance of sensor when the crop to sensor height is varied vertically.
2. The minimum density requirement of the crop such that sensor performance is satisfactory.
3. The performance of the sensor when the angle of incidence of the sensor is varied relative to the crop.
4. The effect of providing directional cone to improve sensitivity of camera.
5. Estimation of crop density from sensor crop height reading.

CHAPTER III

LITERATURE REVIEW

Many studies of combine speed control systems have been made. The most notable contributions made by scientists to develop a speed control systems are given below.

Forward and Threshing Cylinder Speed Control

Eimer (1981) developed a control system where the forward speed and threshing cylinder speed were controlled depending on the feed rate. Forward speed and cylinder speed control were achieved with the help of an electrohydraulic device. He determined the feed rate by correlating indirect measurement of torque at feeder conveyor and feed auger. The measurement could only be done after the crop had been picked up by the combine. Due to the above measurement, the forward speed control occurred in a lag of phase. However the control of threshing cylinder speed was more effective than estimating forward speed. The time required to transport the crop from the cutter-bar to the threshing cylinder requires 1.5 to 2.5 second depending on the size of combine. Having measured the torque at auger or conveyor there was time available 0.6 to 1.5 second to accelerate the cylinder speed.

The experiment concluded that better threshing was achieved with uniform speed. It was also reported that by varying speed of cylinder the percentage of broken grains increased to 0.1 to 0.25 percent.

Automatic Electronic Hydraulic Control System

Kawamura et al. (1980) devised an automatic electronic-hydraulic control system. By sensing the feed rate and speed of cylinder, they controlled the forward speed of combine. The two input signals were the cylinder speed detected by tacho-generator and the feed layer thickness (determines the feed rate). The controller worked on principle that if feed rate signal is less than lower set value the ground speed is increased, and if feed rate signal is higher than the upper set value, ground speed is decreased. Also if the cylinder speed is higher than upper set value, ground speed is increased, and if speed of cylinder is less than the lower set value the ground speed is decreased. Increase and decrease of signals are calculated by logic AND for increases and OR for decreases. By this calculation an electromagnetic solenoid valve was operated and the hydraulic cylinder connected to the swashplate of the hydrostatic transmission was operated to increase or decrease the ground speed. They tested the controller in the field and conducted digital simulation in the laboratory and found very promising results.

Estimation of Feed Rate Parameters

Huisman et al (1980) developed a feed rate control system. The parameters for the control system studied were:

1. Cutting force on the sickle.
2. Torque driving the supply auger.
3. Threshing cylinder torque.
4. Elevator chain.
5. Displacement of elevator chain.

When cutter bar forces were used as a feed rate parameter there was no time lag. Unfortunately this parameter could not be used because of weeds and different cutting height influenced the force. The power for driving the supply auger was a feed rate parameter, measured at front of the machine. It caused a time lag of 0.4 second. A P-I controller was installed for experimental evaluation. It

was concluded that:

1. Walker loss depends on feed rate.
2. The best feed rate parameter for the combine is the torque for driving the supply auger.

Huisman (1983) did intensive work in evaluating control systems for combines. In his experiments he included all the above parameters to measure the feed rate. He concluded that application of auger torque was preferable because time delay was less and there was no difference in quality between the measurement systems. He simulated control system in the laboratory and concluded the following:

1. Cost saving resulting from automatic control system was small compared to a well planned manual system.
2. The control system could not react correctly to the crop property variation, including straw density. Poor reaction was due to delay in the process and considerable measurement noise.
3. The threshing speed control which reacts to variation of feed rate is profitable; however, the process is complicated and expensive.

Laser Based Crop Density Detection

An experiment was conducted by Taylor et al. (1986) to determine crop density using a laser prior to cutting of crop. The experiment was conducted with a helium neon laser to direct a beam of light through the crop into a sensor. The sensor was mounted inside a tube along with interference filter to minimize effect of natural light. The analog signal from the photo sensor was amplified and limited to produce a digital signal. Hard ware timers were used to accumulate the time during one half second intervals that the laser beam did not penetrate the crop was recorded. Torque was measured at the feeder beater by recording chain tension of the beater feeder drive.

They claimed laser based crop density detector was feasible. However the researchers suggested to install more than one detector to overcome high density variation and also proposed additional study to find accurate relationship between ground speed and laser reading. However the detector was unable to differentiate between crops and weeds.

Engine Load Control System

Garvey (1983) investigated the performances of an engine load control system which maintained constant feed rate to a combine. An adjustable load level was maintained in the engine by controlling the displacement of a pump in the hydrostatic drive. The combine ground speed was directly proportional to the pump displacement which is controlled by a lever. The transmission lever position is proportional to particular load level on the engine for a given set of operating conditions.

This load control system maintained feed rate by varying both the vehicle ground speed and operating power level of the engine. He designed a new electronic engine load control system and analyzed the performance of isochronous and droop control systems. The engine load is the sum of harvester load and hydrostatic transmission pump load. The harvester load is total horse power required to drive cutter bar, threshing cylinder, and other mechanisms which process and move the material through the machine. The power demand is proportional to density or vehicle speed. The components of the load control systems were :

1. Engine load sensor.

2. Electronic controller.

3. Actuator to position the transmission lever.

A magnetic speed pick up served as an effective engine speed sensor. The electronic controller compares the actual engine speed as measured by the magnetic pick up with reference speed settings and generated an error signal. The output signal of the electronic control was applied to an electro-hydraulic actuator. The actuator positioned the hydrostatic transmission lever through a mechanical linkage.

Operation with isochronous load control gave satisfactory performance in flat fields, but was not acceptable in hilly terrain. However with adjustable droop control, (in the droop governor, the output shaft position is proportional to the normalized speed error) the system performed in a acceptable manner. During operation on a combine with a grain loss monitor system, the droop control system produced minimum indication of grain loss. Conclusions drawn from the experiment indicated that due to complexity and high cost, the system appears technically feasible but not cost effective.

Optimum Constant Speed and Loss System

Mcgechan et al (1982) performed a study and their objective was to establish the benefits of operating a combine at optimum constant loss relative to optimum constant speed. The experiment determined total quantity of grain lost rather than total cost of harvest. They estimated that loss from the straw walker was the largest and is most influenced by the quantity of M.O.G (material other than grain).

The result of the study suggested that the potential benefits of a combine control systems which maintains constant threshing loss, compared with constant speed operation are very small. However they concluded that benefits of constant loss control system were so small that development of such automatic control system were not worthwhile.

The conclusion of most of the studies showed that development of automatic control systems was not feasible due to high cost compared to savings. However since most of the study were conducted to control the speed of the machine, only after the crop was picked up by the combine, the results obtained were biased. The acceptable savings as estimated by Downs et al (1985) can be obtained only if control action can be implemented before the crop is picked up by the combine. Considering the above concept this research proposes to determine the parameters required to determine the automatic forward speed before the crop is cut by the combine.

CHAPTER IV

EXPERIMENTAL EQUIPMENT AND METHOD

Experimental Setup

The experimental test apparatus consists of a sensor which was attached to a moving frame as shown in Figure 1. The sensor was fixed in the frame such that it could be set at an angle and also the height of sensor could be varied with respect to ground level. The frame could move along its rail in the X and Y plane. Thus the sensor could be positioned in the X, Y, and Z directions, and sensor angle could be varied. The height and angle of the transducer at different positions are shown in Figure 2. Unthrased wheat was inserted into a foam bed at a spacing of 15.24 cm under the frame. The number of wheat heads selected per square meter depended on the yeild required by the experimental trial. The number of heads were selected based on Table 1 as provided by Downs et al (1985).

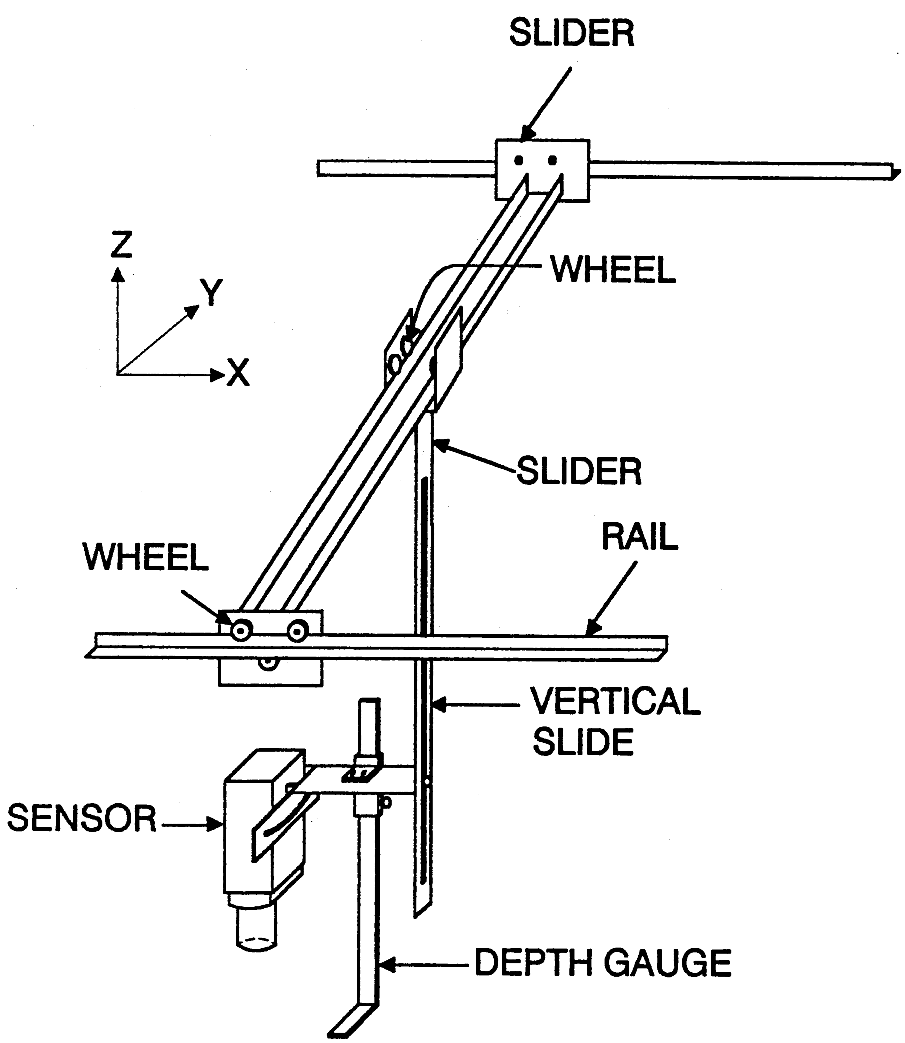


Figure 1. The Moving Frame

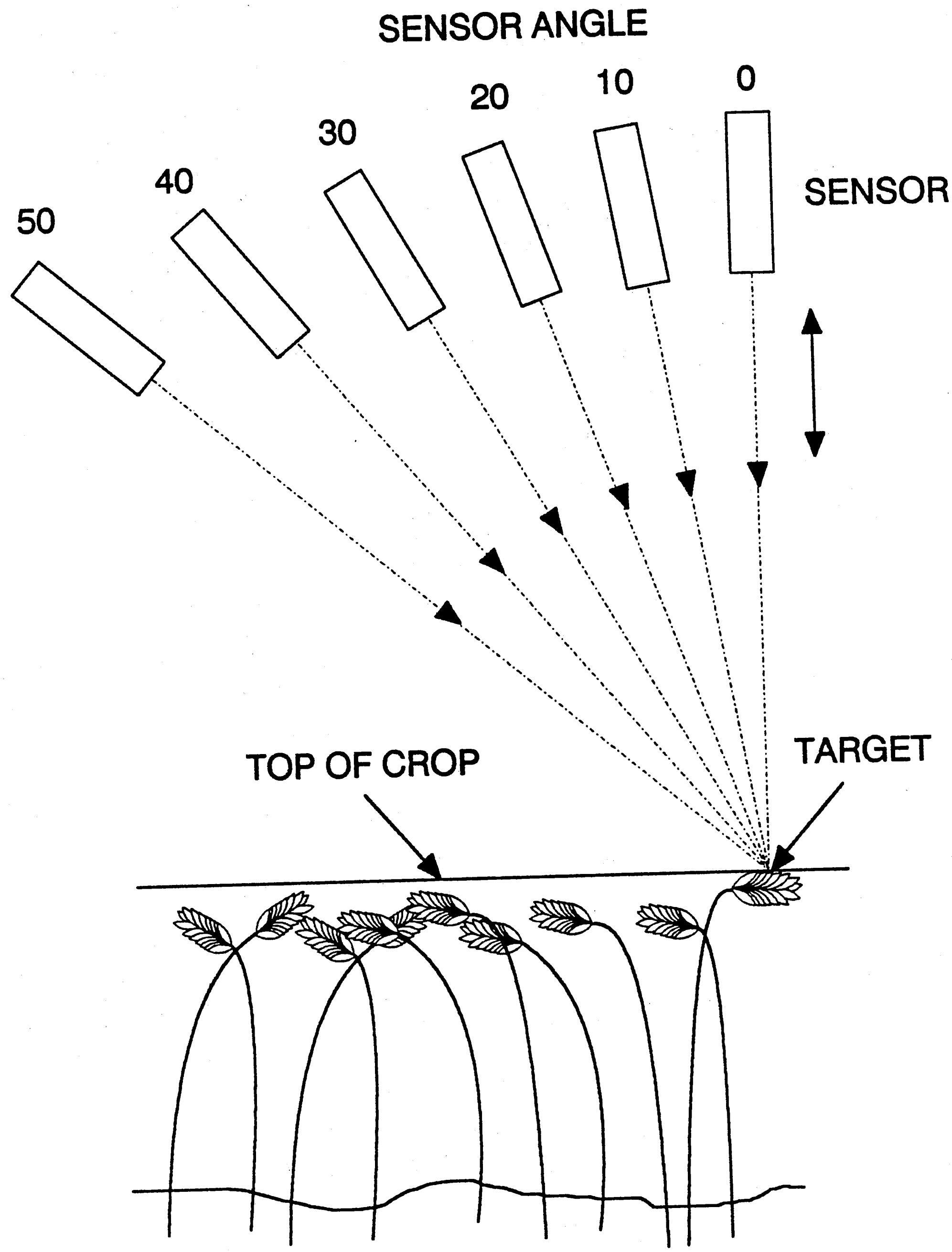


Figure 2. Sensor at Different Position

TABLE 1

RELATION OF NUMBER OF HEADS OF WHEAT PER SQUARE AREA TO YEILD OF WHEAT CROP

Head Size cm	Number of Heads in 1 sq m per 67.2 kg/Ha yield	Grain Yeild kg/Ha	Total Heads Per sq m
2.54	28	4035	1681
2.54	28	2690	1121
2.54	28	1345	560
5.08	17	4035	1021
5.08	17	2690	681
5.08	17	1345	340
7.62	11	4035	660
7.62	11	2690	440
7.62	11	1345	220

Transducer Parts and Its Functions

The experiment was performed with an ultrasonic Sonar Ranging module. The instrument consists of two parts, Texas Instruments ranging Module (model no SN 28827), and Polaroid transducer. A kit containing both was obtained from Micromint (Ciarcia 1984). The specification of the sensor indicates it is capable of measuring distance from 0.405 to 10.5 m with an accuracy of 2 %. The sensor was interfaced to an Rockwell Aim microcomputer. Programs written in Basic and assembly language are used to retrieve and print data. The assembly language program kept track of a counter for time measurement and the Basic language program initialized the module and called the assembly language program, the distance calculated was then printed in the computer. The listing of assembly and Basic language program are shown in Appendix A.

