Story behind the Story about the ARS Coop R&D Project for Laser-Beam Grade-Control on a Draintube Plow

by James L. Fouss, Ph.D., P.E.

<u>Preface</u>:
The U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) is the scientific and engineering research agency whose mission is to develop new and improved technologies to enhance agriculture and food production for public benefit. One of ARS's principal areas of research is soil and water management and conservation which are carried out at a national network of Federal research laboratories, many of which are co-located and cooperative with major Universities. The new knowledge, concepts, and technologies developed and demonstrated by ARS research are transferred to private sector agricultural producers and service providers (e.g., manufacturers) for implementation and delivery of improved products and services to the public.

<u>Foreword</u>:
This is a story about activities of USDA-ARS researchers, namely myself (James L. Fouss, Research Agricultural Engineer), my technician and co-worker (Norman R. Fausey, Engineering Technician), ARS and university professionals, plus industry cooperators (Control Industries, Process Equipment, Laserplane, and Caterpillar Tractor Co.) who were all very important in the development and testing of the original laser-beam automatic depth and grade-control system for the drainage plow that helped to revolutionize the subsurface drainage industry in the early 1970s. This is a previously unwritten story, but parts of it were told a number of times by Jim Fouss over the years to selected colleagues and friends. Many of the activities and events included in this story have never been published.

Introduction

It has been noted in published materials by some internationally known subsurface drainage experts, Dr. Jan van Schilfgaarde, Dr. Glenn O. Schwab, and Mr. Ronald C. Reeve (*all unfortunately now deceased*) that <u>focused</u> research during the 1965-1975 decade advanced and improved subsurface drainage technology more than had occurred during the previous 100 years. The research and development referred to led to the replacement of typically slow trench-installation of rigid clay or concrete drain tile with light-weight corrugated-wall high-density polyethylene (HDPE) plastic drain tubing installed with plow-type equipment or high-speed trenchers controlled by a laser-beam (or Laserplane) automatic depth & grade-control system. The original laser grade-control research and development was conducted by an engineer and his technician employed by USDA, Agricultural Research Service, James L. Fouss (agricultural engineer) and Norman R. Fausey (engineering technician), who were stationed in the Department of Agricultural Engineering at The Ohio State University in Columbus, OH. The ARS researchers worked cooperatively with University researchers, and they established contractual arrangements with industry experts in electronic feedback controls to develop an electronic circuit for a prototype grade-control system to conduct performance and evaluation testing. After field testing provided proof the laser-based system worked, the technology was transferred to drainage equipment industry reps for product development. Field demonstrations were conducted cooperatively by ARS, University colleagues, and Industry partners, on drainage plows and trenching machines. Widespread adoption and use by contractors followed.

This paper on the cooperative research and development for the laser-beam grade-control system follows a **"*story-behind-the-story*"** theme for several key events that occurred during the work on the project. Many of these events have never before been written about nor previously published; however, some were discussed with selected individuals over the years. Some of the "key" events were progressive in nature while others were barriers to progress that had to be overcome, and a few are comic (*now, but not necessarily at the time*). There were, however, three papers or stories that were published and widely distributed about the successful research and development project that led to the laser-beam (or Laserplane) automatic grade-control system for drainage installation equipment. Reference citations for those three publications are listed below (Printed copies of the PDF documents for the published papers (1) and (2) are included in APPENDIX II of this story):

(1) Fouss, J.L. and Fausey, N.R. "Researchers Fouss and Fausey Develop Laser Grade-Control System That Transforms Drainage and Irrigation Technology," published by the Council for Agricultural Science and Technology (CAST), NewsCAST "Success Stories in Agriculture" 31 (01): 15-18, July 1, 2004.[1]

(2) Fouss, J.L. and Fausey, N.R. Research and Development of Laser-Beam Automatic Grade-Control System on High-Speed Subsurface Drainage Equipment. TRANS. of the ASABE. 50 (5): 1663-1667. 2007.[2]

(3) ARS research for development of the Laser-Beam Grade-Control System for High-Speed Drainage Equipment was honored by ASABE with a Historical Landmark Plaque; plaque and accompanying research story was dedicated and mounted in The Food Agricultural, and Biological Engineering Dept., The Ohio State University, Columbus, OH, May 2007. (**Fig. 1**, Historical Landmark Plaque)

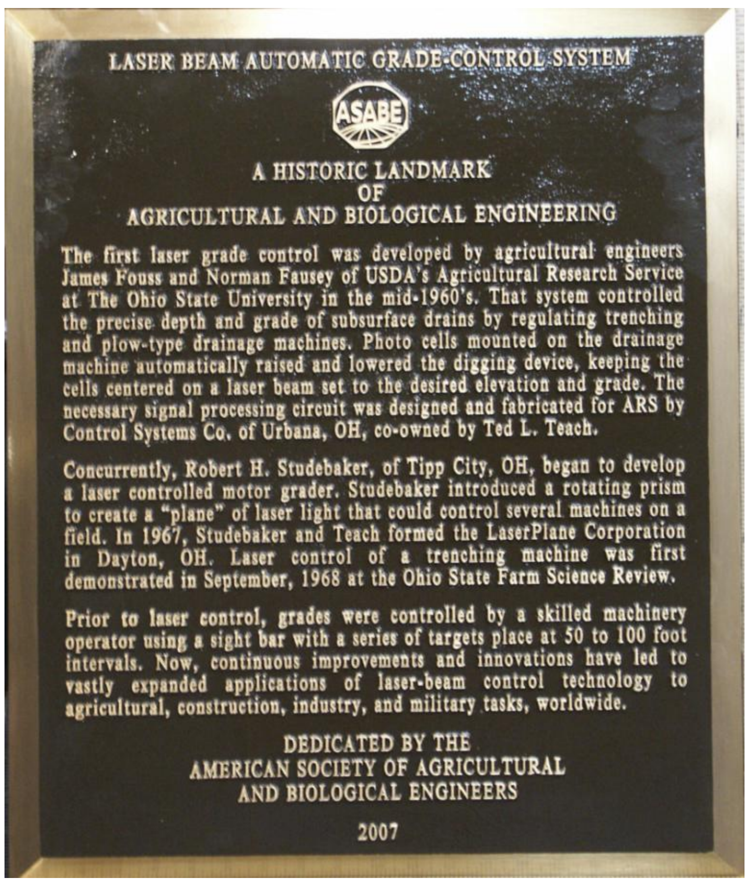

Fig. 1. ASABE Historical Landmark Plaque honoring ARS research for development of the Laser-Beam Grade-Control System for High-Speed Drainage Equipment.

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1 The Council reviewed about 200 ARS research projects, and selected this accomplishment as the first of only four "**success stories**" published to document and demonstrate for the U.S. Congress that research dollars pay off.

2 The Senior Author and Co-Author were invited by the American Society of Agricultural and Biological Engineers (ASABE) to author this article for publication in a special Centennial Issue of the ***Transactions of ASABE***.

Background

High-speed installation of plastic subsurface drain tubing with a drainage plow was possible by the mid-1960's using coilable lengths of corrugated-wall high-density polyethylene (HDPE) plastic tubing (3 - 4 inches in diameter). There is another "*story-behind-the-story*" on how and when the original sample of corrugated-wall HDPE tubing was acquired and its potential for use as the experimental drainage conduit was quickly recognized. That additional background story is written about separately, and covers the earlier phases of the ARS research project (1955-1965) that involved the development and testing of a Vinyl sheet plastic-liner formed into an arch or a circular conduit and placed within a 3-inch diameter mole drainage channel formed by a mole plow. The authors were responsible for the last phase of the earlier project when a "zippered" plastic mole-drain circular "liner" was formed and placed into the mole drain channel. Edges of the 0.015-in. thick Vinyl plastic sheet were "zippered" together within the installation equipment to form a closed circular mole-drain channel liner. The experimental plow-type equipment used to install the "zippered" mole-drain liner is shown in Fig. 2. Grade-control on the mole-plow was maintained manually by the tractor operator to hydraulically adjust the plowing depth to maintain a pointer-stick on the plow frame aligned with a stretched string along the drain path (**Fig. 2**); the stretched string was preset to the drain gradient.

Fig. 2. Floating-Beam Mole-Drain Plow equipped with a "zippered" plastic mole-drain liner installation attachment; wheels on plow frame were for transport only when out of the ground, not plow depth control.

These early field trials with the equipment shown in Fig. 2 confirmed that manual control of depth and grade of the drain plow by the operator at ground speeds of 30-45 meters per minute (100-150 feet per minute) was not acceptable or practical. Traditional depth/grade control on slow moving trenching machines was accomplished visually by the operator aligning a sighting cross-bar on the trencher digging mechanism frame with targets aligned to the drainpipe design grade-slope across the field. This required constant attention of the equipment operator, but was reasonably accurate for the slower trenching speeds of 3-11 meters per minute (10-35 feet per minute). Another technique for a trencher (more commonly used in construction projects, but not for agricultural drainage installations) was to use a wire stretched parallel to the design bottom slope for the trench. The trencher operator visually maintained a reference bar or pointer in line with the taut line. To insure more accuracy on specific installation jobs, the stretched wire was used as a reference line for a feeler-sensor-arm to activate hydraulic solenoid valves to automate the depth control on the trencher. However, the time and cost of setting a reference wire for each drainline would have been excessive and thus not acceptable, especially for high-speed drainage plow equipment. It was estimated that it could require from 9 to 12 workers (in teams of 3 workers each) to stay ahead of the drainpipe installation with the high-speed plow to pre-set such grade reference wires.