The sonar module is designed to drive a 50 Khz, 300 volts electrostatic transducer. The operating principle is that a pulse transmitted towards a target produces an echo which is detected by the same transducer. The elapsed time between the transmission and echo detection is a function of distance to the target. It takes approximately 1.78 msec per round trip 0.3 m.

$$\text{DISTANCE} = \text{ELAPSED TIME} \quad * \quad \text{SPEED OF SOUND} \qquad (2)$$

The transducer acts as a speaker in the transmit mode and microphone in the receiver mode. It is 381 mm in diameter and consists of 3 mm gold plated foil stretched over a concentrically grooved aluminium disk as shown in Figure 3. The foil is the moving element in the transducer that converts electrical energy into sound and its returning echo into electrical energy. The transducer operates on a single mode, that is, only one target exits and that a single distance value is desired. The distance measuring is accomplished by activating the INIT input line to a logic 1 state. A sonic output pulse is then generated. To prevent ringing, the circuit is provided with an internal blanking signals for 2.38 msec (ie, 0.405 m) fixing the minimum distance measurement. When the ranging module hears an echo, the output line goes high. The difference in time between INIT and ECHO going high can be used to compute distance to the target using the formula as mentioned above. The timing diagram is shown in detail in Figure 4. Since sound intensity is reduced proportional to increases in distance the T.I. module is provided with 12 gain step amplifier within the range of 0 to 10.5 m which adjusts the amplification automatically. The circuitry was housed in a rectangular metallic cover and the transducer was fixed in the directional cone in front of the rectangular cover. In order to increase the sensitivity of the camera a directional cone about 3.8 cm in length was provided as shown in Figure 5. Experimentally it was found that with an additional cone attachment of 3.8 cm in length the focus area of the sensor was approximately 7 to 8 degrees from the central focus point. However when the additional cone attachment of 1.27 cm in length the focus area of the sensor was about 9 to 10 degree. The Table 2 shows the cone angle measurement. Lengthening of cone attachment reduces the focus area of the sensor. When height of the sensor was increased vertically from the ground level the focus area also increased proportionally, and as such the sensor target area also increased.

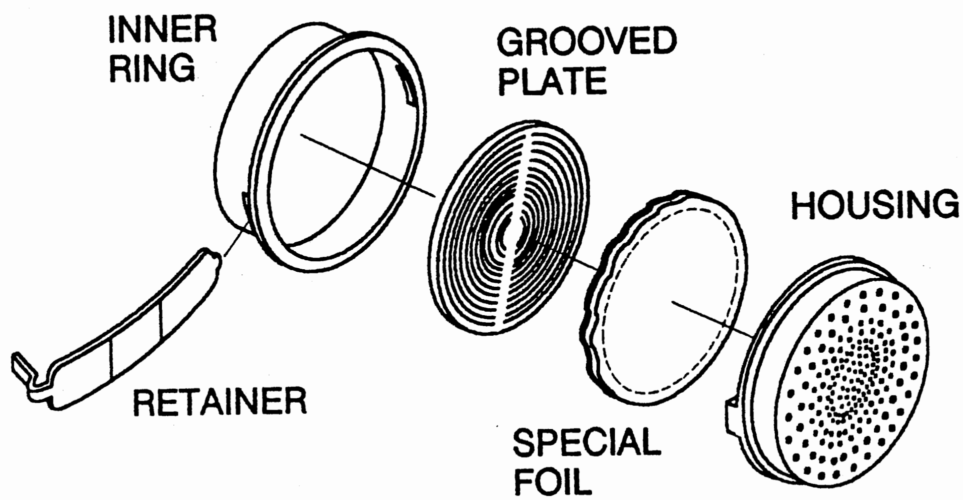


Figure 3. Parts of Transducer

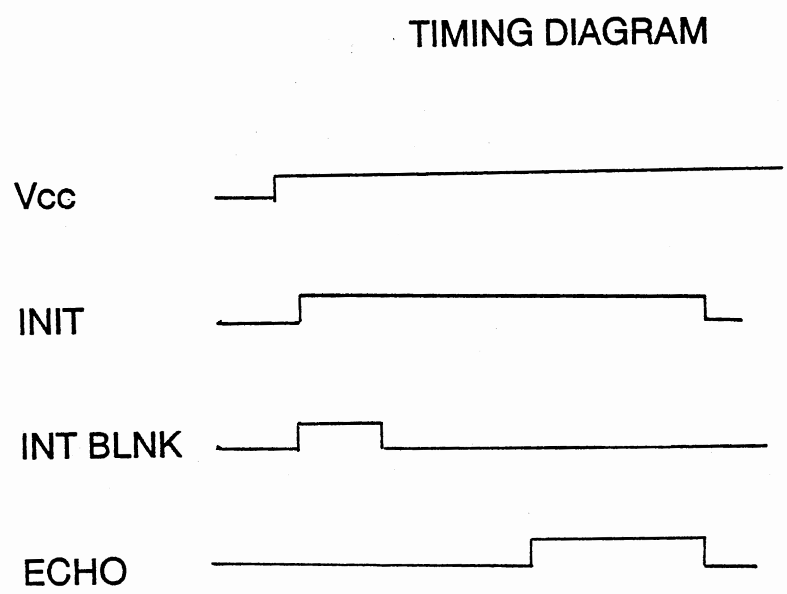


Figure 4. Timing Diagram of Sensor

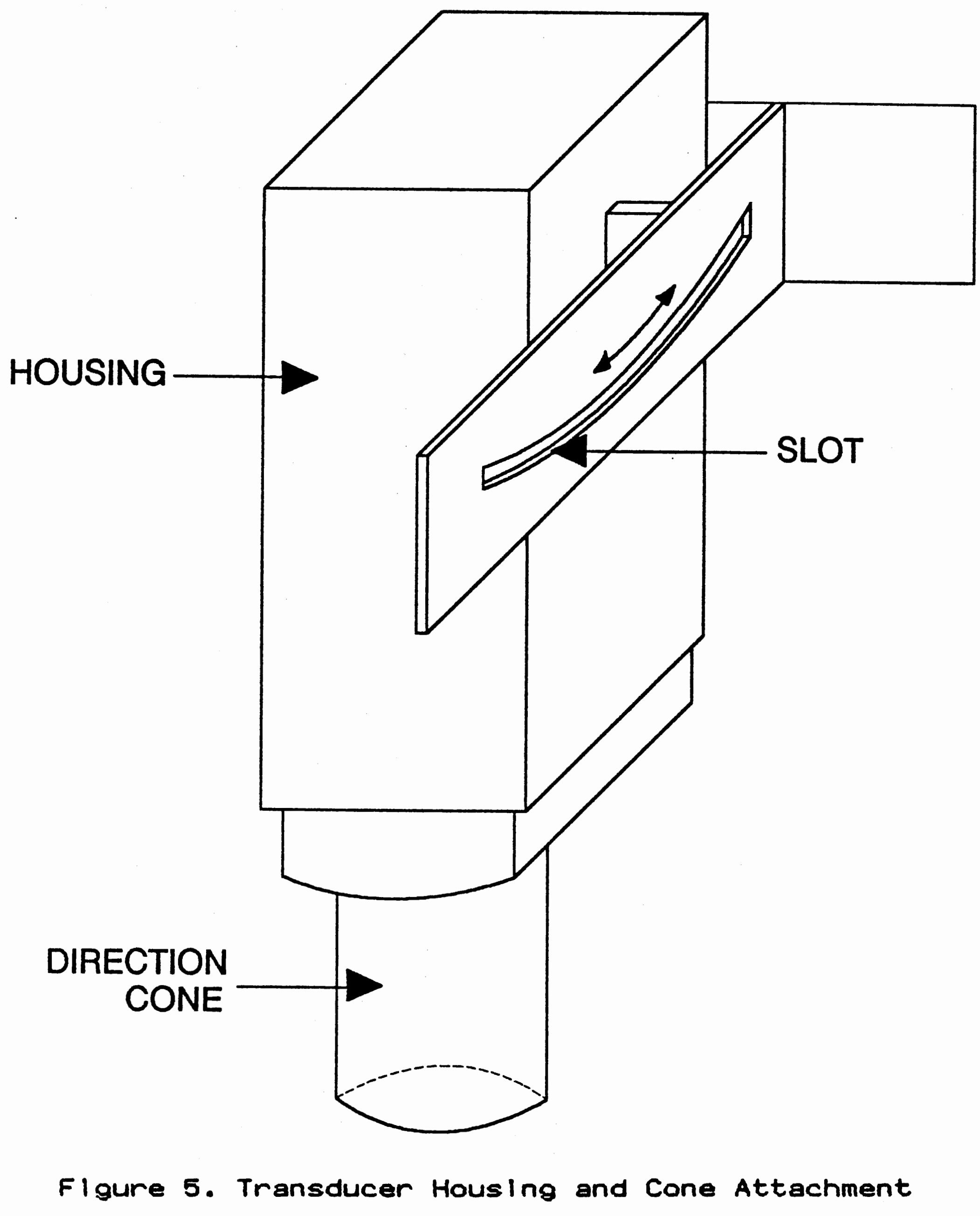


Figure 5. Transducer Housing and Cone Attachment

TABLE 2

RELATION BETWEEN LENGTH OF CONE ATTACHMENT AND FOCUS ANGLE

Length of Cone Attachment cm	Height of Sensor cm	Radius of Focus point cm	Focus Angle degree
1.27	60.96	9.9	9.2
1.27	76.20	12.9	9.6
1.27	91.44	15.8	9.8
1.27	106.68	17.7	9.4
1.27	121.92	19.5	9.1
1.27	137.16	23.4	9.7
3.80	60.96	8.4	7.8
3.80	76.20	10.2	7.6
3.80	91.44	12.7	7.9
3.80	106.68	13.7	7.3
3.80	121.92	15.8	7.4
3.80	137.16	17.3	7.2

CHAPTER V

EXPERIMENTAL PROCEDURE

The experimental design was selected to study the performance of sensor by varying the independent variables. The independent variables considered were, height of transducer (with respect to ground level), sensor angle (with respect to vertical axis) and crop yeild. Standard deviation of error was considered as dependent variable. Error was defined as the difference of height between mechanically measured crop height and sensor reading. The experimental design consisted of three layers. In the first layer the sensor height was varied to study the effect of increase of height. In second layer the height and sensor angle were varied to study the effect of both parameter. In the final layer, the height, sensor angle , and crop yeild were varied to study the effect of all the independent variables.

For this study a total of eight positions of transducer height were studied with reference to ground level as shown below:

1. 124 cm
2. 139 cm
3. 154 cm

4. 169 cm

5. 177 cm

6. 185 cm

7. 193 cm

8. 200 cm

The highest position of sensor was taken as 200 cm which was the maximum height available in the experimental test apparatus. Assuming that sensor performance would be better at higher height due to more focus area, a smaller interval of height (7 cm) was used between position 5 and 8, compared to 15 cm at lower levels. More data could be obtained at higher sensor position for analysis.

The transducer angle levels were selected at 10 degree intervals from 0 to 40 degree. A 40 degree maximum was selected since beyond the above limit sensor focus range went out of the wheat bed. A total of five levels of angle were chosen for the experiment.

Three sets of crop yield was chosen at 4035, 2690 and 1345 kg/Ha. The average wheat yield is about 2690 Kg/Ha in Oklahoma, where as 4035 and 1345 Kg/Ha represent the thick and thinner yield of crop. In this study it was assumed that the wheat head size were nominally 5 cm, and accordingly 1021, 681 and 340 heads/per sq m were selected to represent 4035, 2690 and 1345 Kg/Ha.

The frame was moved along the rail in different fixed points in the X and Y plane and sensor crop height readings were recorded for different positions. Reference crop height readings were recorded by depth gauge at the same positions. Data were collected for fixed heights and sensor angles. A computer program as shown in Appendix B was developed to read the data files of sensor crop height measurement and reference crop height measurements. The program calculates the actual and reference crop height and then calculates the errors between them at each X and Y position. Finally, the mean and standard deviation of the entire set of error was calculated.

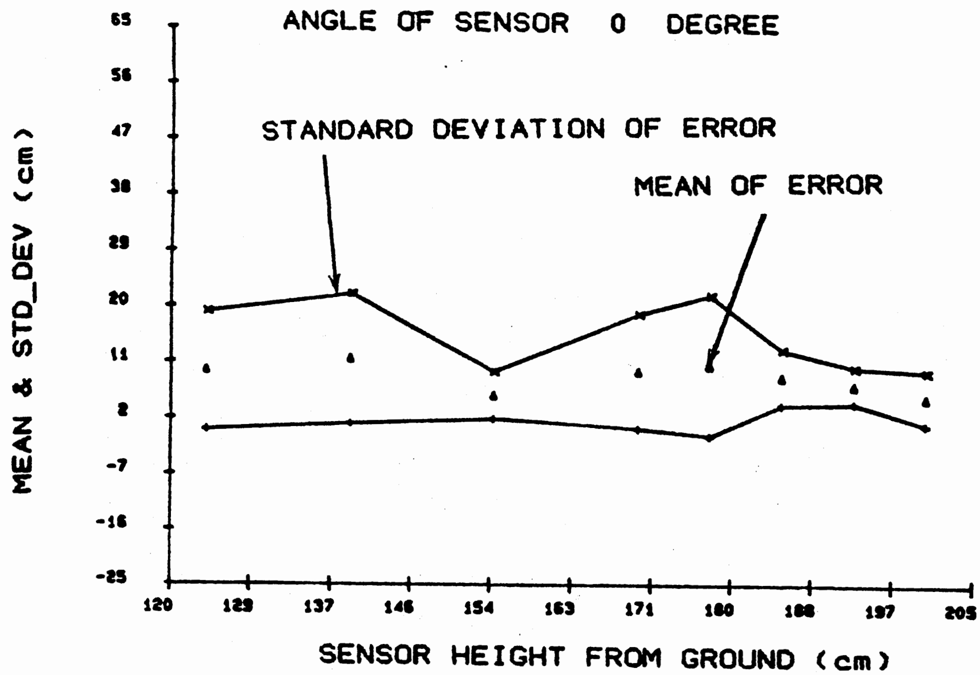
Table 3 describes the Figure and Table numbers, and also the parameter description of the entire experiment.

Figure 6 to 14 represent plot of mean and one standard deviation of error vs sensor height at different sensor angle and crop yield. Table 11 to 25 are given in Appendix D and show the standard deviation of error and sensor reading, and mean of error for a particular sensor angle and a fixed value of crop yeild.