Early Field Research to select Plow Frame Design

Even before the corrugated-wall HDPE tubing was selected for the drain pipe material, when testing and evaluation of the plastic-lined mole drains continued with the drainage plow, a series of field tests were conducted to characterize and evaluate the “floating-beam” principal of operation for the drainage plow. As shown in Fig. 2, the initial mole drainage plow was modified to install the plastic-lined mole drains, and two crawler tractors pulling in tandem were used so that the downward draft-line with the plow hitched to the drawbar of the trailing tractor would not cause the front of the tractor to raise or lower as the plow depth hydraulics were operated to control drain depth and grade. Any upward and downward tipping motion of the crawler tractor would have made accomplishing accurate grade-control much more difficult for the operator. By the second year of the project at OSU, another plow unit was designed and constructed that was directly mounted on the larger tractor with forward hitch points. The downward draft-line from the forward plow hitch points maintained the crawler tracks relatively flat on the ground as grade-control changes were made by hydraulically adjusting the vertical position of the plow hitch points along the sides of the crawler; this second floating-beam type plow is shown in **Fig. 3**. Still, two crawler tractors (a D-7 plus a D-4) were required to pull the drainage plow approximately 3-ft. deep in a heavy clay soil.

Fig. 3. Tool-Bar Mounted Floating-Beam Mole-Drain Plow installing “zippered” plastic mole-drain liner; wheels on plow frame are for plow depth control in fields pre-graded to suitable slope for constant depth drains or periodic minor depth changes along drainline path.

Field Trials with Fluid-Dampened Pendulum as an On-Plow Grade-Control Reference

A hydraulically-stabilized (fluid-dampened), self-leveling pendulum control system (as used on side-hill cereal-grain combine equipment, with self-leveling only in the direction of travel) was mounted **on** the plow beam, as shown in Fig. 3. Field tests were conducted to determine how accurate the installed drain depth and grade could be controlled with such a simple on-plow vertical referencing system. The hydraulic response needed to adjust the plow's hitch height for control of grade at the high ground-speed of the drainage plow was also evaluated in these field tests. After only a few field tests, results confirmed that an off-machine elevation referencing system would be needed with an on-plow **sensor** that could monitor or sense changes in the plow beam elevation during rapid forward motion. The field tests we did conduct with the on-plow pendulum device provided valuable design information for the speed of hydraulic response required at the plow hitch point to adequately control depth and grade at the high speed of installing drain tubing with the drainage plow.

Early Laser-Beam testing and selection of a commercial unit

It had been envisioned by the ARS lead researcher (Fouss) about this time in the mid-1960's that a helium neon gas laser-beam system, with its high-intensity and collimated-light-beam (which was in the late stages of development by Dr. Charles Townes[3] at U.C. Berkley, CA), would provide an excellent off-machine light-beam referencing system needed on the high-speed drainage plow. The idea showed promise only if a suitable plow-mounted laser-beam sensor or receiver could be found or developed to detect the laser-beam projected on-grade for operating the hydraulics system on the plow. The hydraulic system response would need to keep the sensor centered on the laser-beam for controlling the drain depth and grade as the drainpipe was installed at the fast ground speeds. When word got out at the ARS Beltsville office of what I was attempting doing, it was suggested in a hand-written note by the ARS Administrator (Mr. T. W. Edminster) that I should **not** use the laser as it would be too expensive. I took note of the advice, but with no other good option or alternative in mind decided to proceed as I had originally planned. (***There is a related Short-Story to this advice that occurred many years later. See attached Related Short-Story #1 in*** **APPENDIX III**). Thus, our search began for a suitable laser-beam projector system (if it could be acquired so early in its development stage, and at a cost that the ARS project budget could support), while at the same time searching for a suitable sensor or receiver for the projected laser-beam in the grade-control system.

A graduate student associate of mine at The Ohio State University (I have forgotten his name) who worked in the Physics Lab of the Battelle Memorial Laboratory near the OSU Campus had a laboratory-type laser unit (a helium-neon gas-laser; I do not recall its **mW** output) that he agreed to *loan* to me. He was taking about a 2 month work-related trip to Europe and would not need it while he was out of the country. We (Norm and I) picked it up from his lab and set it up in the basement area of the Agricultural Engineering Building (Ives Hall) at OSU. We wanted to be in a dark room where ambient light would not be a factor in our initial selection trials with different photo-tubes for their sensitivity in detecting the projected red laser-beam light.

After we began the testing of various photo-cell units in the Ives Hall basement laboratory with the borrowed laser-beam unit, it was soon found that in the mid-1960's a suitable photo-cell was apparently not commercially available to sense the bright red light emitted by the helium neon gas laser-beam. As we began the search for photo-**tubes** that were sensitive and responsive enough for

[3] Dr. Charles Townes was 99 yrs. old 07/28/2014, and a birthday party was held for him at Univ. of California., Berkeley.

our intended research application, our search efforts were temporarily interrupted as related in another short side-story. [***See Side-Story #2 associated with the loan of the laser-beam unit that is included in* APPENDIX III *about the interruption & excitement during this phase of the project***]. After resolving the situation causing the interruption, a suitable phototube was soon located, but then we quickly learned that it was also very sensitive to sunlight. Thus, we designed and fabricated the prototype laser-beam sensor device like a multi-baffled shadow-box to block random sunlight rays from entering and striking the photo-tube elements. The design, configuration, and sensitivity testing of the prototype laser-beam receiver unit are described and illustrated in the following sections.

Conceptual Design for the Laser-Beam Feedback Depth & Grade-Control on a Drainage Plow

The conceptual design envisioned for the Laser-Beam Feedback (Automatic) Depth and Grade-Control System on a Floating-Beam type Drainage Plow is illustrated in Fig. 4. The figure illustrates the physical relationship of the system components on the tractor, drainage plow, projected Laser-Beam, and drain-grade reference line ("chopped" Laser-Beam). A Block Diagram of all the System Components is shown in Fig. 5. A more detailed illustration of the critical dimensional relationships of the Laser-Receiver mounted on the drainage plow frame (beam) is shown in Fig. 6. (*Note: The drawing in Fig. 6 is a revised and updated version of the envisioned system drawn after the prototype system was developed and some testing and evaluations were completed*.)

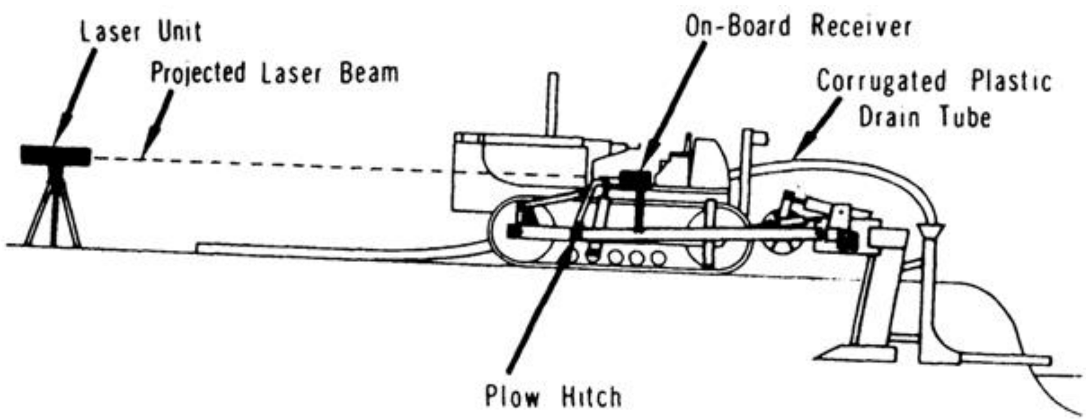

Fig. 4 – Conceptual Laser-Beam Depth & Grade-Control System on a Drainage Plow.