TABLE 3

PARAMETER VARIATION AND CORRESPONDING FIGURE AND TABLE NUMBER OF THE EXPERIMENT FOR A SET OF FIXED POINTS IN X ANY Y PLANE

Crop Yeild Kg/Ha	Sensor Angle Degree	Figure Number	Table Number
4035	0	8	13
4035	10	9	14
4035	20	10	15
4035	30	11	16
4035	40	12	17
2690	0	13	18
2690	10	14	19
2690	20	15	20
2690	30	16	21
2690	40	17	22
1345	0	18	23
1345	10	19	24
1345	20	20	25
1345	30	21	26
1345	40	22	27



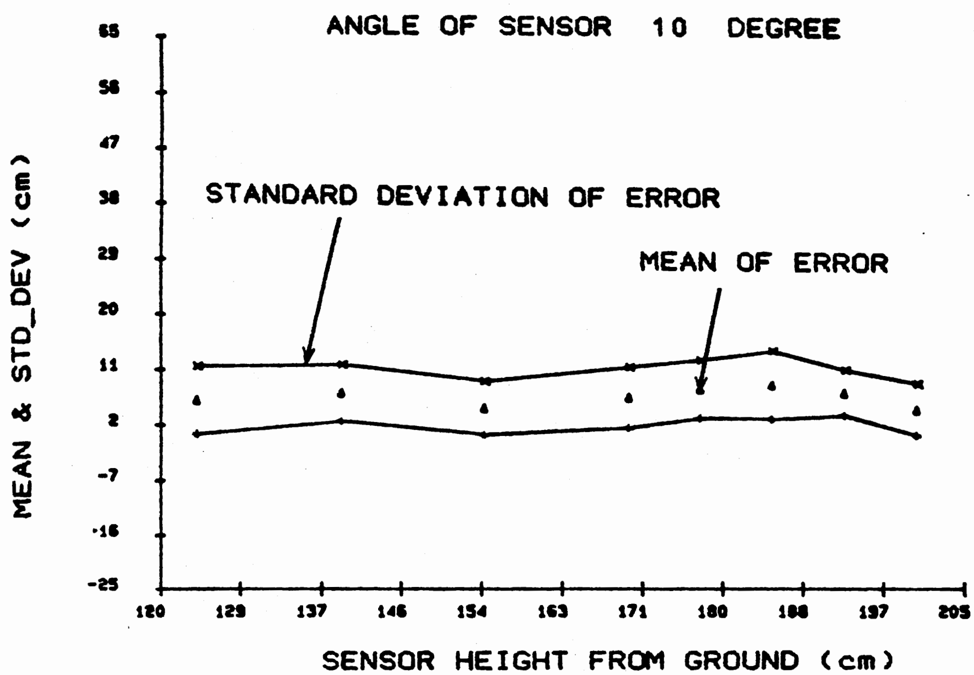
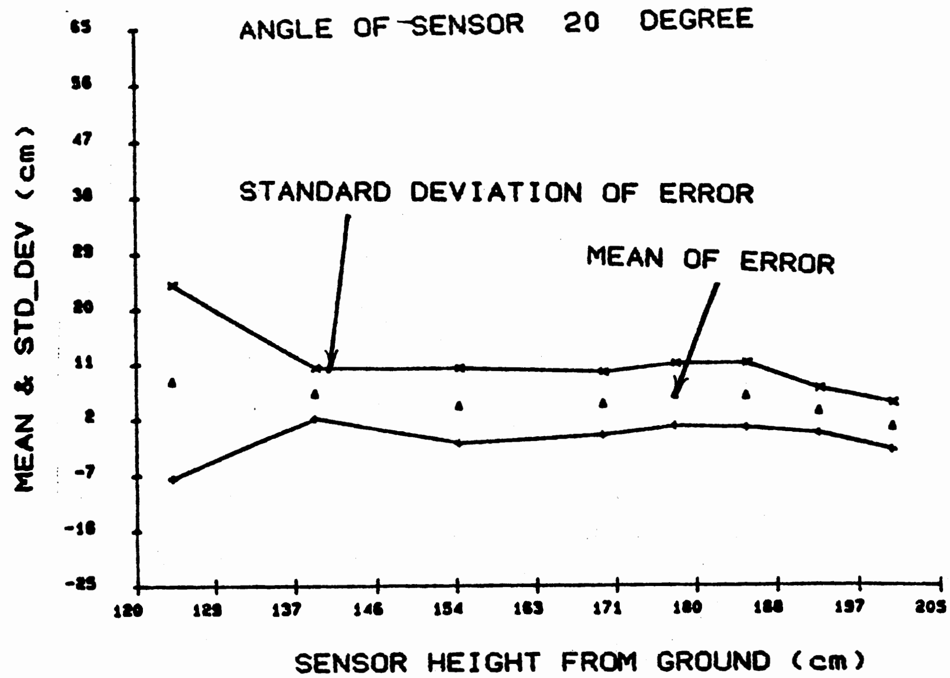


Figure 6. Mean and Standard Deviation of Measured Error, Sensor Angle 0 (Top Diagram) & 10 Degree (Bottom Diagram), Crop Yield 4035 Kg/Ha



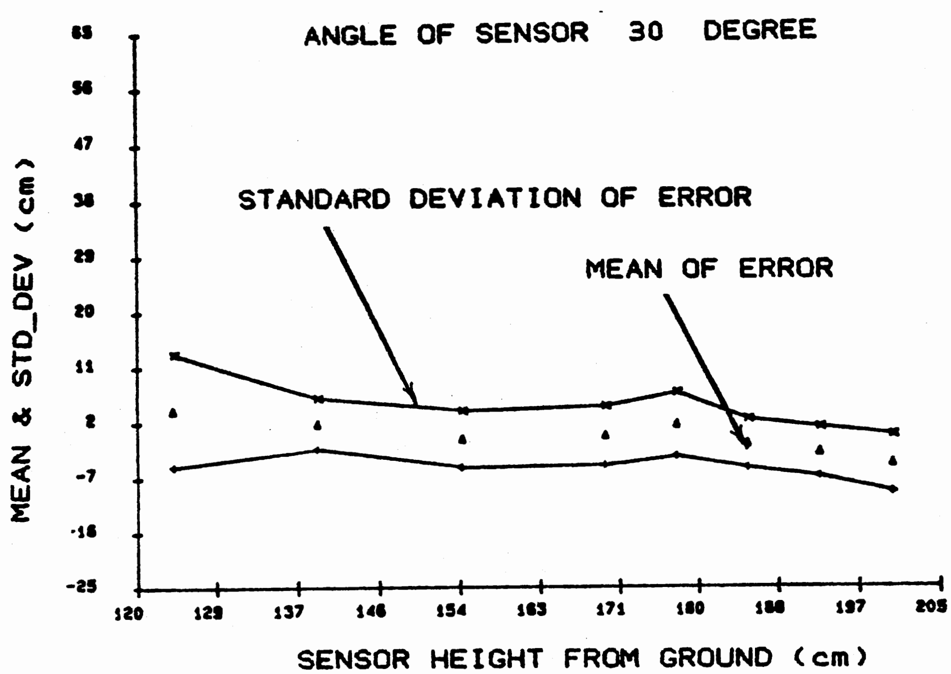


Figure 7. Mean and Standard Deviation of Measured Error, Sensor Angle 20 (Top Diagram) & 30 Degree (Bottom Diagram), Crop Yield 4035 Kg/Ha

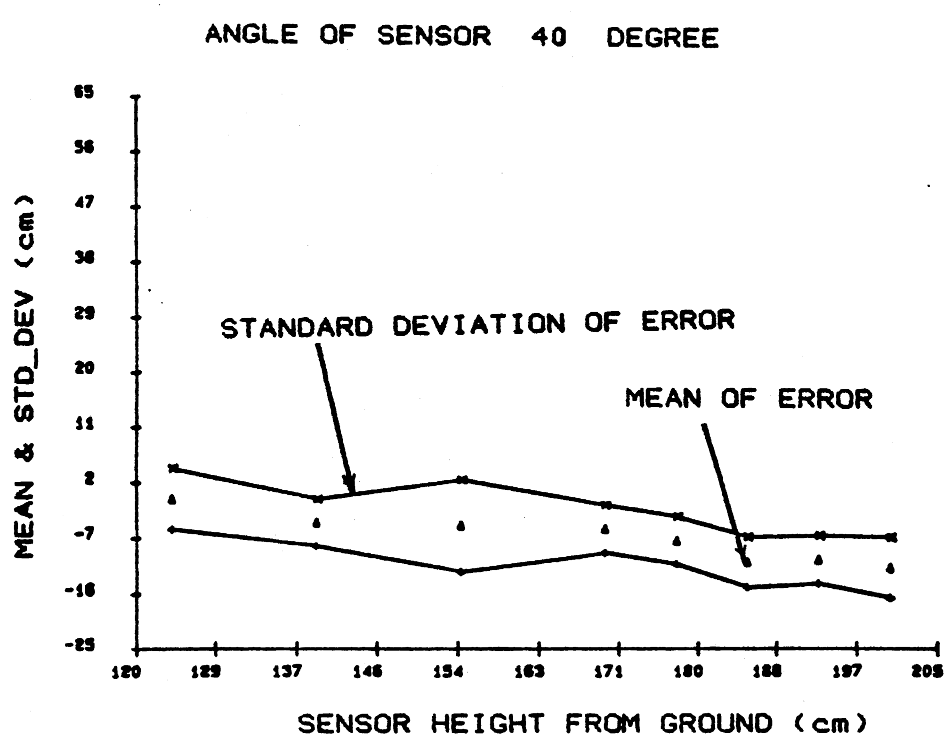
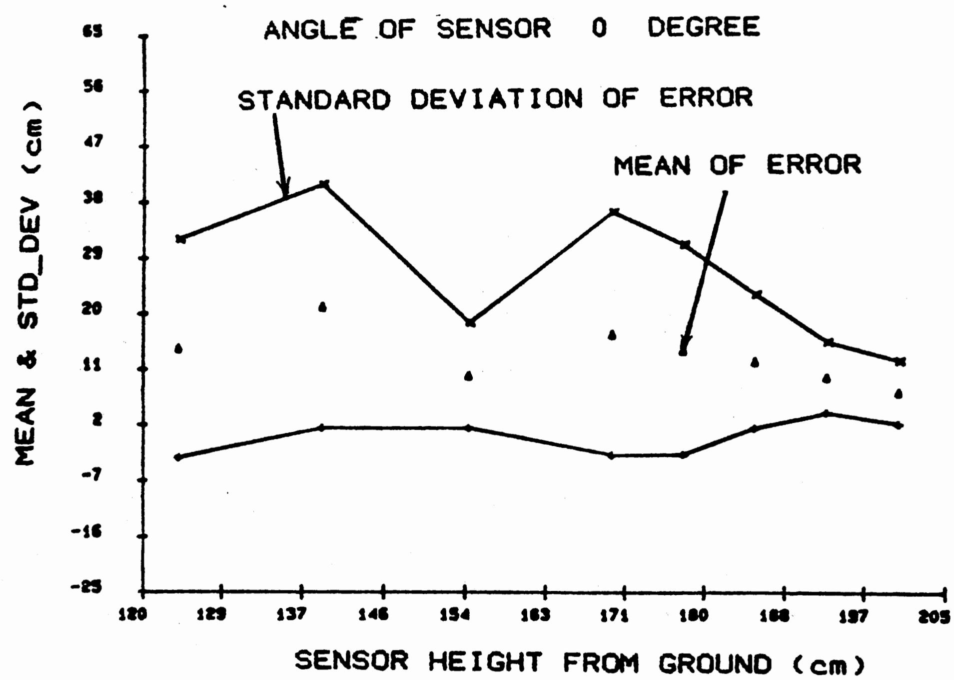


Figure 8. Mean and Standard Deviation of Measured Error, Sensor Angle 40 and Crop Yield 4035 Kg/Ha



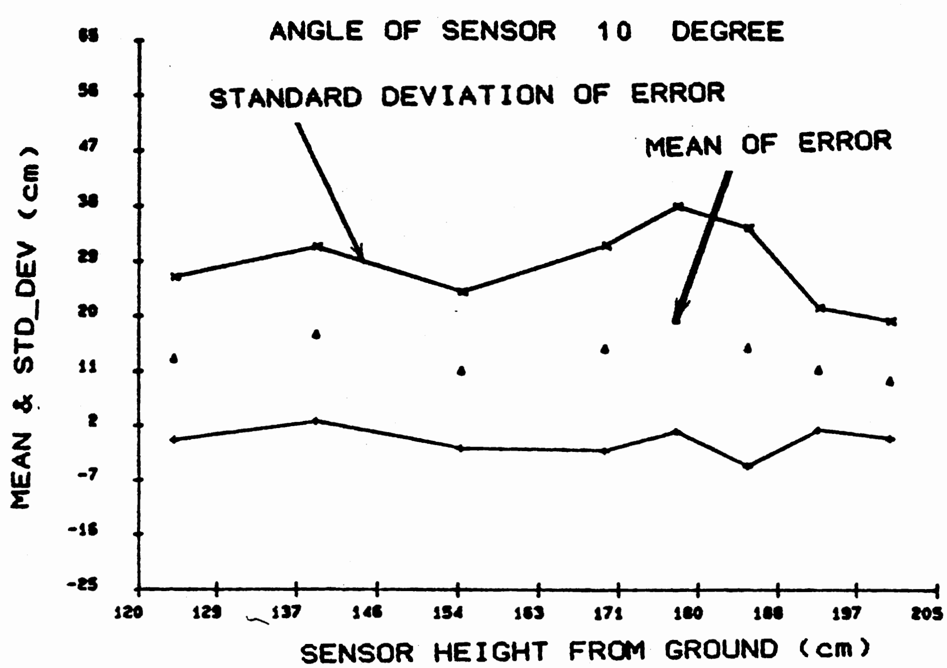
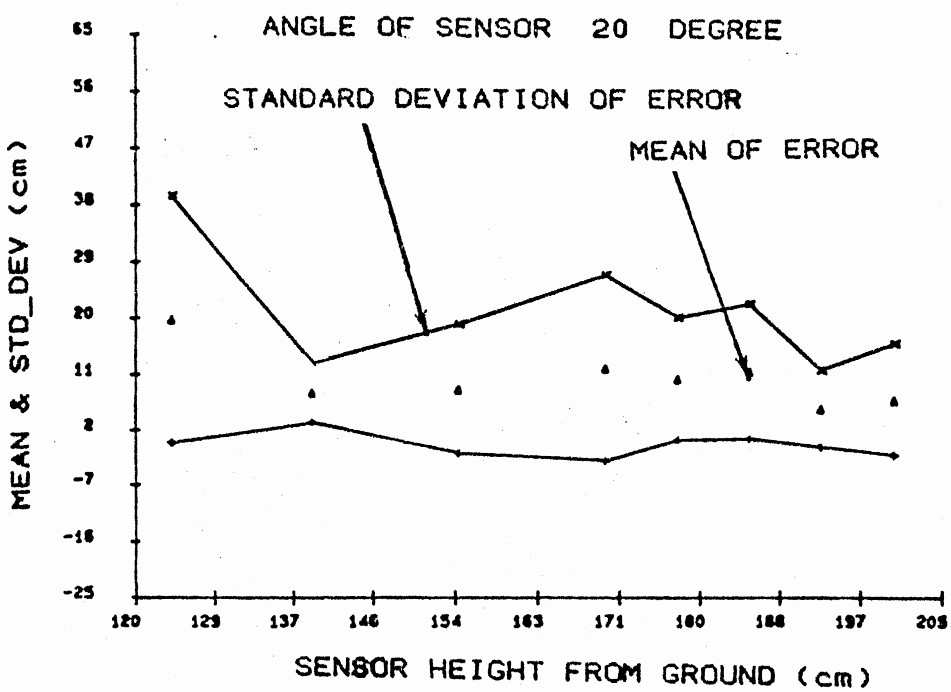


Figure 9. Mean and Standard Deviation of Measured Error, Sensor Angle 0 (Top Diagram) & 10 Degree (Bottom Diagram), Crop Yield 2690 Kg/Ha



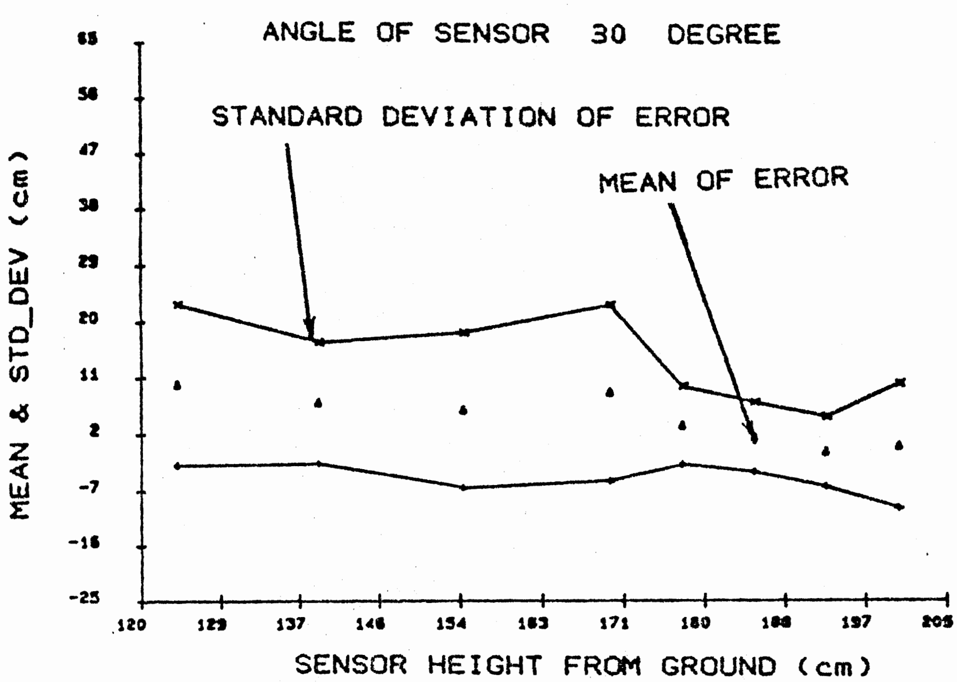


Figure 10. Mean and Standard Deviation of Measured Error, Sensor Angle 20 (Top Diagram) & 30 Degree (Bottom Diagram), Crop Yield 2690 Kg/Ha

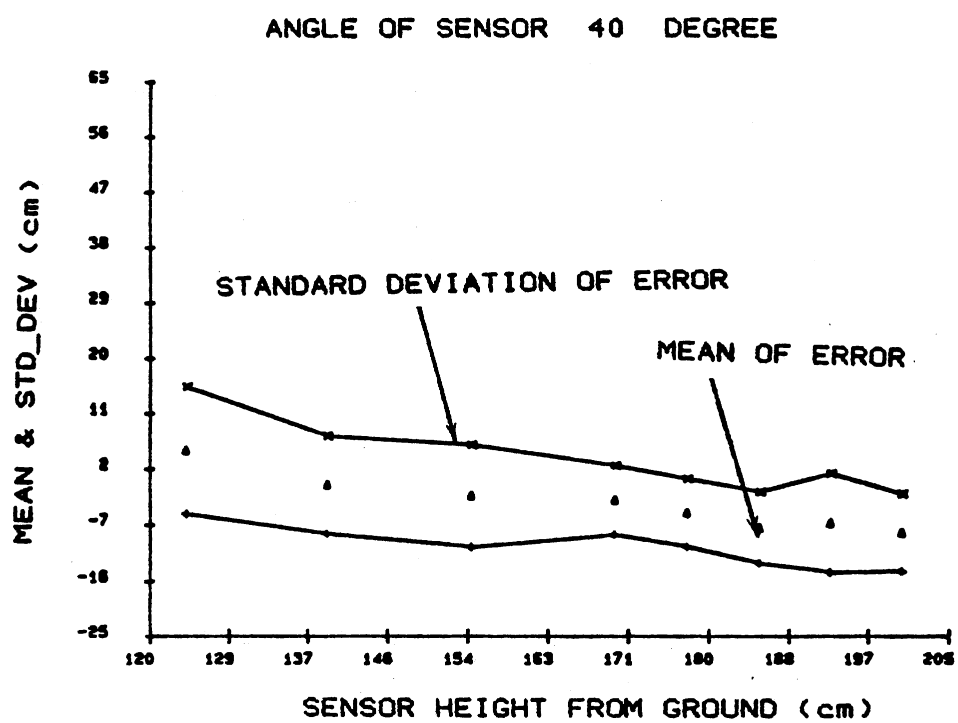


Figure 11. Mean and Standard Deviation of Measured Error, Sensor Angle 40 and Crop Yield 2690 Kg/Ha

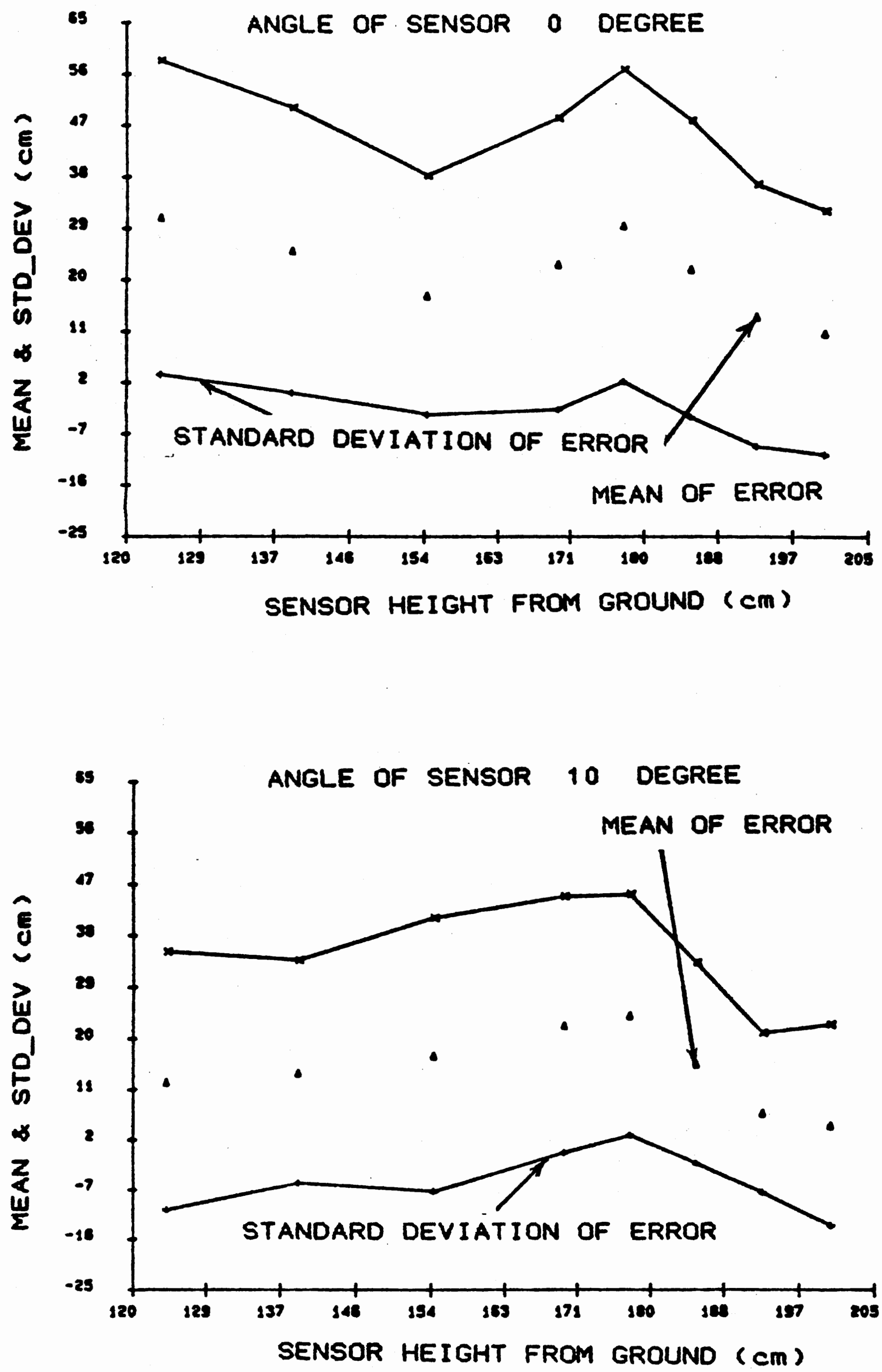
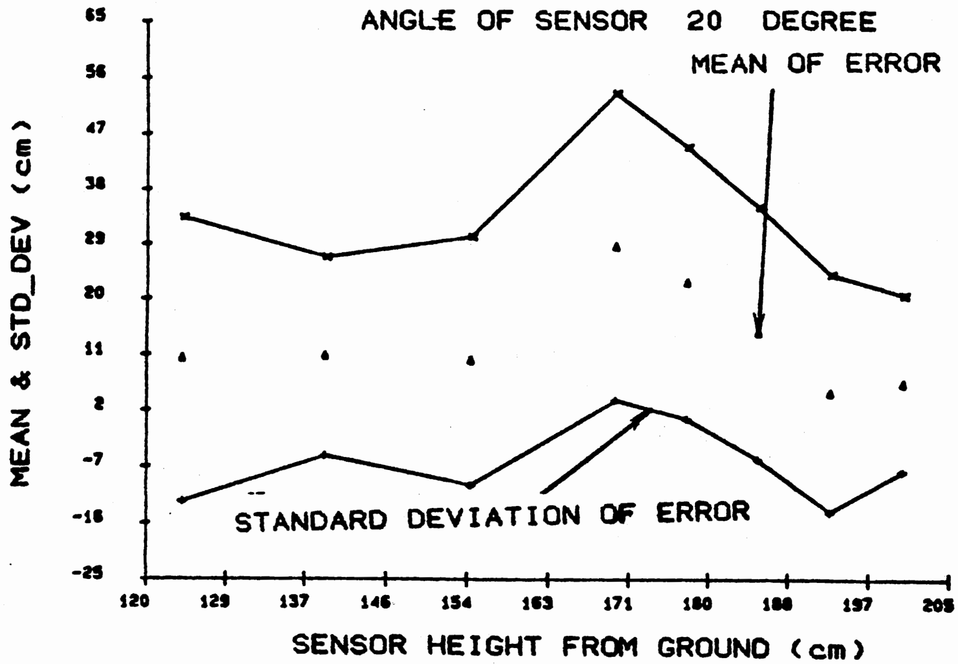


Figure 12. Mean and Standard Deviation of Measured Error, Sensor Angle 0 (Top Diagram) & 10 Degree (Bottom Diagram), Crop Yield 1345 Kg/Ha



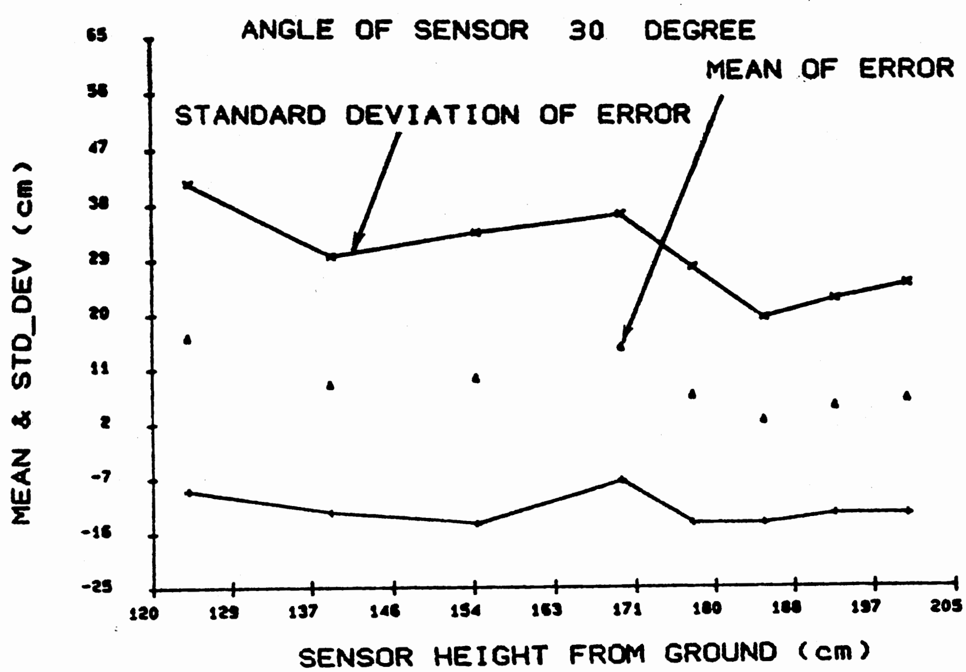


Figure 13. Mean and Standard Deviation of Measured Error, Sensor Angle 20 (Top Diagram) & 30 Degree (Bottom Diagram), Crop Yield 1345 Kg/Ha

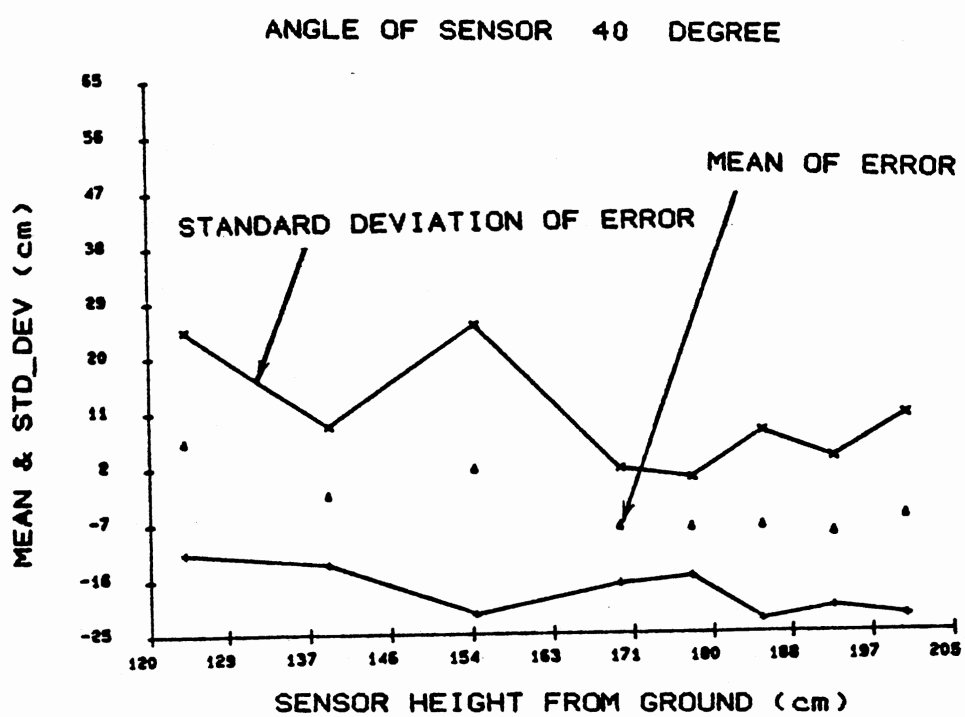


Figure 14. Mean and Standard Deviation of Measured Error, Sensor Angle 40 and Crop Yield 1345 Kg/Ha

CHAPTER VI

RESULTS AND DISCUSSION

From Table 11 to 25 it was observed that there was an error associated between sensor and reference crop height reading. The error occurred due to two factors:

1. During experiment it was observed that the signal intercepted the bend portion of the wheat head and the echo was detected by the transducer. No echo was measured from top of the wheat head or from the beards. Apparently the signal is only effective when some minimum width of the target object is available. The error occurred due to the difference in height between the top and the bend portion of the wheat head.
2. In the second case the error was due to signal penetrating through the crop. The degree of penetration depends on crop density and focus area of the sensor. The focus area of the sensor depends on the height and angle of the sensor.

Crop Yield 4035 Kg/Hectare

Based on Figure 6 to 8 and Table 11 to 15 a comparison of mean and standard of error at different height and angle of the transducer can be made. The results are summarized in Table 4.

TABLE 4

COMPARISON BETWEEN MEAN AND STANDARD DEVIATION OF ERROR AT DIFFERENT HEIGHT AND ANGLE OF THE SENSOR, YIELD 4035 KG/HECTARE

Sensor Angle	Mean of Error due to change of Sensor Height		Standard Deviation of Error due to change of Sensor Height	
	from 124 cm	to 200 cm	from 124 cm	to 200 cm
0	9.5966	5.4623	9.5239	4.3057
10	6.0361	4.4828	5.4975	5.2257
20	8.2770	0.7542	15.7778	3.8248
30	4.0362	-4.7500	9.1408	4.6417
40	-0.6564	-11.6257	4.9655	4.8966

From Table 4 it was observed that standard deviation and mean of error were reduced when sensor height was increased. When the height of the sensor was increased, the sensed area of the sensor also increased proportionally causing reduced deviation. It is likely that the signal would pick up more wheat heads due to more focus area and the probability of signal penetrating through the wheat crop become less. When the sensor angle was increased from 0 to 40 degree the mean and standard deviation of error also decreased. At higher sensor angle the direction of signal towards the target changed (ie, from vertical to flatter direction). This resulted in lower chances that the signal penetrated through the crop. The non zero value of the mean of error indicates that the height calculated was not correct. At higher sensor angles the target was assumed at the central focus point, but actually there was possibility that the echo was from the extreme near end of the focus area and the height calculated was less than the theoretical height which resulted in negative mean of error. In addition, it was also likely that due to more focus area the signal picked up higher heads before it could reach the target area.

Crop Yeild 2690 Kg/Hectare

Based on Figure 9 to 11 and Table 16 to 20 a comparison of mean and standard of error at different height and angle of the transducer can be made. The results are summarized in Table 5.

From Table 5 it was observed that the mean and standard deviation of error was reduced with increased height and angle of incidence of sensor. However since the crop yeild had been reduced from 4035 to 2690 Kg/Ha the mean and standard of error was much higher compared to result of

Table 4 for same sensor height and angle. At reduced crop yeild the probability of sensor signal penetrating the crop is much higher at same position and sensor angle.