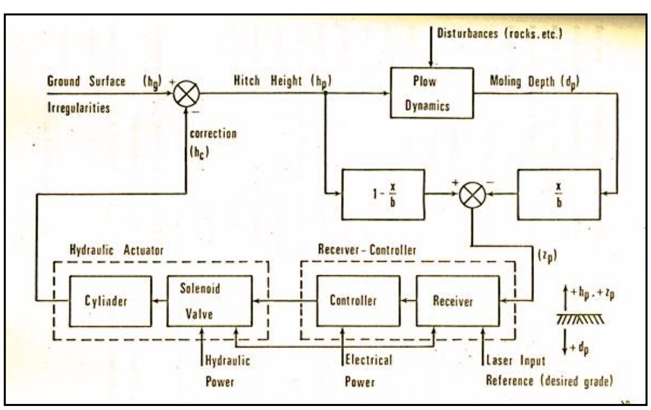

Fig. 5 – System Block-Diagram for the Laser-Beam Automatic (Feedback) Depth & Grade-Control

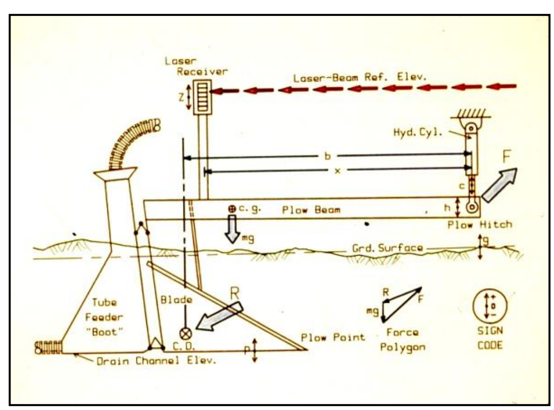

Fig. 6 – Dwg. of the Envisioned Laser-Beam Depth & Grade-Control System on a Plow

In Fig. 6 the Laser-Beam Receiver is positioned at distance "**X**" rearward from the plow's hitch point. The "effective" length of the floating-beam on the drainage plow is represented by "**b**", which is the distance between the plow hitch point and the center-of-draft on the drainage plow blade. As explained in more detail later in this story, it is important that the Laser-Beam Receiver be positioned on the plow's floating-beam at some point forward of the center-of-draft but also more than one-half the beam length (**b**) behind the plow hitch point. This forward position of the Receiver allows the Receiver to detect vertical changes in the hitch position relative to the drain depth during forward motion of the plow (e.g., especially when traveling over an undulating ground surface), before the plow blade (center-of-draft) reaches that location in forward travel. The time delay for travel of the center-of-draft to move forward the distance (b – X) allows time for the feedback control system to hydraulically adjust (correct) the hitch point vertical position so that the drain is installed at the design depth and grade. The Receiver position illustrated in Fig. 6 is somewhat closer to the center-of-draft than the **optimum** position found (**X/b ~ 5/6**; as explained later) through theoretical (simulations) and field testing with the prototype laser-beam and commercial Laserplane depth and grade-control system on the drainage plow. Simulation and field test graphical results are shown later.

Development of Prototype Laser-Beam Grade Control System

The design objective and assembly of the prototype laser-beam automatic grade-control system was to meet the specific needs of the high-speed plow-type drain installation equipment. The prototype system was assembled and tested between 1965 and 1967 by ARS agricultural engineer James L. Fouss and ARS engineering technician Norman R. Fausey at Columbus, OH. The laser-beam transmitter selected was a low-power 0.3 mW output helium-neon gas laser that emitted a 6.328 Angstroms wave-length laser-beam (cost of the laser was about $450.00; if I recall correctly). The laser-beam was projected **backwards** through a 10X-power telescope to expand and collimate the laser-beam to a 1.25-cm (0.5-in.) diameter, and an electric-motor-driven slotted disc to "chop" the beam at 150 Hz (cycles per second). Projecting the small laser-beam backwards through the 10-X Power telescope (that is, projecting the laser beam into the eye-piece end of the telescope) increased the diameter of the laser-beam and collimated it so that it did not expand in diameter as much over the distance it was projected to intercept the laser-beam receiver unit.   Over a distance of about 1,000 ft.

Fig. 7 – Prototype Laser-Beam Projection unit mounted on camera tripod.

the collimated laser-beam changed in dia. from 1.25-cm (0.5-in.) to about 7.5-cm (3.0-in.). The assembled prototype laser-beam projection unit was mounted on a sturdy camera tripod, as shown in **Fig. 7** (Shielding over transmitter unit was removed to show the telescope and chopper blade).

The laser-beam receiver unit consisted of two closely spaced horizontal rows of the selected phototubes mounted in a multi-baffled shadow-box type housing. The interior surfaces were painted "flat" black to reduce reflection and enhance absorption of ambient light rays that entered the baffled receiver box through the slotted openings. Seven (7) phototubes were mounted side-by-side in each horizontal row of the receiver that measured 23 cm (9.0 in.) in width. The vertical spacing between the two horizontal rows of phototubes was adjustable. Some of the gap left between the upper and lower rows (an adjustable gap) contributed to the control "dead zone" for intercepting & detecting the position of the projected laser-beam on the receiver. The receiver unit prototype is shown in **Fig. 8.** The multi-baffled shadow-box of the unit was made from sheet aluminum to reduce weight.

The initial testing of the laser receiver unit (Fig. 8) was to measure its sensitivity to vertical displacements from the center-line of the projected laser beam. The receiver unit was mounted on a sturdy camera tripod so that it could be manually moved upward and downward while the laser- beam was projected directly into it from a significant distance. A simple voltage monitoring circuit was configured and wired to read the output from the two horizontal rows of phototubes while the laser-beam was projected (without "chopping" the beam with the 5 blade disk as shown in Fig. 7) from a distance of about 140 m (460 ft.). The initial tests were conducted at night and the test setup was underneath The Ohio State University football stadium (Ohio Stadium) in order to be in nearly total darkness and to block the effects of any nighttime wind blowing on the projector or receiver.

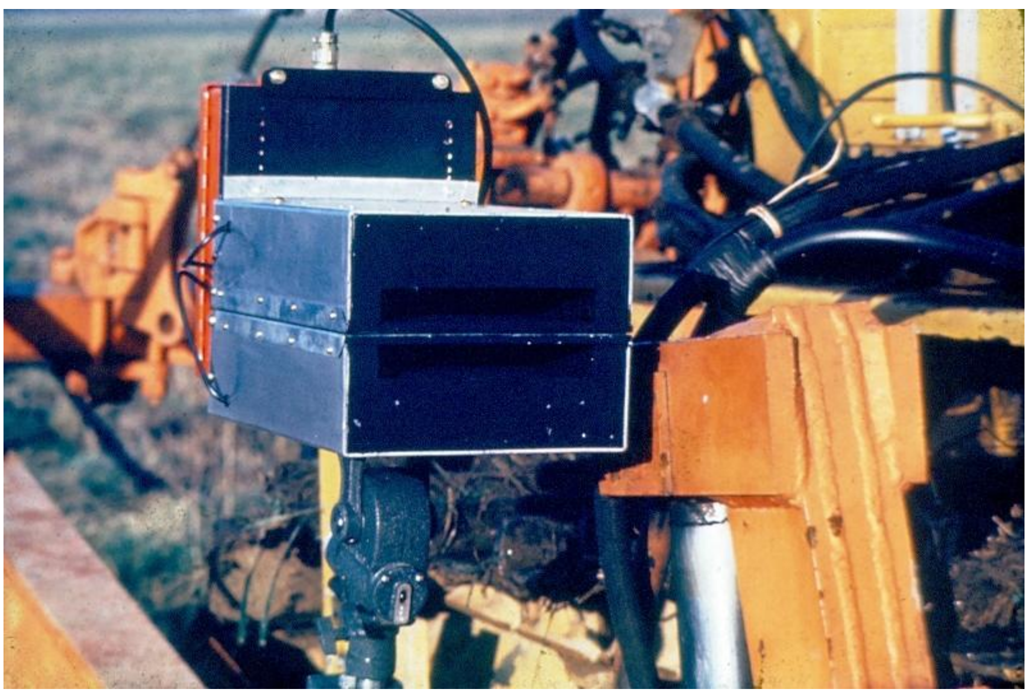

Fig. 8 – Prototype Phototube Laser-Beam Receiver Unit.

These early tests indicated that the receiver could detect slight upward and downward movements of less than about **+/-** 7 mm (**+/-** 0.3 in.) from the center of the projected laser-beam; the receiver positions were indicated by (**+**) volts [**for high**], (**0.0**) volts [**for centered**], and (**-**) volts [**for low**] in the monitoring circuit. These initial night-time tests were abruptly interrupted (again by OSU police) and were not completed with other trial settings or variables, as explained in the Related Side-Story **#3. [*See Side-Story #3 in APPENDIX III about the interruption of the night-time laser receiver early testing underneath Ohio Stadium*]**. I do not recall that any further sensitivity testing was conducted that night with other trial settings or variables after the interruption at the Ohio Stadium. The primary objective of the early tests that night had been completed, fortunately, and we proceeded on with the next step of our laser grade-control development project.