TABLE 5

COMPARISON BETWEEN MEAN AND STANDARD DEVIATION OF ERROR AT DIFFERENT HEIGHT AND ANGLE OF THE SENSOR, CROP YIELD 2690 KG/HECTARE

Sensor Angle	Mean of Error due to change of Sensor Height		Standard Deviation of Error due to change of Sensor Height	
	from 124 cm	to 200 cm	from 124 cm	to 200 cm
0	14.4013	7.6019	17.6996	5.1938
10	13.0672	9.6452	13.4303	9.7144
20	19.6578	6.9149	19.8170	9.1143
30	9.9854	0.02436	12.8172	9.9585
40	5.0635	-8.1145	10.3282	6.1629

Crop Yield 1345 Kg/Hectare

From Figure 12 to 14 and Table 21 to 25 a comparison of mean and standard deviation of error at different height and angle of the transducer can be made. The results are summarized in Table 6. It was observed that the mean and standard deviation of error also reduced with increase of height of sensor. Since the crop yield was reduced further from 2690 to 1345 Kg/Ha the mean and standard deviation of error are higher compared to result in Table 5 for same sensor position and sensor angle.

TABLE 6

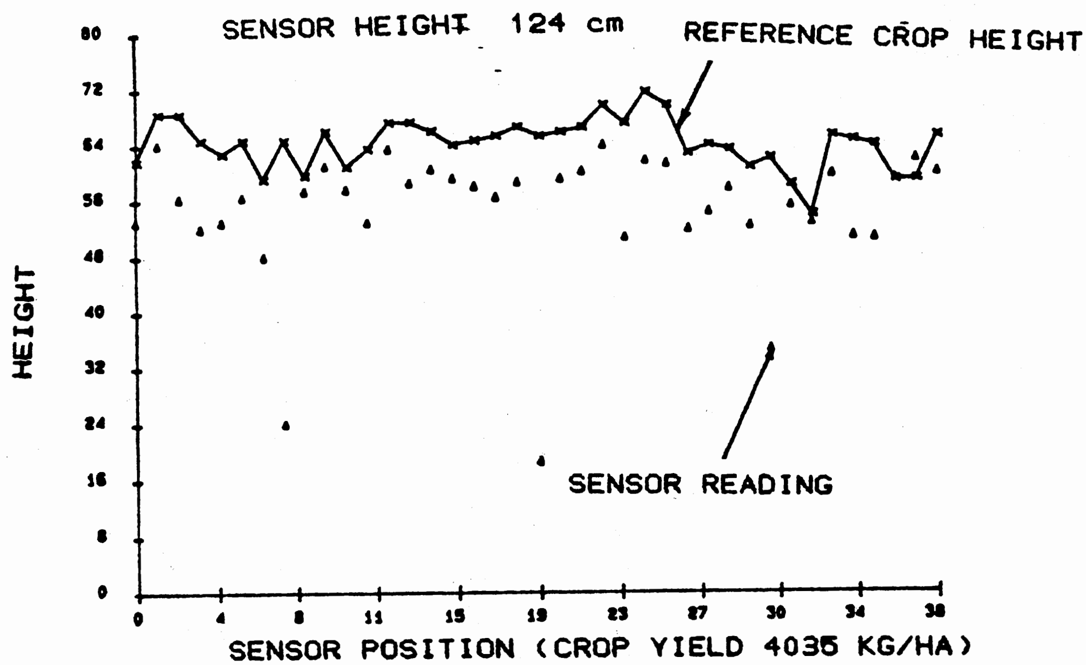
COMPARISON BETWEEN MEAN AND STANDARD DEVIATION OF ERROR AT DIFFERENT HEIGHT AND ANGLE OF THE SENSOR, CROP YIELD 1345 KG/HECTARE

Sensor Angle	Mean of Error due to change of Sensor Height		Standard Deviation of Error due to change of Sensor Height	
	from 124 cm	to 200 cm	from 124 cm	to 200 cm
0	30.9548	10.8700	27.5146	21.5495
10	12.3639	4.6664	22.9009	18.0911
20	10.4325	6.7014	22.9752	14.2393
30	16.2629	5.4735	25.2616	18.8945
40	6.3023	-6.0483	18.0344	16.2771

The above figures and tables gives a good indication of the performance of sensor while measuring crop height.

Analysis of Crop Height

To determine crop height some signal processing is required. Figure 15 to 17 shows plot of reference crop height and sensor measured crop height. It was apparent from the Figures if higher points were selected from sensor readings (ie, higher points represent top of crop level), and if sensor reference height is known (ie, height of sensor from the ground level) then crop height can be predicted irrespective of crop yield.



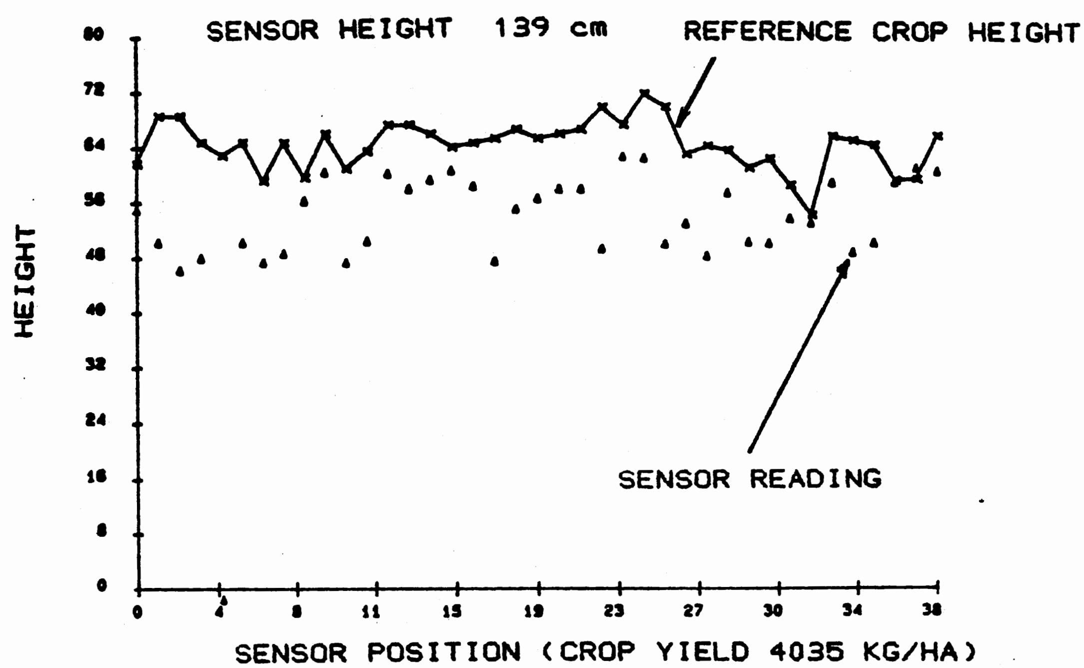
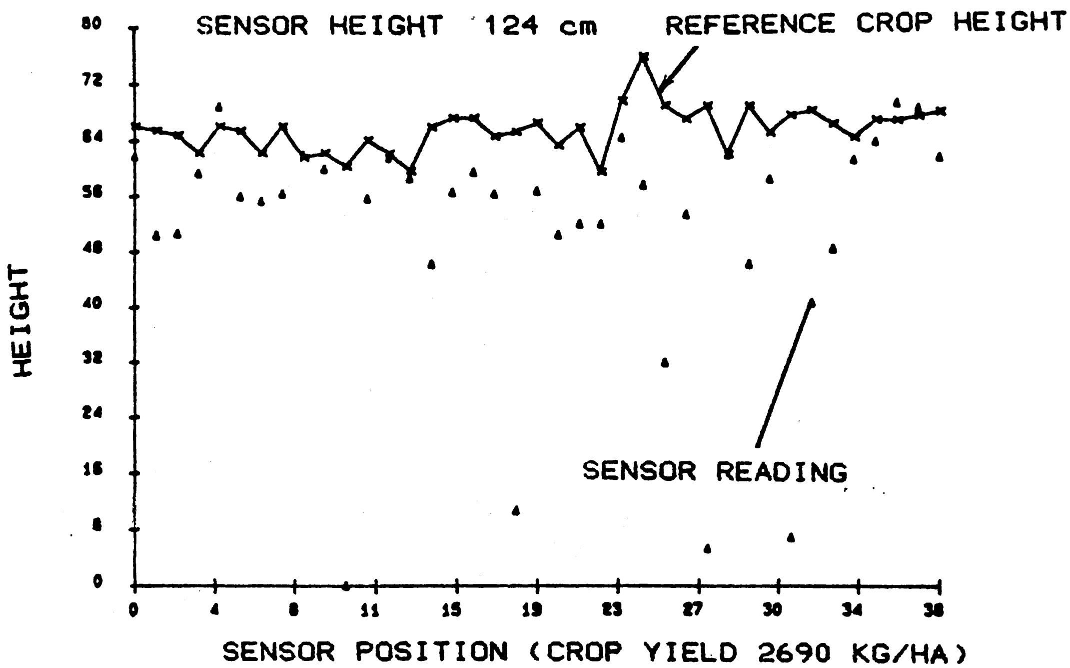


Figure 15. Plot Between Reference Crop height and Reading, Sensor Height 123.8 (Top Diagram) & 139 cm (Bottom Diagram) sensor Angle 0 Degree, and Crop Yield 4035 kg/Ha



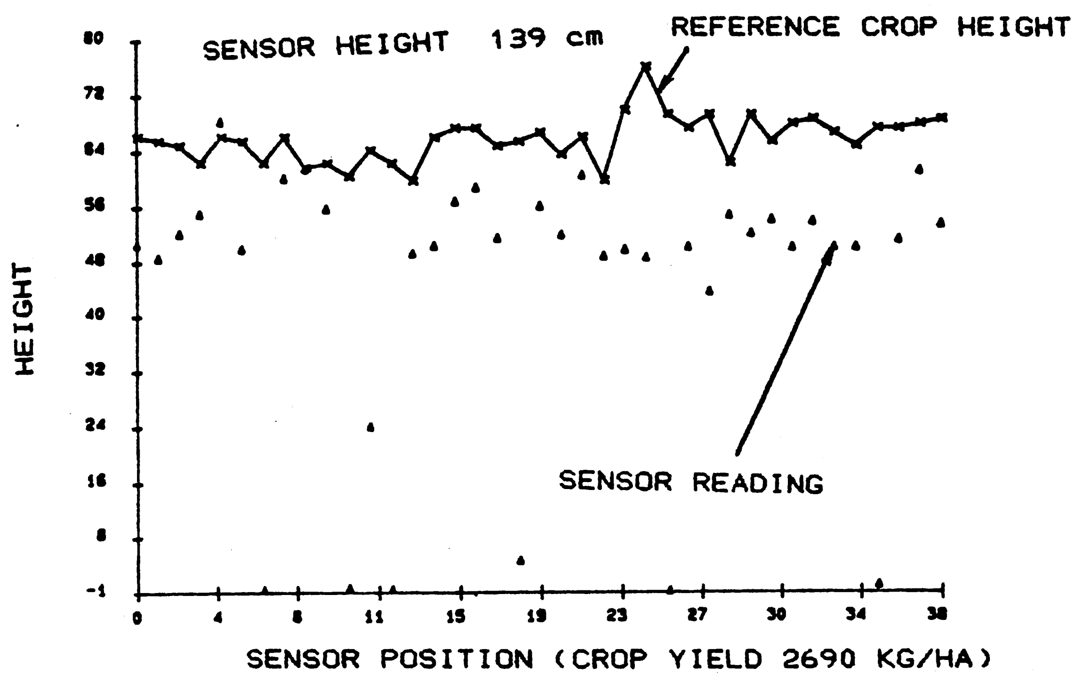
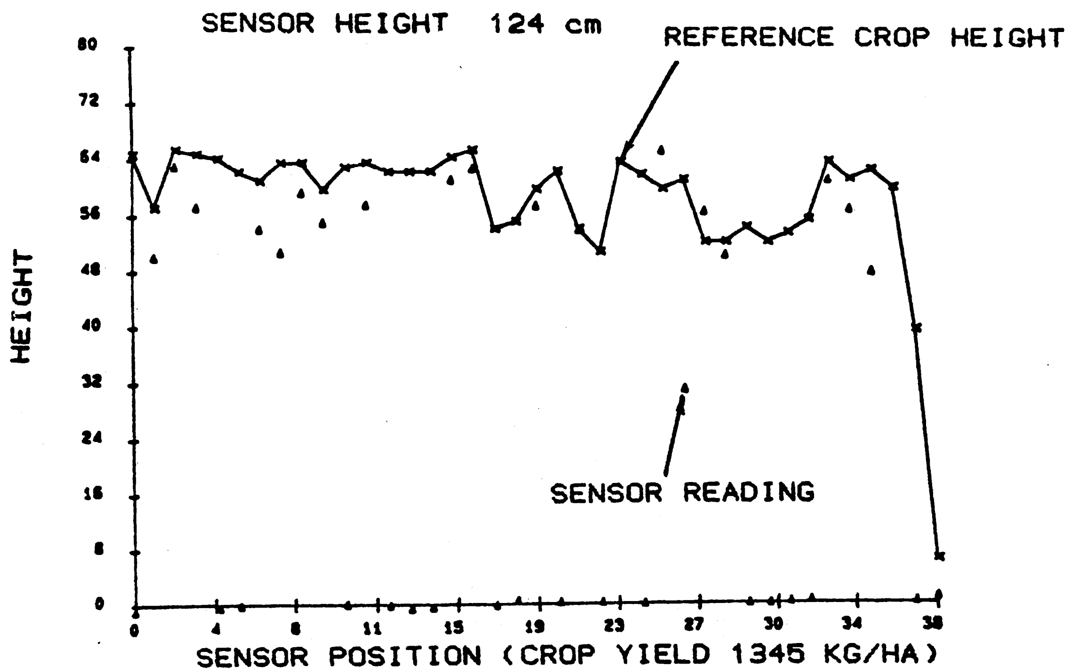


Figure 16. Plot Between Reference Crop height and Reading, Sensor Height 123.8 (Top Diagram) & 139 cm (Bottom Diagram) sensor Angle 0 Degree, and Crop Yield 2690 kg/Ha



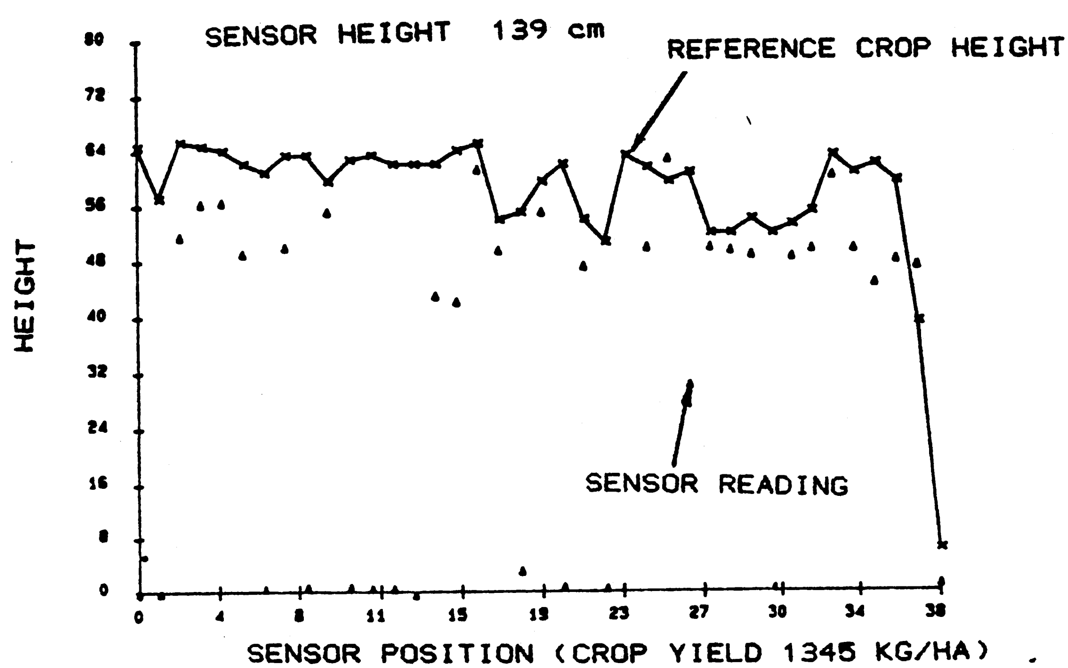


Figure 17. Plot Between Reference Crop height and Reading, Sensor Height 123.8 (Top Diagram) & 139 cm (Bottom Diagram) sensor Angle 0 Degree, and Crop Yield 1345 Kg/Ha

Analysis of Density of Crop

The standard deviation of error increased when crop yield was reduced. In order to estimate the density from the sensor reading, a plot was made relating standard deviation of error at crop yield 4035, 2690 and 1345 Kg/Ha to height of the sensor for different values of sensor angle (0,10,20,30 40 degree). Figure 18 to 20 shows the above plot as discussed. A plot was also made relating standard deviation of the sensor reading and the yield of crop. Figure 21 to 23 shows the above plots. It was found that the value of standard deviation of error is very similar to standard deviation of sensor reading only. Thus it could be concluded that standard deviation was mainly associated with sensor reading only, and did not include a significant contribution from the reference crop height reading.