Following the initial night-time sensitivity testing of the prototype receiver at the Ohio Stadium, a more enhanced signal processing circuit for the laser-beam receiver unit was designed and fabricated for ARS under a USDA-ARS Government contract awarded to **Ted L. Teach** and his partner in the firm, Control Industries of Urbana, OH. The electrical signals from the phototubes included a D-C component mainly from ambient light and an A-C component from the "chopped" (frequency modulated) laser-beam light. The modulation frequency of 150 Hz (cycles/second) was selected for the "chopped" laser-light beam. The 5 slots in the rotating disc on the laser-beam transmitter (Fig. 7) created the 150 Hz "chopped" laser-beam. The 150 Hz frequency was selected because it was considered a high enough frequency to reduce interference with ambient light fluctuations, and also electrical circuit filter components for this frequency were readily available at a low cost. For example, such circuit filter components were used in an audio sound frequency modulated aircraft landing system manufactured by Control Industries to assist pilots in aligning their flight path with small airport runways during low visibility (e.g., in fog or rain) and night-time landings.[4]

The initial sensitivity testing of the new phototube receiver unit circuitry was conducted at the Urbana, Ohio airport taxi-way by aligning the projected chopped laser-beam and the receiver unit along the straight edge of the taxi-way pavement. It was late at night when those initial tests were conducted and the sensitivity results were much better than we expected. The receiver could detect a vertical off-center displacement of the projected chopped laser-beam of about 3.25 mm (1/8 inch) over a distance of 240 m (800 ft) or more. We truly did not understand why or how, *at that moment*, it could be so sensitive to such small vertical movements over such a long range.

The laser-receiver amplifier circuit assembled by Control Industries is shown in **Fig. 9a.** Signal detection and sensitivity were amplified in this circuit via photo-multiplier components to boost the voltage from each row of phototubes. That also compensated for the lower laser light energy reception resulting from the "chopped" laser-beam effect (i.e., the on-off reception of the laser light versus a constant laser light source). The corresponding depth & grade-control circuit box shown in **Fig. 9b** filtered the "chopped" output signals from the laser receiver unit circuit and activated the proper electrical relay switches to operate solenoid valves in the hydraulic system for adjusting the plow hitch position upward or downward as needed for depth and grade control.

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4 - The audio sound system to assist pilots align with a runway during low-visibility landings was based on two electrical signal generators, one at 90 Hz and the other at 150 Hz, that were located along opposite sides of the airport runway. The electrical signals were detected by instrumentation in the approaching plane preparing to land, and the signals were filtered into the 90 and 150 Hz frequencies and converted to audio sounds routed to ear-plug speakers in the pilot's left and right ears. The sound frequency heard by the pilot would indicate to him when he was approaching the runway on the low frequency side (90 Hz) or the high frequency side (150 Hz), and if the sound he heard was a steady "**hum**" it was an indication he was lined up with the center-line of the runway and could proceed to land.

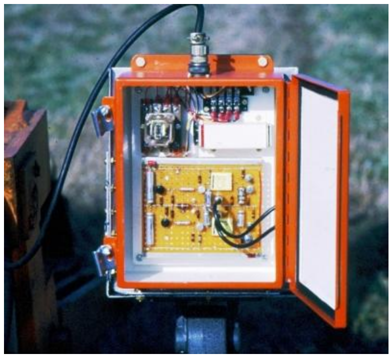

Fig. 9a – Laser-Beam Receiver Amplifier Circuit

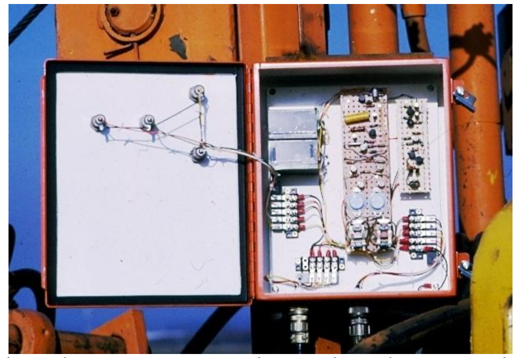

Fig. 9b – Laser-Receiver Signal Processing Circuit for Depth & Grade Control

Initial Physical Testing of the Laser-Beam Feedback Control System Components when Mounted on the Caterpillar Tractor and attached Drainage Plow.

While the Caterpillar Tractor with the Drainage Plow attached was still loaded on the low-boy trailer and parked at the curb outside the OSU Agricultural Engineering Dept. building (**Fig. 10a & Fig. 10b**), all the feedback control system components were mounted on the tractor and plow. The system components included**:** The complete hydraulic and electrical solenoid valve system to control hitch height and plowing depth; the laser-beam receiver connected to the electronic feedback control circuits as shown in Figs. 9a and 9b; plus the electrical power on-off controls near the tractor operator's seat. The laser-beam projection unit, that was tripod-mounted, was positioned at a distance of more than 50 m (>160 ft.) away aligned along the car parking curb. The initial testing of the Laser-Beam Automatic Depth and Grade-Control System in the setup shown in Figs. 10a and 10b confirmed that the total feedback control system **worked!!** When minor vertical movements [**+/-** 3 to 5 mm (**+/-** 1/8 to 3/16 in.)] were manually made of the Laser-Beam Receiver from the center-line of the projected Laser-Beam, the electronic-hydraulic feedback control system quickly returned the Receiver back such that the Laser-Beam again was centered onto the receiver photo-tubes. At this point it was decided we were ready for initial field testing and some special purpose laboratory calibration and testing monitored with an Analog Computer. In addition to some specific field tests we wanted to conduct**,** the Analog Computer approach provided a means to calibrate the control system response to specific inputs and to conduct some simulation studies where different ground surfaces changes could be input.

Fig. 10a – Laser-Beam Projector at 50 m away.

Fig. 10b – Laser-Beam Received on Plow Beam.

Analog Computer Simulation to Determine Optimum Laser-Receiver Default Settings.

Following the initial curb side testing of the laser-receiver and the associated control circuits with the Caterpillar tractor and attached drainage plow loaded on a low-boy trailer (as shown in Fig. 10b), a preliminary simulation study was conducted on an Analog Computer to evaluate various parameter settings for the laser-beam automatic control system. For example, a key parameter was the control Dead-Zone (gap between the upper and lower rows of photo-tubes) and its relation to the laser receiver's sensitivity to off-center movements of the projected chopped laser-beam. The physical laser-receiver circuit and the depth & grade control circuit boxes (orange boxes) were used in the electronic circuit of the Analog Computer as shown in Fig. 11.

The configuration of the Analog Computer simulation equipment shown in Fig. 11 (a fully expanded EAI TR-48 analog computer; Electronics Associates, Inc.) was programmed to include the actual (physical) laser-receiver and signal processing & control activation circuits. That is, the laser-beam depth & grade-control system circuit-box electronics were not simulated in the analog computer program. The analog computer did not have sufficient logic capacity to simulate the controller components. There was also concern that the nonlinear characteristics of the available logic (dead-zone, hysteresis, etc.) would not match those of the physical controller unit. The analog computer program (circuit) did simulate, however, the "chopped" output of the phototubes in response to the simulated positions of the drain plow hitch and associated laser-receiver as inputs to the physical laser-receiver circuit box follower amplifiers. The variation in voltage outputs from the top and bottom rows of phototubes in the receiver vs. vertical (**+/-**) displacement of the Receiver Unit from the centerline of the chopped Laser-Beam (determined by lab testing of the physical Receiver with the projected "chopped" Laser-Beam) are shown graphically in Fig. 12.

Fig. 11 – Analog Computer Simulation setup to evaluate the Laser-Beam Depth & Grade-Control Circuits. Observers: (L to R)[5]; C. Wadleigh, W. Raney, R. Stewart, G. Schwab, with J. Fouss; (missing from the photo is M. Hamdy, an adviser to Fouss on the analog simulation project.)

The dimension "**S**" shown in Fig. 12 is the vertical distance between the top and bottom rows of

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[5] Dr. Wadleigh, Director, Soil and Water Conservation Research Div. (SWC), ARS, USDA, Beltsville, MD; Dr. Raney, Chief Soil Scientist, SWC, ARS, Beltsville; Dr. Stewart, Chairman, Agricultural Engineering Dept., OSU; Dr. Schwab, Prof. (*my major professor*), Agricultural Engineering, OSU; and Dr. Hamdy (not shown), Prof. in AE.

phototubes in the Receiver unit. For the prototype Laser-Receiver unit the outputs of the top and bottom rows of phototubes were not identical (Fig. 12) and the geometrical center between the top and bottom rows of phototubes, S/2, deviated a distance **δ** from its null central point (where the outputs of the top and bottom rows of phototubes were equal). The difference in the outputs from the top and bottom rows of phototubes, which the diode bridge in the Controller unit detected, was essentially linear and extremely sensitive to very small vertical movements of the Receiver unit relative to the center of the projected Laser-Beam[6] over a relatively large range of motion above and below the null position. The feedback control activated the hydraulics to move the receiver position to coincide with the projected laser-beam center-line to maintain depth and grade for the drain being installed. The speed of the hydraulic response had to be fast enough for the ground speed of the drainage plow to ensure good depth and grade-control.

The circuit diagrams for the Receiver and Controller boxes are shown in **Fig. 13.** These components were not simulated in the analog computer program, but were connected into the program circuits as physical devices (Orange boxes shown in Fig. 11). Thus, the simulations conducted by the Analog Computer setup were in "**real-time**" and not in time-delay or time-accelerated modes as possible and commonly used in analog computer simulation studies.