From above Figures it was found that up to sensor height of 139.0 cm and also when sensor angles were within 10 degree the relation between variation of standard deviation and crop yield was approximately linear. To find the relationship between standard deviation of error/sensor reading, crop yield, and sensor height and angle, mathematical model was developed with help of a statistics package.

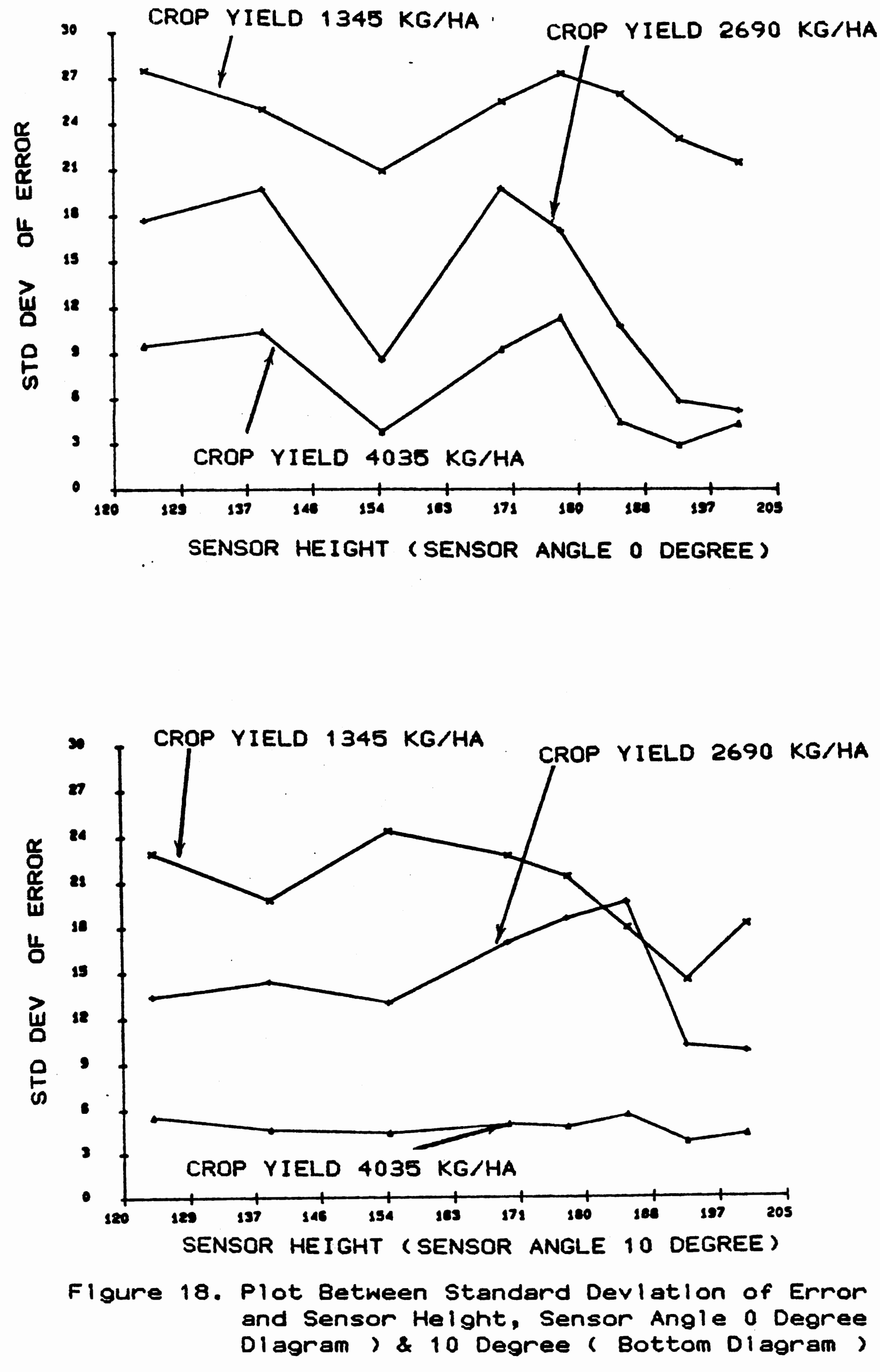
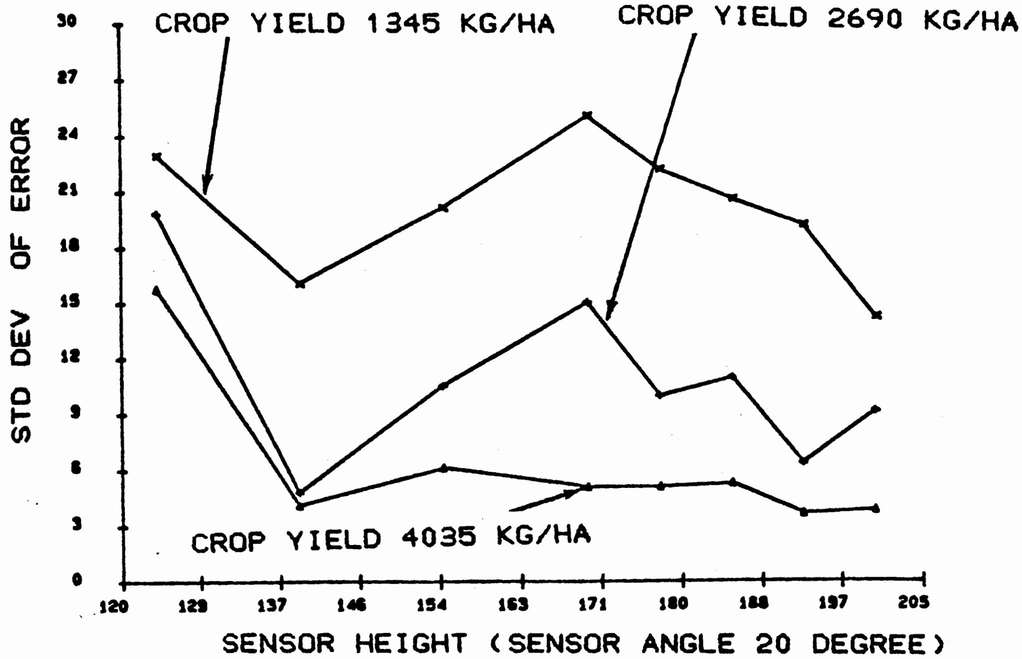


Figure 18. Plot Between Standard Deviation of Error and Sensor Height, Sensor Angle 0 Degree (Top Diagram) & 10 Degree (Bottom Diagram)



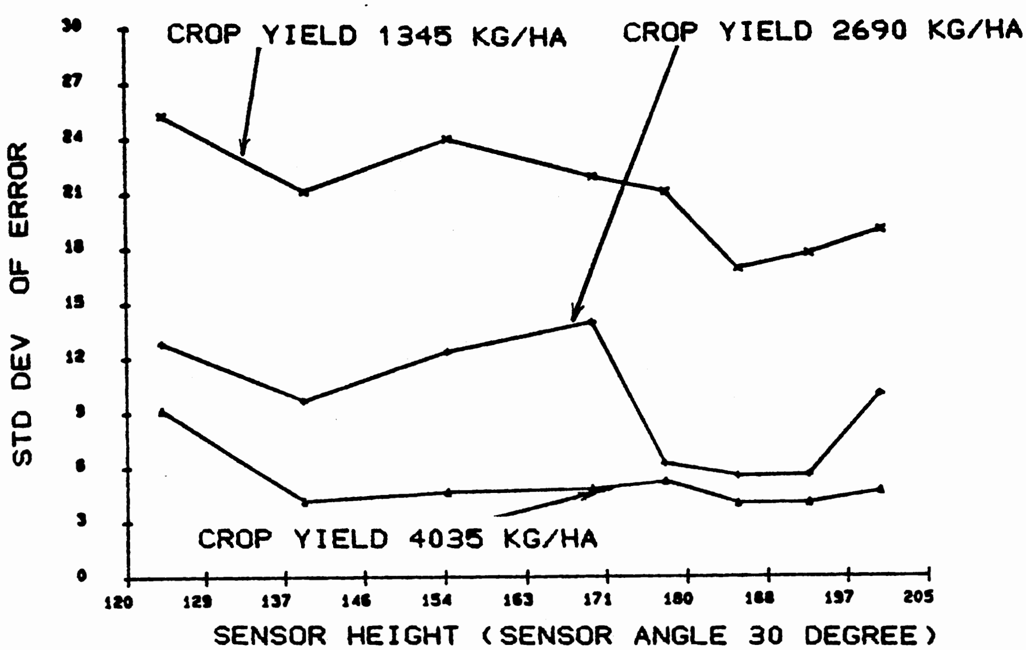


Figure 19. Plot Between Standard Deviation of Error and Sensor Height, Sensor Angle 20 Degree (Top Diagram) & 30 Degree (Bottom Diagram)

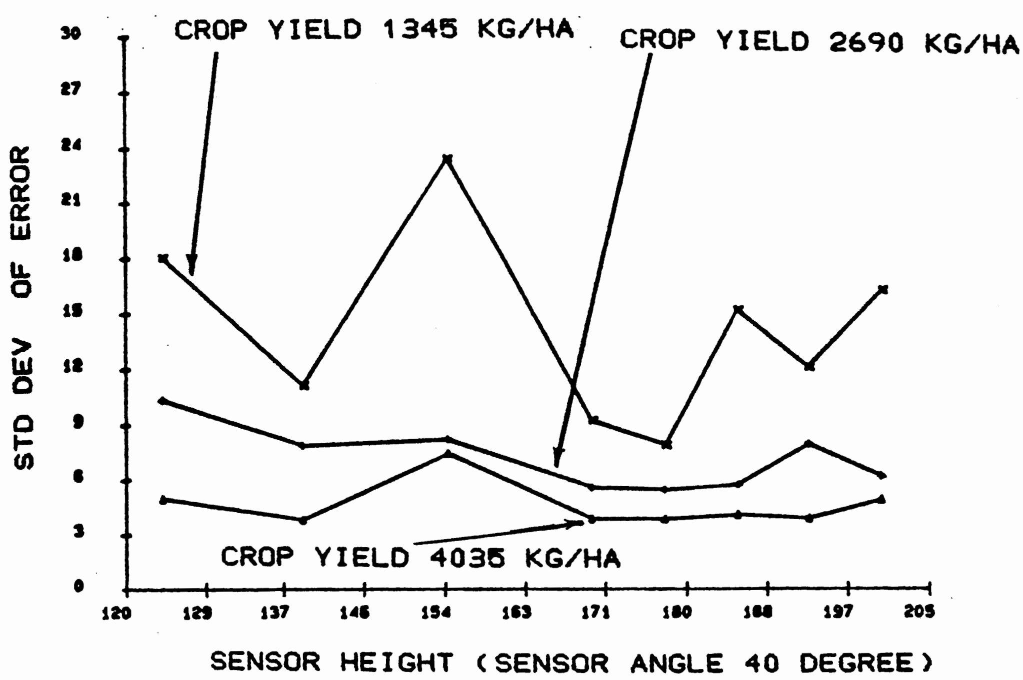
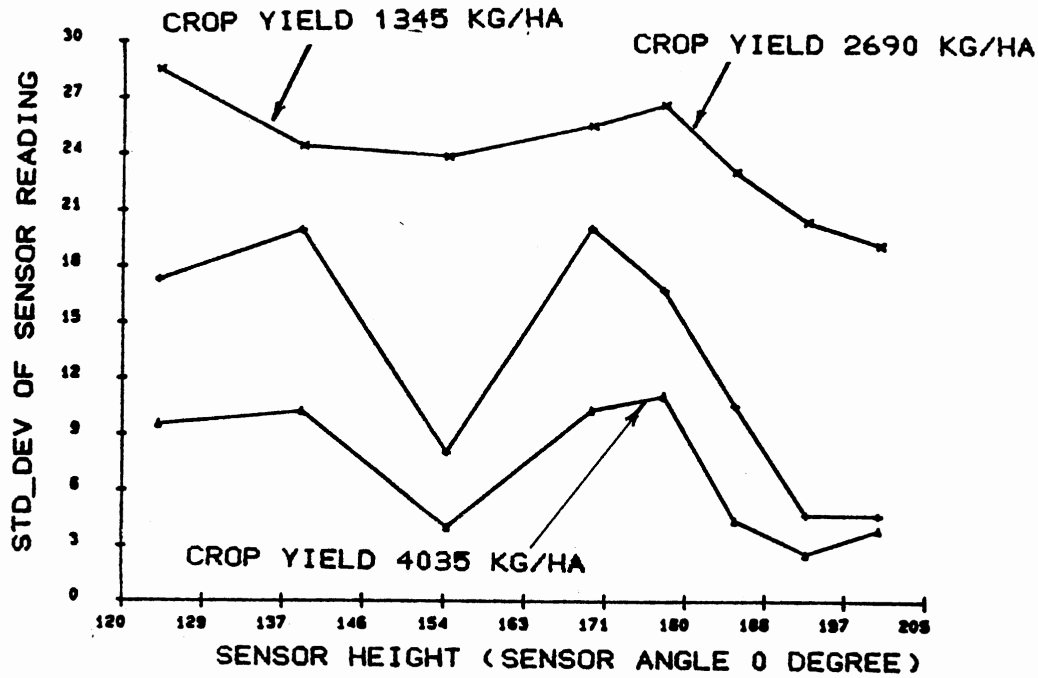


Figure 20. Plot Between Standard Deviation of Error and Sensor Height, Sensor Angle 40 Degree