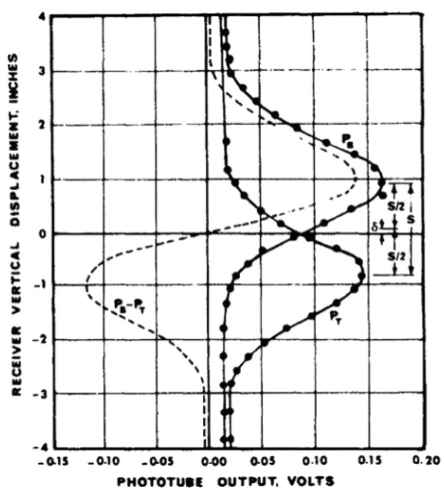

Fig. 12 – Variation in Top/Bottom Rows of Phototubes with Receiver Displacement.

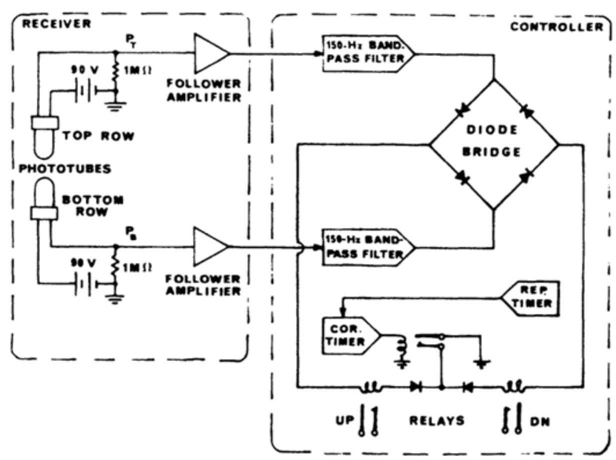

Fig. 13 – Laser-Beam Receiver and Feedback Controller Circuit Diagrams (*not simulated*).

For the preliminary analog computer simulation, the automated system's performance was based on an evaluation of the accuracy that the plow hitch point was maintained near a straight-line forward motion path with minimum upward & downward fluctuations; i.e., closely parallel to the desired drain gradient. The plowing depth was ***assumed*** to follow the hitch elevation changes with

6 This Receiver response characteristic (shown graphically in Fig. 12) explained for us why we were able to observe the very sensitive response of the prototype Laser-Beam Receiver Unit on the initial night-time tests conducted at the Control Industries firm in Urbana, Ohio. That is, as the receiver moved off-center (off-null) of the laser-beam a very small distance, the very rapid decrease in laser light received by one row of phototubes and the corresponding very rapid increase in laser light received by the other row, quickly created the magnified electrical unbalance that initiated a feedback correction for the vertical position of the laser-receiver. That unbalance was amplified by the Gaussian wave distribution of the projected laser-beam across its diameter, with the brightest intensity at the center of the beam.

a time lag. That assumption implied that if the fluctuations of the hitch point position were not large in magnitude or long in time-duration from the straight-line parallel to the desired gradient, the corresponding variations in plowing depth would be very small. In an advanced simulation study (conducted later for my Ph.D. research), the non-linear dynamics of the drainage plow operating depth in response to changes in soil forces on the plow blade and to upward & downward control of the plow hitch point by the Automatic Laser-Beam Control System were modeled and included in the simulation program (circuit). That advanced simulation study more fully evaluated the accuracy of depth and grade control for the plowing depth (not just the plow hitch point), and is discussed in a following section of this story.

It is beyond the scope of the text and figures included in the main body of this "***story***" to cover the different analog computer programs and circuit diagrams used in the design and evaluation studies to develop the Laser-Beam Automatic Depth and Grade-Control System. Only highlights are given within the main body of this story. However, included in the following Appendices are full details on procedures and results including tables, figures, illustrations, and discussion for the interested reader: **(a)** Appendix **IV**; My full Ph.D. dissertation[7] on the attached CD in PDF format that provides documentation of the research conducted; and **(b)** Appendix **V**; A reprint of the published technical paper on the preliminary simulation study (*publication citation given in footnote*[8]). The dissertation includes full field testing and analog computer simulation procedures and programs (circuit diagrams) used in developing and evaluating the Laser-Beam Automatic Depth and Grade-Control System for the floating-beam type drainage plow.

The reader is referred to the Appendix V publication reprint [8] for a full discussion of the preliminary simulation results on the accuracy that the hitch point elevation was controlled by the Laser-Beam Automatic Depth & Grade-Control System. The simulated laser-beam receiver was positioned above the hitch point to record the vertical feedback motion of the hitch during the simulations. Only a few major observations are covered here. The simulation results were able to illustrate the importance of setting the response velocity for the hydraulic cylinder fast enough for adjusting the vertical position (elevation) of the plow hitch point in reaction to control signals from the Laser-Beam System. Examples to show this relationship are given in **Figs. 14** and **15** for cylinder velocities of 2.5 and 3.0 in./sec. (ips), respectively. This can be seen by comparing the simulation results in Figs.14 & 15 that show the higher cylinder speed improved control system accuracy in maintaining the hitch position near the zero elevation. This was found true for several types (shapes) of simulated ground surface inputs considered in the study. For the slower cylinder speed, the hitch position did not "overshoot" the zero elevation with each corrective motion and was either above or below it for prolonged distances of forward travel. At the 3.0 ips cylinder speed the simulated hitch point position was maintained within about $\pm$ 0.75 in. of the zero elevation. This agreed well with later initial field tests where the auto-control system was observed to maintain the hitch within $\pm$ 1.0 in. of the zero elevation for several ground surface conditions.

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[7] Fouss, James L. 1971. Dynamic Response of Automatically Controlled Mole-Drain Plow. Unpublished Ph.D. Dissertation, Department of Agricultural Engineering, The Ohio State University, Columbus, OH; 133 pp.

[8] Fouss, J. L. and M. Y. Hamdy. 1972. Simulation of a Laser Beam Automatic Depth Control. Transactions of the ASAE, 15(4): 692-695. [*This paper received an Honorable Mention by ASAE for excellence in technical reporting.*]

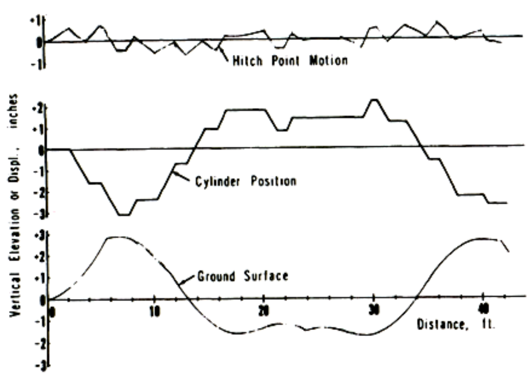

Fig. 14. Simulation results for hydraulic cylinder velocity of 2.5 in./sec.

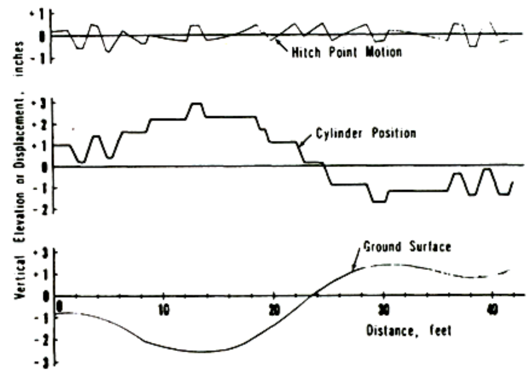

Fig. 15. Simulation results for hydraulic cylinder velocity of 3.0 in./sec.

Two additional summary comments are important here. The simulation results and <u>initial</u> field testing revealed that an ***on-off*** type of automatic control mode, even with a narrow dead-zone (e.g., about ± 1/16 in.), provided good control of the hitch point position, when the hydraulic cylinder response speed was set high enough to cause the control system to "hunt' up & down about the center of the projected laser-beam. For the drainage plow, a "hunting" cycle frequency somewhat below 1.0 Hz and amplitude range of 1.0 in. (i.e., ± 0.5 in. measured at the hitch point) provided a good compromise of sensitivity and stability over several types of ground surfaces.

One major highlight of note is the value and advantages of such simulation studies for analyzing and adjusting the automated control system. To accomplish such analyses and/or adjustments using field testing alone would have been difficult, expensive, and time consuming because of random variation in field conditions and numerous combinations of system operational parameters and adjustments. Simulations permitted use of the same *test* ground profile repeatedly.

Research Plow field tests to determine responses in plowing depth to changes in hitch height:

Before more <u>advanced</u> simulations could be conducted for the drainage plow equipped with the Laser-Beam Depth and Grade-Control System, some field testing of the plow dynamic response to changes in the plow hitch height were required. Field testing with the ARS research drainage plow was conducted to determine the dynamic response delay coefficients (or mathematical damping coefficient) under field operating conditions for defined height changes in the plow hitch point relative to the ground surface during forward travel. Step and ramp-step changes in the height of the plow hitch point were used for these tests, and changes in hitch position were made via <u>manual control</u> by the tractor operator. The plow was equipped with the prototype laser-beam depth and grade-control system (as shown in Fig. 16), *but the laser-beam system was not used for these early field tests*. Results of the field tests (<u>data points</u>) are shown in Figs. 17, 18, and 19 graphs, and compared **with an analog computer simulated change (line graph) in plowing depth for the same change in hitch height** (*simulation procedure are discussed later in this story, and fully described on pages 28-31 in the Ph.D. dissertation included in Appendix IV*). The field data points shown in the graphs were the measured depth of plowing at 5-ft. intervals for 20-ft. of travel after the hitch point height was changed, and at 10-ft. intervals thereafter when the rate of change of the plowing depth was less.

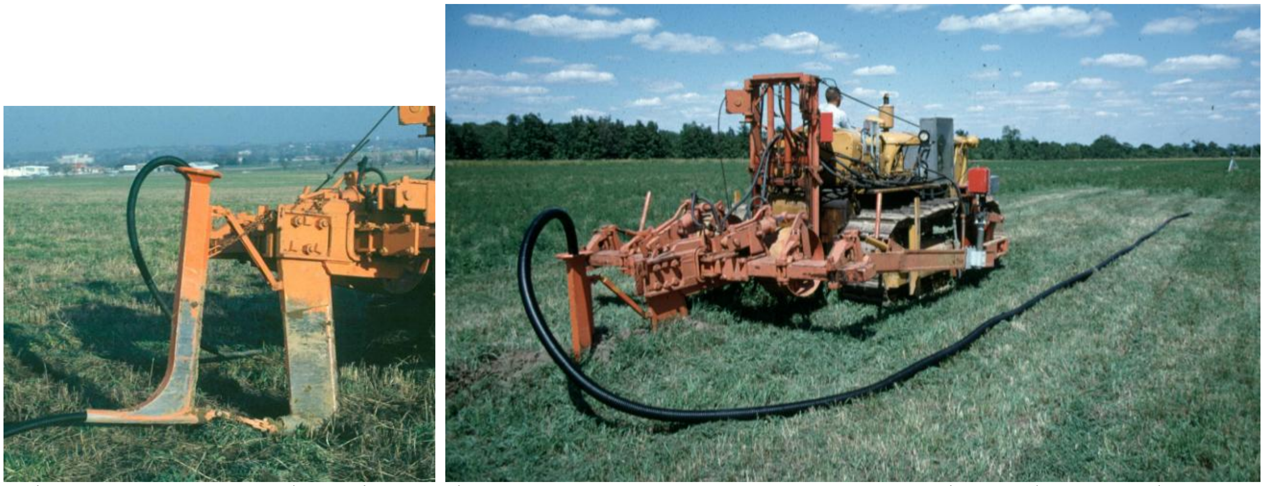

Fig. 16. ARS Research Drainage Plow & Prototype Laser-Beam Automatic Grade-Control System

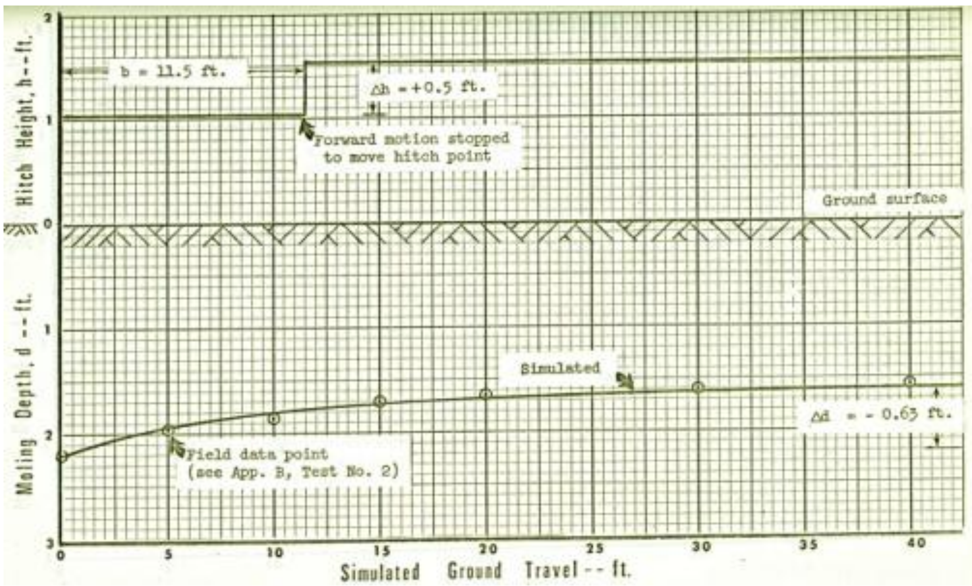

Fig. 17. Comparison of actual and simulated drainage plow operating depth to an 'upward vertical-step' movement of the plow hitch point.

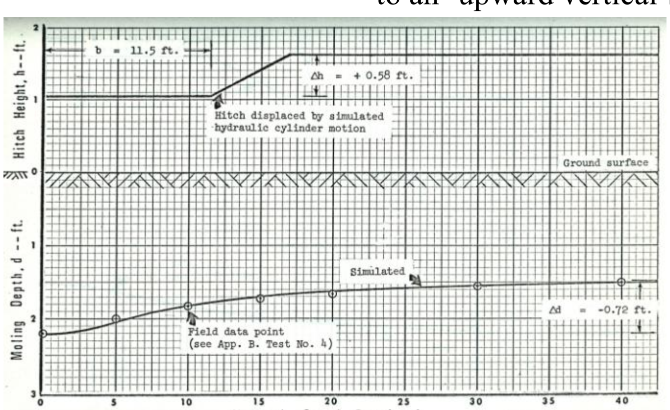

Fig. 18. Comparison of actual and simulated drainage plow operating depth to an 'upward ramp-step' movement of the plow hitch point.

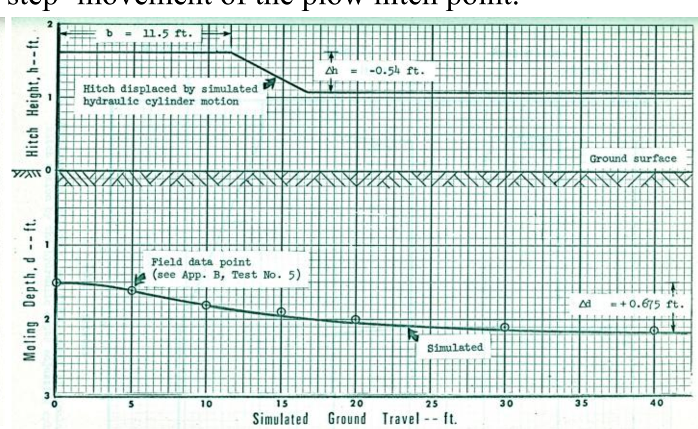

Fig. 19. Comparison of actual and simulated drainage plow operating depth to a 'downward ramp-step' movement of the plot hitch point.

Some early preliminary grade-control field tests were conducted with the ARS Research Drainage Plow as shown in Fig. 16 equipped with the research prototype Laser-Beam Automatic Depth and Grade-Control System. However, the field data collected from those early tests was misplaced or lost in my transfers in the early 1970's between research offices in Columbus, OH (The Ohio State University) and the ARS Soil and Water Conservation Research Center in Florence, SC. Also lost in those data sets were the positions that the laser-beam receiver unit was mounted on the long floating-beam of the drainage plow for the tests. It is recalled, however, that all the best positions for the receiver-unit were much closer to the plow blade than to the hitch point. It was reported in some of technical papers published on the testing of the research prototype Laser-Beam Automatic Depth and Grade-Control System that the laser-beam receiver unit could be maintained in an approximate range of ± 0.4- to ± 0.5-in. of the laser-beam centerline that was projected at the design grade of the drain. That is, the auto-control circuit would cause the receiver unit to rapidly "hunt" up & down in the range of ± 0.4- to ± 0.5-in. As I recall, we did hesitate during those early days in stating any field test results on just how accurate the drain pipe was installed in the soil, because there were so many variables involved. I will note here that field-trial accuracy tests were conducted later with the ARS Big Red Draintube Plow (*as it was called*) to document the accuracy that the drainpipe could be "plowed-in" to the design depth and grade with the Laserplane Grade-Control System mounted on the large floating-beam plow. Field test results were published in the Drainage Contractor magazine (*details given in a following section*).

Simulating Floating-Beam Plow depth responses following changes in plow hitch height:

As a part of my Ph.D. research, a mathematical model was developed for the floating-beam type drainage plow to describe (predict) the dynamic responses in the plowing depth as a function of changes in the height of the plow hitch point relative to the ground surface during forward travel. That model was needed to determine if the floating-beam drainage plow operating depth responses to vertical-step and ramp-step changes in hitch height could be theoretically predicted to match the actual field test response data plotted in the graphs of Figs. 17, 18, and 19. Full details of the mathematical model development procedures are presented in my *Ph.D. dissertation, Chp. II, pp. 22-28, included in Appendix IV*; only final equations are presented here within the story text. A free-body diagram of the floating-beam plow model is shown in Fig. 20. The dimensional and motion parameter variable names are shown in this Figure. The resulting mathematical model for describing the plow's dynamic response to hitch height (position) changes is represented by the set of three Eqs. [1], [2], and [3] shown on the next page.