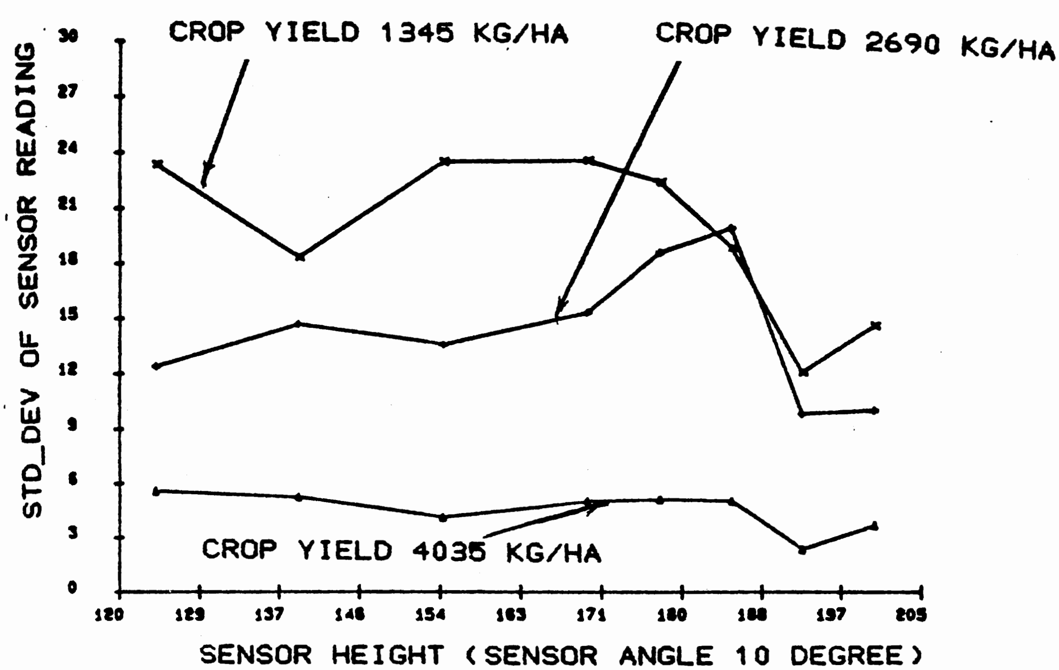
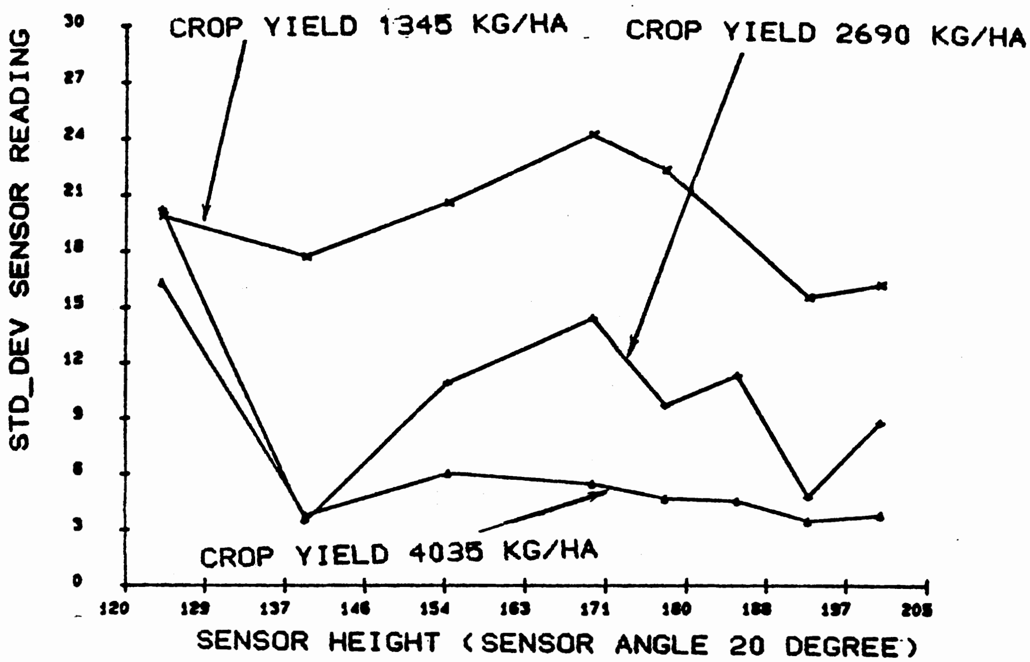


Figure 21. Plot Between Standard Deviation of Sensor Measurement and Sensor Height, Sensor Angle 0 Degree (Top Diagram) & 10 Degree (Bottom Diagram)



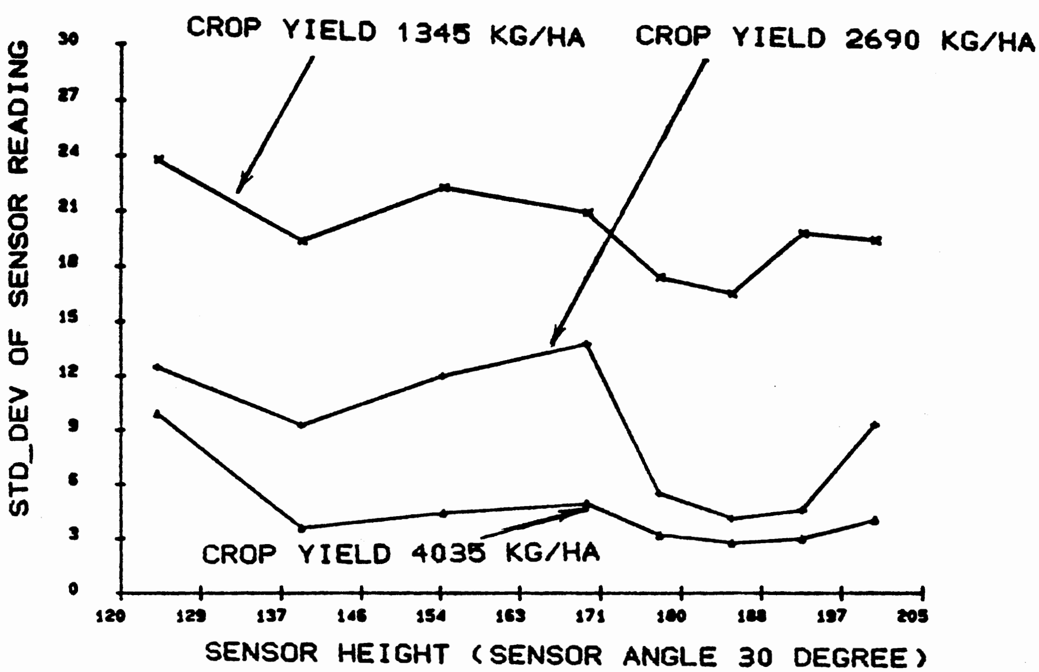


Figure 22. Plot Between Standard Deviation of Sensor Measurement and Sensor Height, Sensor Angle 20 Degree (Top Diagram) & 30 Degree (Bottom Diagram)

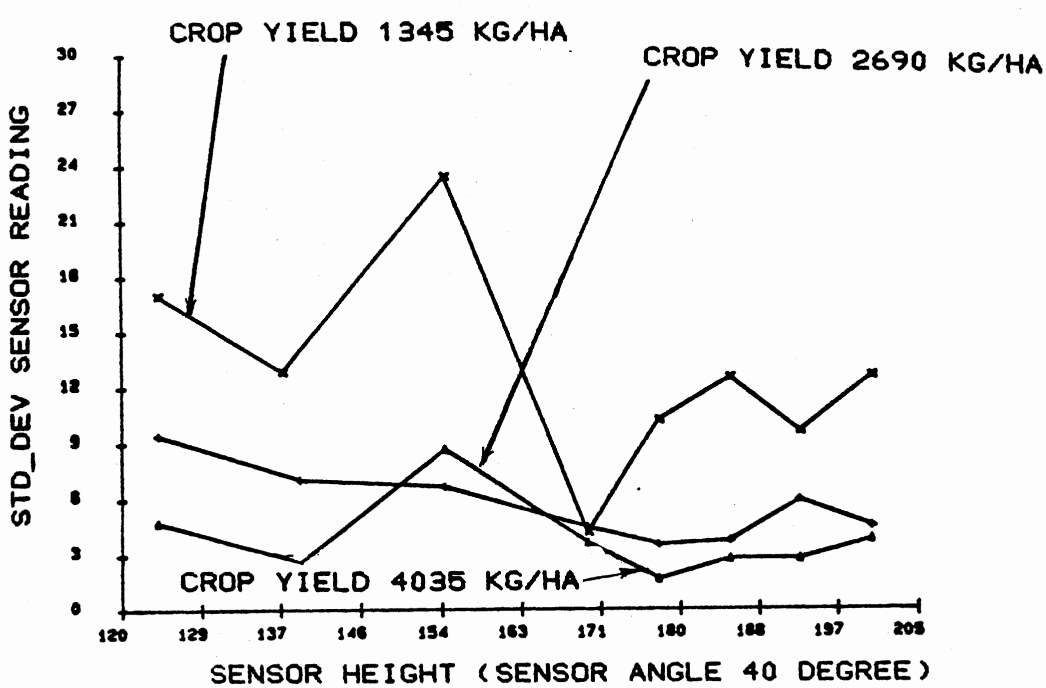


Figure 23. Plot Between Standard Deviation of Sensor Measurement and Sensor Height, Sensor Angle 40 Degree

Model of Standard Deviation of Error

A regression analysis was made between standard deviation of error vs crop yield, height, and sensor angle. From the correlation matrix, Table 7, it was observed that there was no correlation between the independent variables. It was also found that correlation of the independent variables, height, angle, and yield to the dependent variable, standard deviation was 0.20472, 0.27060 and 0.81361 respectively. Hence it was apparent that correlation between standard deviation and yield was very high compared to height and angle.

TABLE 7

CORRELATION MATRIX FOR STANDARD DEVIATION OF ERROR

	Sensor Ht	Std Dev	Angle	Yield
Sensor Ht	1.00000			
Std dev	-0.2047	1.00000		
Angle	0.0000	-0.2706	1.0000	
Yield	0.0000	-0.8136	0.0000	1.0000

The coefficient of multiple determination R SQUARED, was 0.778 as shown in Table 8, and the value was not satisfactory due to poor correlation between standard deviation, height and angle. The mathematical model developed is shown below :

$$\text{Std dev} = 39.4059 - 0.0054 * \text{yield} - 0.0597 * \text{height} - 0.1389 * \text{angle} \quad (3)$$

TABLE 8

SUMMARY OF REGRESSION ANALYSES OF
ERROR READING

VARIABLE	REGRESSION COEF	STD.ERR	T(DF=116)	PROB
YIELD	-0.0054	0.0002	-18.560	0.000
SENSOR HT	-0.0597	0.0128	-4.670	0.000
ANGLE	-0.1389	0.0225	-6.173	0.000
CONSTANT	39.4059			

SOURCE	SUM OF SQUARES	D.F	MEAN SQ	F RATIO
REGRESSION	4915.172	3	1638.39	134.798
RESIDUAL	1409.909	116	12.15	
TOTAL	6325.081	119		

R SQUARED 0.7771

* Dependent variable : Standard deviation of error
* Independent variable: Crop yield, height & sensor angle

Model of Standard Deviation of Sensor Reading

From the correlation matrix Table 9 it was found that correlation of the independent variables height, angle, and yield to the dependent variable, standard deviation was 0.24050, 0.30734 and 0.77891 respectively. The independent variables were not correlated. As shown in Table 10 the R SQUARED was 0.7577 which was similar to the model of standard deviation of error. The mathematical model developed is given below :

$$\text{Std dev} = 40.7119 - 0.0052 * \text{yield} - 0.0705 * \text{height} - 0.1606 * \text{angle} \quad (5)$$

TABLE 9

CORRELATION MATRIX FOR STANDARD DEVIATION OF SENSOR READING

	Sensor Ht	Std Dev	Angle	Yield
Sensor Ht	1.0000			
Std dev	-0.2405	1.000		
Angle	-0.00087	-0.3073	1.0000	
Yield	0.00395	-0.7789	0.0000	1.000000

TABLE 10

SUMMARY OF REGRESSION ANALYSES OF SENSOR READING

VARIABLE	REGRESSION COEF	STD.ERR	T(DF=116)	PROB
YIELD	-0.0052	0.0003	-17.021	0.00
HEIGHT	-0.0705	0.0136	-5.200	0.00
ANGLE	-0.1606	0.0239	-6.729	0.00
CONSTANT	40.7119			

SOURCE	SUM OF SQUARES	D.F	MEAN SQ	F RATIO
REGRESSION	4956.0853	3	1625.028	120.889
RESIDUAL	1585.2164	116	13.665	
TOTAL	6541.3017	119		
R SQUARED	0.7577			

* Dependent variable : Standard deviation of error
* Independent variable: Crop yield, height & sensor angle

The above two models were considered to show that standard deviation of error or standard deviation of sensor reading can be used to determine crop yield (which indicates crop density). Both the parameters almost gives the same result. In reality it would be convenient to consider standard deviation of sensor reading.

However when the height of sensor was within 139 cm, and angle of incidence of the sensor was upto 10 degree there was very strong correlation between standard deviation of sensor reading and yield of crop. If sensor is positioned as mentioned above, the density of crop calculated is quite accurate.

CHAPTER VI

CONCLUSION

The height of sensor from the ground level should be placed within 139 cm. However the minimum distance of the sensor from top of the crop bed should be 46 cm away (the minimum distance the sensor can measure). If the sensor can be fixed within the range then crop height and density can be predicted quite accurately. There are other advantages of lower positioning of sensor which are given below:

1. More readings can be obtained in shorter time.
2. Possibility of less vibration.
3. It is likely sensor sensitivity would be better due to shorter distance.

The sensor is capable of working in the range of 4035 to 1345 Kg/Ha crop yield to evaluate the crop height and density.

Experimentally it was found that when the angle of sensor was within 10 degree the performance of the sensor was best in determining both the above parameters.

The advantage of the experiment was that, from the value of the sensor reading, crop height and density could be determined quite accurately.

Suggested Further Studies

Following factors may be considered while considering further studies:

1. Shorter range sensor should be selected for better sensitivity in predicting crop height and density.
2. Vibration of the machine must be considered while measuring the above parameters.
3. Experiments need to be conducted to find the effect of crop variety and spacing on sensor reading.
4. When the sensor is mounted on a combine the sound created by the machine may distort the signal. It would be desirable to filter the data before processed.
5. Experimental verification is required to find if speed has any effect on parameter measurement.
6. Experimental analysis is also required to find the sensor performance at different temperature and dusty condition.
7. If crop height is estimated then torque at the sickle may also be considered as a feed rate parameter to determine automatic forward speed of combine. Earlier it could not be considered due to varying length of wheat and M.O.G entering the combine. When a desired ratio of grain to M.O.G would enter combine a correlation can be made between torque at the sickle and sensor reading so that desired level of feed rate can be achieved without any time delay.

8. Due to variation in crop yield it would be desirable to install a multiple sensors so that a true representation of the crop yield can be obtained.

Sampling and Control Strategy

Assuming the sensor is fixed at a height of 140 cm from the ground level it would take approximately 8.2 msec between transmission of the pulse and detecting echo by the transducer. Thus it is possible to take approximately 100 samples of crop height reading per sec. Assuming a control strategy would be to manipulate the header of the combine every 0.3 m travelled, with a speed of 13 km/hour. Then a total of 8 samples could be taken. Considering three sensors installed, a total of 24 samples would be available to determine standard deviation, crop height and density of crop.

Considering above it could be concluded that with an ultrasonic sensor it is possible to estimate crop height and density, and automatic forward speed can be evaluated without any time delay measurement.