Since Equation [3] was non-linear, the usual methods of mathematically quantifying the floating-beam plow's dynamic response parameters could not be applied. Therefore, an analog computer program (circuit) was developed (*see Fig. 11, p. 30 in Ph.D. dissertation; App. IV*) to solve the non-linear equations that described the plow's response to simulated changes in the hitch height. This phase of the simulation studies conducted was for the plow's response only to manual changes in the plow hitch height (i.e., *simulation **line** shown in the graphs of Figs. 17, 18, and 19*). The simulation program (circuit) for this phase of the study did not have components to simulate the laser-beam depth and grade-control system. The model and analog simulation program for the floating-beam drainage plow was more complex than the one used for the preliminary simulation discussed earlier, because it included components and features that represented the soil forces (draft) on the plow blade as a function of plowing depth. Details of the mathematical development

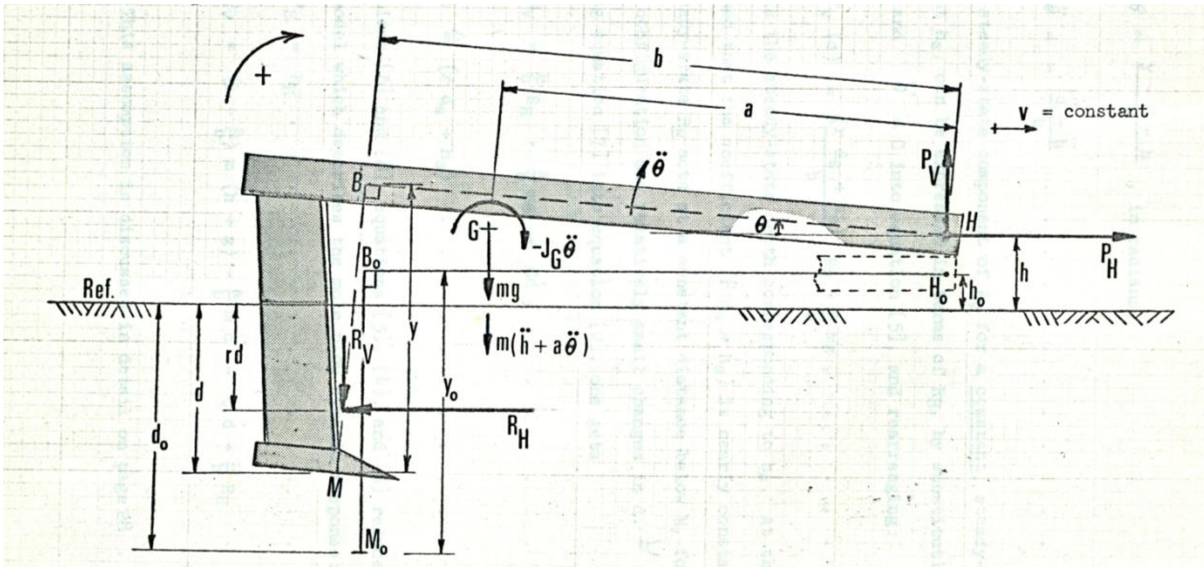

Fig. 20. Free-Body Diagram of Floating-Beam Drainage Plow for Dynamic Analysis

$$P_H = R_H \quad \ldots\ldots \quad [1]$$

$$P_V = \left(1 - \frac{a}{b}\right) m \left(\ddot{h} + g\right) - \frac{a}{b} m \ddot{d} - C \dot{d} + \frac{n}{b} R_H \quad \ldots \quad [2]$$

$$\ddot{d} + \left(\frac{b^2 C}{J_H}\right) \dot{d} + \left(\frac{b(rd + h - n)}{J_H}\right) R_H = \left(\frac{a\,b\,m}{J_H} - 1\right) \ddot{h} \,, \quad [3]$$

where, $$J_H \triangleq J_G + a^2 m \quad \ldots\ldots$$

for the soil draft relationship on the drainage plow blade are given in *Appendix C, pp. 110-127, of my Ph.D. dissertation in Appendix IV* of this story. The draft relationship on the plow blade was found to be a Power Function of the form, $\mathbf{P_H = K^d}$, again another non-linear formula. The soil resistance (draft) relationship for the research drainage plow was set on a variable function generator in the analog computer circuit. A graph of the draft force (P_H) vs. plowing depth (d) programmed into the variable function generator for this advanced simulation is shown in *Appendix C, Fig. 63, p. 127, of my Ph.D. dissertation in Appendix IV*. The excitation for the analog simulation circuit was the hitch acceleration (generated by the simulated hydraulic cylinder that controlled the hitch height) and/or the initial displacement of the hitch point (i.e., vertical-step movement to reposition the hitch when simulated travel of the plow was temporarily stopped).

The results of simulations obtained for this phase of the project were compared with the actual field measured changes in plowing depth for defined changes in the plow hitch height as illustrated in Figs. 17, 18, and 19. In conducting the analog simulation runs a *trial-and-error* procedure was used to adjust the operational coefficients and parameters, such as the damping coefficient (C) which affected the plow's response to relatively rapid changes in the plow hitch height during forward motion. The trial and error parameter adjustment procedure was successfully used to modify the analog computer simulation results such that they closely matched the field test results (Figs. 17, 18, and 19). The field test results as well as the analog simulation results for changes in plowing depth that occurred in response to on-the-move adjustments in hitch height showed the following: (1) The plow could penetrate to a greater depth faster (i.e., in a shorter distance of forward travel) than it could decrease in operating depth; and (2) The speed of response for changes in plowing depth increased with increasing plowing depth.

I will note here that a few years after the analog computer simulations made for my Ph.D. research, a method was developed to simulate the analog computer processes on a digital computer. However, the early digital simulation method in the 1970s did not have the capability to simulate the complexity of the plow dynamics as completely as the analog computer technology.

Nonlinear Response of Drainage Plow Operating Depth to Changes in Plow Hitch Height:

Because the drainage plow operated in a slightly nonlinear response to changes in the plow hitch height during forward motion, it was not possible to install a drainpipe with a given gradient by controlling the hitch point on a path that followed a line parallel to the desired drain grade. The simulation results that illustrate this are given in **Fig. 21** (this simulation was for the research drainage plow configuration). The governing factor in the mathematical model is the **r**-term in Eq. [3] where changing the hitch height is the method for controlling plowing depth. {The term **r** is the fraction of the plow operating depth where the soil resistance force **R** acts on the plow blade}.

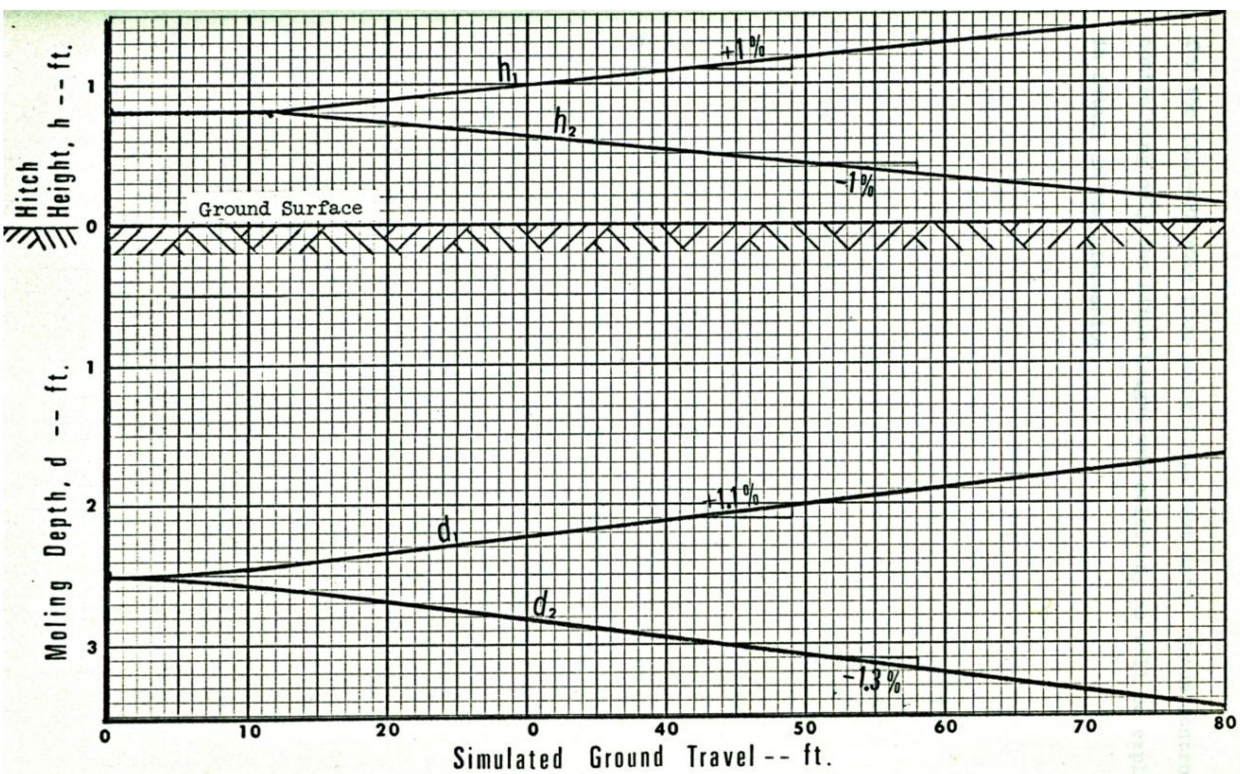

Fig. 21. Simulated drainage plow response for level land where the hitch height varied directly proportional to desired uniform drain grade of = +1% and -1%.