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APPENDIX A

LISTING OF ASSEMBLY AND BASIC LANGUAGE SOURCE CODE

```
*************************************************************
*                                                           *
*           LIST OF ASSEMBLY LANGUAGE PROGRAM               *
*                                                           *
*************************************************************

/*  Column number 1 :  Address        */
/*  Column number 2 :  OP Code        */
/*  Column number 3 :  Mnemonic       */
/*  Column number 4 :  Argument       */


0F02   A9   LDA   #FF     /* INIT HIGH TO START PULSE */
0F04   8D   STA   A000
0F07   8D   STA   A008    /* DELAY                    */
0F0A   EA   NOP           /* TO MATCH READING TIMER   */
0F0B   8D   STA   A008
0F0E   8D   STA   A009
0F11   A2   LDX   #FC
0F13   8E   STX   A004    /* WAIT 2.3 MS INCASE NOISE */
0F16   A2   LDX   #08     /* ON ECHO LINE             */
0F18   8E   STX   A005
0F1B   2C   BIT   A00D
0F1E   50   BVC   0F1B
0F20   8D   STA   A004    /* START T1  INCASE NO ECHO */
0F23   8D   STA   A005
0F26   2C   BIT   A000
0F29   70   BVS   0F38    /* CK PB6 ECHO              */
0F2B   2C   BIT   A00D    /* CK T1  IN CASE NO ECHO   */
0F2E   50   BVC   0F26
0F30   8D   STA   0F01    /* $FFFF FLAG FOR NO ECHO   */
0F33   8D   STA   0F00    /* 36. + FT DISPLAYED       */
0F36   70   BVS   0F53
0F38   AD   LDA   A008    /* READ T2                  */
0F3B   AE   LDX   A009
0F3E   C9   CMP   #05
0F40   B0   BCS   0F43    /* INCASE ROLLOVER          */
0F42   E8   INX
0F43   18   CLC
0F44   49   EOR   #FF
0F46   69   ADC   #01     /* 2' COMLIMENT             */
0F48   8D   STA   0F00
0F4B   8A   TXA
0F4C   49   EOR   #FF     /* OF T2 IN $F00 & $F01     */
0F4E   69   ADC   #0D
0F50   8D   STA   0F01
0F53   60   RTS           /* BACK TO BASIC            */
```

```
**********************************************************
*                                                        *
*          LIST OF BASIC LANGUAGE PROGRAM                *
*                                                        *
**********************************************************

                                        /* PB7 OUTPUT          */

5    PB = 40960 : POKE PB + 2,128   /* MAKE INIT LOW       */

7    POKE PB,127                    /* BOTH TIMER ONE-SHOT*/

12   POKE PB + 11,0

20   POKE 123, 0 : POKE127,00

30   POKE142, 15 : TH = TL+1        /* DATA FROM ASSEMBLY */

40   TL = 256 * 15 : TH = TL + 1    /* @ $F00 & $F01

50   POKE4,2 : POKE 5,15

70   X = USR(Y) : TI = PEEK(TL)

     + 256 * (PEEK(TH))

75   POKE PB,127                    /* INIT BACK LOW       */

80   DI$ = STR$(TI/1780 DI$,6)LEFT$(DI$,6)

90   PRINT DI$

100  GO TO 70

/*   PB7 : INIT START PULSE                     */
/*   PB6 : ECHO STOPS FROM SENSOR               */
```

APPENDIX B

LISTING OF COMPUTER SOURCE CODE TO CALCULATE MEAN AND STANDARD DEVIATION OF ERROR

```
/***********************************************************
*                                                          *
*      COMPUTER SOURCE CODE TO DETERMINE MEAN AND          *
*                                                          *
*      STANDARD DEVIATION OF ERROR                         *
*                                                          *
***********************************************************/


#define   inch     12.0
#define   camera   48.75
#define   gauge    47.50

        /*********       INCLUDE FILES      **********/

#include <math.h>
#include <stdio.h>

    /**********      DECLARATION OF VARIABLES   *********/

char     cropfile[20],outfile[20],sensfile[20],ch,chk,cch;
FILE     *ofi,*fopen( ),*of;
double   ang,ht,sensor[100],mean,crop[100],differ[100],
         stdev,delm[100],angle[100],height[100],stdv[100],
         totdiffer,sum,del[100],var,p=0.5,avdiff[100],
         ccrop[100],ssensor[100],cos( ),pi=3.1415927,
         avdiff[100],ccrop[100], ssensor[100],
int      i,ii,j,k,row,count,position,pos[100],nn;

   /**********    START OF MAIN PROGRAM    *************/

main( )

{
 ch= ' ';
 cch=' ';
 ii=0;


       /*******    CREATING THE OUTPUT FILE    ********/


  printf("\nENTER THE NAME OF  OUTPUT  FILE ::");
  scanf("%s",outfile);
  of=fopen(outfile,"w");
  fprintf(of," density  height   angle     mean
  stddiv\n\n");


  while(!((cch=='n')||(cch=='N')))
  {

/********   READING THE REFERENCE VALUE   *********/
```

```
printf("\nENTER NAME OF THE THEORITICAL CROP HEIGHT
       FILE:");
scanf("%s",cropfile);
ofi=fopen(cropfile,"r");
printf("\nENTER TOTAL NUMBER OF DATA ");
scanf("%d",&nn);
for(row=0; row<=(nn-1); ++row)
{
 fscanf(ofi,"%E",&ccrop[row]);
 crop[row]= ccrop[row];
}
close(ofi);
while(!((ch=='n')||(ch=='N')))
{
totdiffer=0;

********   READING THE SENSOR MEASUREMENT   *********/

printf("\nENTER NAME OF SENSOR CROP HEIGHT FILE:");
scanf("%s",sensfile);
ofi=fopen(sensfile,"r");
for(j=0; j<=(nn-1); ++j)
{
 fscanf(ofi,"%E",&ssensor[j]);
 if(j==0)
 ht =ssensor[j];
 else if(j==1)
 ang = ssensor[j]*pi/180.0;
 else
 sensor[j]=ssensor[j]*inch*cos(ang);
}
close(ofi);
printf("\nENTER VALUE OF DENSITY  ::::");
scanf("%d",&position);
height[ii]=ht;
angle[ii]=ang*180.0/pi;
pos[ii]=position;
totdiffer=0.0;

/***   CALCULATING THE MEAN AND STANDARD DEVIATION   ****/

for(k=2; k<=(nn-1); ++k)
{
 differ[k]=((gauge-crop[k])-(ht-sensor[k]))*2.54;
 totdiffer+=differ[k];
}
k=(k-2)*1.0;
mean=totdiffer/k;
sum=0.0;
```

```
avdiff[ii]=mean;
for( i=2; i<=(nn-1); ++i)
{
 delm[i]=(differ[i]-mean);
 del[i]=delm[i]*delm[i];
 sum+=del[i];
}
 i=(i-3)*1.0;
 var=sum/i;
 stdev=(pow(var,p));
 stdv[ii]=stdev;
 fprintf(of," %4d %8.4f %8.4f %8.4f %8.4f\n\n",pos[ii],
         height[ii]*2.54,angle[ii],avdiff[ii],stdv[ii]);
 ii+=1;
 scanf("%s",&chk);
 printf("\nWANT TO TRY ANOTHER SET OF FILE ::::: Y/N ");
 scanf("%s",&ch);
 %6.3f",ht,ang,mean,stdev);
}
 printf("\nWANT TO TRY ANOTHER CROP FILE ::::: Y/N ");
 scanf("%s",&cch);
}

 fclose(of);
}

    /***********    END OF PROGRAM    ***************/
```

APPENDIX C

LISTING OF COMPUTER SOURCE CODE TO CALCULATE STANDARD DEVIATION OF SENSOR READING

```
/*****************************************************************
*                                                                *
*      COMPUTER CODE TO DETERMINE STANDARD DEVIATION             *
*                                                                *
*                     OF SENSOR READING                          *
*                                                                *
*****************************************************************

#define   inch      12.0
#define   camera    48.75
#define   gauge     47.50

    /**************    INCLUDE FILES    ****************/


#include <math.h>
#include <stdio.h>


     /********   DECLARATION OF VARIABLES   ***********/

char     cropfile[20],outfile[20],sensfile[20],ch,chk,cch;
FILE     *ofi,*fopen( ),*of;
double   ang,ht,sensor[500],mean,ssum[500],stdev,delm[500],
         angle[500],height[500],stdv[500],totdiffer,sum,
         del[500],var,p=0.5,avdiff[500],ssensor[500],cos( ),
         pi=3.1415927;
int      i,ii,j,k,row,count,position,pos[500],nn;

main( )

{
 ch= ' ';
 cch=' ';
 ii=0;
   printf("\nENTER THE NAME OF  OUTPUT  FILE ::");
   scanf("%s",outfile);
   printf("\nENTER TOTAL NUMBER OF DATA ");
   scanf("%d",&nn);
   printf("\nENTER VALUE OF DENSITY  ::::");
   scanf("%d",&position);
   of=fopen(outfile,"w");
  while(!((ch=='n')||(ch=='N')))
  {

     printf("\nENTER NAME OF SENSOR CROP HEIGHT FILE:");
     scanf("%s",sensfile);
     ofi=fopen(sensfile,"r");
     for(j=0; j<=(nn-1); ++j)
      {
       fscanf(ofi,"%E",&ssensor[j]);
       if(j==0)
```

```
          ht =ssensor[j];
        else if(j==1)
          ang = ssensor[j]*pi/180.0;
        else
          sensor[j]=ssensor[j]*inch*cos(ang);
       }
      fclose(ofi);
      height[ii]=ht;
      angle[ii]=ang*180.0/pi;
      pos[ii]=position;
      totdiffer = 0.0;


/**********   CALCULATION OF STANDARD DEVIATION   **********/


      for(k=2; k<=(nn-1); ++k)
       {
        ssum[k]=(ht-sensor[k])*2.54;
        totdiffer+=ssum[k];
       }
      k=(k-2)*1.0;
      mean=totdiffer/k;
      sum=0.0;
      avdiff[ii]=mean;
      for(i=2; i<=(nn-1); ++i)
       {
        delm[i]=(ssum[i]-mean);
        del[i]=delm[i]*delm[i];
        sum+=del[i];
       }
      i=(i-3)*1.0;
      var=sum/i;
      stdev=(pow(var,p));
      stdv[ii]=stdev;
      fprintf(of,"%8.4f %8.4f\n",height[ii]*2.54,stdv[ii]);
      ii+=1;
      i=j=k=0.0;
      scanf("%s",&chk);
      printf("\nWANT TO TRY ANOTHER SET OF FILE ::::: Y/N ");
      scanf("%s",&ch);
  }

      fclose(of);
}


          /*********   END OF PROGRAM   ***********/
```

APPENDIX D

EXPERIMENTAL DATA

TABLE 11

DATA FOR SENSOR ANGLE 0 DEGREE AND CROP YIELD 4035 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	9.5966	9.5239	9.5416
139	11.5325	10.4602	10.2620
154	5.6499	3.8054	4.0246
169	9.6193	9.3348	10.3695
177	10.5892	11.4020	11.1434
185	8.7002	4.4455	4.4058
193	7.4326	2.9010	2.5902
200	5.4623	4.3057	3.9038

TABLE 12

DATA FOR SENSOR ANGLE 10 DEGREE AND CROP YIELD 4035 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	6.0361	5.4975	5.5873
139	7.1753	4.5881	5.2257
154	4.7433	4.3516	4.1122
169	6.4714	4.9523	5.0119
177	7.8546	4.7357	5.1002
185	8.4696	5.5339	5.0136
193	7.2063	3.6919	2.3682
200	4.4828	4.2226	3.6721

TABLE 13

DATA FOR SENSOR ANGLE 20 DEGREE AND CROP YIELD 4035 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	8.2770	15.7778	16.3148
139	6.2313	4.1374	3.8045
154	4.1805	6.1109	6.0394
169	4.5268	5.1115	5.4716
177	5.9353	5.1061	4.6933
185	5.8139	5.2704	4.5468
193	3.2371	3.6439	3.4726
200	0.7542	3.8248	3.7915

TABLE 14

DATA FOR SENSOR ANGLE 30 DEGREE AND CROP YIELD 4035 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	4.0362	9.1408	9.8938
139	1.8069	4.1225	3.5728
154	-0.7174	4.6102	4.3937
169	-0.1710	4.7944	4.9174
177	1.5916	5.1755	3.1669
185	-1.5413	3.9573	2.7438
193	-2.9030	4.0081	2.9755
200	-4.7500	4.6417	4.0225

TABLE 15

DATA FOR SENSOR ANGLE 40 DEGREE AND CROP YIELD 4035 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	-0.6564	4.9655	4.7658
139	-4.4541	3.8158	2.6202
154	-4.8968	7.4385	8.6810
169	-5.4275	3.8510	3.6693
177	-7.2834	3.8417	1.6804
185	-10.7604	4.0542	2.7814
193	-10.3469	3.8700	2.7767
200	-11.6257	4.8966	3.8342

TABLE 16

DATA FOR SENSOR ANGLE 0 DEGREE AND CROP YIELD 2690 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	14.4013	17.6996	17.3022
139	21.2351	19.7581	19.9998
154	10.1794	8.6180	8.0618
169	17.0147	19.8313	20.1373
177	14.4208	17.0913	16.8454
185	12.5889	10.8920	10.6222
193	9.9965	5.8190	4.7139
200	7.6019	5.1938	4.6816

TABLE 17

DATA FOR SENSOR ANGLE 10 DEGREE AND CROP YIELD 2690 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	19.6578	19.8170	20.2275
139	8.0105	4.8270	3.4827
154	8.5764	10.5003	10.9496
169	11.9933	15.0690	14.4652
177	10.2580	9.9634	9.7143
185	11.4752	10.9350	11.3629
193	5.4686	6.3370	4.7681
200	6.9149	9.1143	8.7414

TABLE 18

DATA FOR SENSOR ANGLE 20 DEGREE AND CROP YIELD 2690 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	8.2770	15.7778	16.3148
139	6.2313	4.1374	3.8045
154	4.1805	6.1109	6.0394
169	4.5268	5.1115	5.4716
177	5.9353	5.1061	4.6933
185	5.8139	5.2704	4.5468
193	3.2371	3.6439	3.4726
200	0.7542	3.8248	3.7915

TABLE 19

DATA FOR SENSOR ANGLE 30 DEGREE AND CROP YIELD 2690 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	9.9854	12.8172	12.4692
139	7.1200	9.6714	9.2486
154	5.9655	12.3507	11.9964
169	8.7699	13.9580	13.7662
177	3.5046	6.1720	5.4614
185	1.6072	5.4799	4.1061
193	-0.6618	5.5412	4.5506
200	0.2436	9.9585	9.2847

TABLE 20

DATA FOR SENSOR ANGLE 40 DEGREE AND CROP YIELD 2690 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	5.0635	10.3282	9.4145
139	-0.5310	7.8879	7.0532
154	-2.2375	8.2118	6.6761
169	-2.9299	5.5731	4.5100
177	-4.9569	5.4470	3.5654
185	-7.3341	5.7339	3.7757
193	-6.5605	7.9161	5.9700
200	-8.1145	6.1629	4.5474

TABLE 21

DATA FOR SENSOR ANGLE 0 DEGREE AND CROP YIELD 1345 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	30.9548	27.5146	28.5008
139	25.1902	24.9819	24.4457
154	17.3881	20.9493	23.9240
169	22.9307	25.5532	25.6213
177	29.7207	27.4031	26.7692
185	22.0714	26.0500	23.1823
193	13.8438	23.0927	20.5168
200	10.8700	21.5495	19.2530

TABLE 22

DATA FOR SENSOR ANGLE 10 DEGREE AND CROP YIELD 1345 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	12.3639	22.9009	23.3707
139	14.0781	19.8036	18.3442
154	17.0614	24.2801	23.5471
169	22.4793	22.6622	23.6065
177	24.2053	21.2794	22.4540
185	15.6525	17.8792	18.8763
193	6.9126	14.3642	12.0909
200	4.6664	18.0911	14.6265

TABLE 23

DATA FOR SENSOR ANGLE 20 DEGREE AND CROP YIELD 1345 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	10.4325	22.9752	19.8697
139	10.8739	16.0901	17.7304
154	10.2298	20.1362	20.6461
169	28.8856	25.0972	24.2693
177	22.9643	22.2162	22.4179
185	14.9073	20.5881	22.4179
193	5.1318	19.1893	15.6053
200	6.7014	14.2393	16.2589

TABLE 24

DATA FOR SENSOR ANGLE 30 DEGREE AND CROP YIELD 1345 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	16.2629	25.2616	23.7793
139	8.5120	21.1186	19.3719
154	9.5275	23.9402	22.2463
169	14.4889	21.8555	20.8847
177	6.5914	21.0205	17.3874
185	2.4463	16.8408	16.5248
193	4.7797	17.6478	19.7567
200	5.9735	18.8945	19.4022

TABLE 25

DATA FOR SENSOR ANGLE 40 DEGREE AND CROP YIELD 1345 KG/HECT

Sensor Height in cm	Mean of Error in cm	Standard Deviation of Error	Standard Deviation of Sensor Reading
124	6.3023	18.0344	17.0054
139	-2.4270	11.1342	12.8825
154	1.7589	23.4411	23.4714
169	-7.5582	9.2197	4.2247
177	-7.7838	7.8901	10.2712
185	-7.6004	15.1761	12.5603
192	-8.7204	12.0730	9.6501
200	-6.0483	16.2271	12.6609

VITA

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