An alternative method could have been implemented to control plowing depth by changing the angle between the plow beam and the plow blade, which in effect would have been a change in the **n**-term in Eq. [3] while the height **h** of the hitch relative to the ground surface was held constant. {The term **n** is the distance below the plow hitch point **H** where the soil resistance force R acts on the plow blade}. Also, simultaneous control of both hitch height and the blade-to-beam angle (that is, both **h** and **n** in Eq. [3]), would have been a possible alternative method to obtain the desired drain gradient. However, these latter two concepts would have required nonlinear control of the blade-to-beam angle in order to obtain an approximate linear relationship between hitch height and plowing depth. Depth & grade control selected for the drainage plow in this project was via control of the hitch height using a long-beam type plow (*which was also slightly non-linear*).

"Hinged" Plow-Beam Configuration:

A related plow beam and hitch point configuration was evaluated in the Ph.D. study because some drainage plows known about in research projects (in England, Canada, and Europe) used the hinged-beam design.[9] The hinged-beam design feature was used to control plowing depth while the hitch point on the tractor was at a constant height above the ground. The mole plow (shown in Fig. 2) used to install the plastic-lined mole drains in the early phases of the ARS research project had a hinged-beam. The hinged-beam linkage on that mole plow is kinematically illustrated in *Fig. 58, p. 116, of the Ph.D. dissertation in Appendix IV*. This figure illustrates that the plow blade is moved closer to, or farther back from, the forward moving pulling tractor as the hinge is hydraulically adjusted to change plowing depth. Such relative motion of the plow blade with respect to the constant forward speed of the pulling tractor causes the plow blade to accelerate in forward motion as the front of the plow beam is raised at the hinge, or the plow blade tends to temporarily stop forward motion as the front of the plow beam is lowered at the hinge. This type of movement of the plow blade relative to the pulling tractor causes short-term surges or relaxation in draft power required to pull the plow. That is, an increase in draft occurs when the beam in raised. and a nearly zero draft force exists when the blade temporarily stops as the plow beam is lowered.

"Virtual" Plow Hitch Design:

Another plow hitch configuration adopted for a few early experimental plows, especially in England and Canada, was the "**virtual**" hitch design, patterned somewhat after the 3-point hitch design developed for the Ferguson farm tractor.[10] The floating, or hydraulically controlled 3-point linkage that connected the plow blade to the back of the pulling tractor, created a "**virtual**" hitch point at some distance in front of the tractor. The hydraulics connected to the 3-point linkage could move the virtual hitch upward or downward to control depth of grade at the plow blade. When this type plow was equipped with a laser-receiver unit, the receiver-unit was mounted on a short cantilever arm that extended forward from the plow blade. This virtual hitch configuration was popular on several models of drainage plows that became available throughout the world by the mid- to late-1970's and into the early 1980's. Some additional details on several different types of plows are briefly reviewed in a related story from this ARS research project covered in the "*Story behind the Story on the Development of the ARS Big Red Draintube Plow with Laserplane Automatic Grade-Control System*", by James L. Fouss. The reader is referred to that story for

[9] An early German manufactured drainage plow by Hoes, available in the 1970's, also used the hinged-beam design.

[10] Harry Ferguson patented the three-point linkage for agricultural tractors in Britain in 1926. The Badger Plow in England, and the Krac and Steiger plows in Canada had the 3-point hitch type attachments.

additional details. The plow story was the final report written about the ARS-USDA R&D project to develop new subsurface drainage materials and installation methods during the 1955-1975 Era.

Advanced Analog Computer Simulation of Long Floating-Beam Drainage Plow equipped with a Laser-Beam (or Laserplane) Automatic Depth & Grade-Control System:

Following the successful simulation showing the dynamic response of the floating-beam drainage plow to changes in the plow hitch height during forward motion, the next step was to simulate the drainage plow operational response under the automatic control of the laser-beam (or Laserplane) depth and grade-control system. Figure 5 (shown earlier in this story) illustrates in a Block Diagram the total system simulated and discussed in this section. **The primary purpose of simulating the dynamic performance of the total Plow-Laser-Hydraulic system was to: Develop an analysis & evaluation method to determine the optimum position for mounting the laser-beam (or Laserplane) receiver-unit on the floating-beam of the plow to hydraulically adjust the plow hitch height for the most accurate feedback control of plowing depth and drain grade.** This simulation approach reduced the need for extensive field testing to evaluate grade-control accuracy of various trial mounting positions for the laser-beam receiver-unit on the plow frame. Some follow-up field testing was required, however, to confirm the "optimum" mounting position for the receiver-unit on the drainage plow beam. Those confirming field test procedures and results are covered in a following section of this story.

To improve the accuracy of the total system analysis and computer simulation, the input and output variables used in the mathematical model for the drainage plow were defined as perturbation quantities about some steady-state operating level. That is, the plow hitch height (h) and plowing depth (d) were defined as follows:

$$h = h_s + h_p \text{ ---------- } [4]$$

and

$$d = d_s + d_p \text{ ---------- } [5]$$

where **hs** and **ds** are the steady-state hitch height and plowing depth, respectively, and **hp** and **dp** are the perturbation variables of interest in the simulation.

The simulations conducted for the Ph.D. research with the originally derived drainage plow model (Eq. 3) revealed that typical plow hitch velocity (upward or downward) by actions of the hydraulic adjusting cylinder did not have a significant dynamic effect on plowing depth. This observation was also confirmed by field tests with the research drainage plow. Therefore, substituting Eqs. [4] and [5] into the Eq. [3] of the original drainage plow model, and assuming

$\ddot{h} = 0$ in [Eq. 3], the revised and simplified drainage plow dynamic model became:

$$\ddot{d}_p = -\left(\frac{b^2 C}{J_H}\right) \dot{d}_p - \left(\frac{b}{J_H}\right) (r\, d_p + h_p)\, R_H \text{ ---------- } [6]$$

Again where, $J_H \triangleq J_G + a^2 m$.

The enhanced analog computer circuit developed for this total system simulation is shown in *Fig. 25, p. 59, of the Ph.D. dissertation in Appendix IV*. It is noted that a "Bang-Bang" type of Receiver-Controller was used in the total system analog circuit configuration. A "Bang-Bang" receiver-controller does not have a "dead-zone" and thus for most systems the controller corrective actions continuously limit-cycles (or "hunts") for all stable systems. Three other types of receiver-controller units (*not shown here*) were considered in the simulations conducted for the Ph.D. research, as follows: (a) Dead-Zone on-off; (b) Digital on-off; and (c) Proportional. All four types of receiver-controller units are illustrated in analog computer circuit format in *Figs. 25, 26, 27, and 28 on pages 59-62 in the Ph.D. dissertation*, and discussed in detail in the *Ph.D. dissertation on pages 57-82 along with graphical results of simulation runs for each type*.

The analog computer program was configured (as illustrated in *Fig. 25, p. 59, of the Ph.D. dissertation in Appendix IV*) to solve Eq. [6] for simulation of the total **plow-laser-hydraulics** system. Only example results are shown here to illustrate and summarize the primary conclusions made from the many different simulations run with the advanced analog computer circuit. If the reader is interested, the results of the entire series of different simulations run are given and discussed in the *Ph.D. dissertation on pp. 57-82, included in Appendix IV*.

For the example simulation results shown and discussed here, the purpose was to evaluate the ability of the automatic laser-beam depth and grade control system to install a subsurface drain to specified depth and grade where the average land slope was zero. Simulation runs were made for three mounting positions of the laser-beam receiver-unit on the plow beam, at X = 4-, 7-, and 10-ft. behind the hitch point on the 11.5-ft. long floating-beam of the research drainage plow. The simulated laser-beam input reference grade for the drain was set to uniformly vary (rise) by 0.5-ft. per 100-ft. of simulated travel; that is, at 0.5% slope. The simulated results for the horizontal ground surface and X = 4-, 7-, and 10-ft. laser-receiver positions, are given in **Fig. 22**. It can be seen that a laser-receiver mounting position of X = 10-ft. maintained the drain channel ($\mathbf{d_p}$) closest to the desired 0.5% grade-line. For the X = 7-ft. position, a gradual drift of the drain channel (d_p) above the 0.5% grade-line occurred; and if the simulation had continued for 100-ft. or more the total error in drain-line grade would probably have exceeded a 0.05-ft. (0.6-in.) considered permissible displacement of the drain channel from the design grade-line in the simulation study.

In subsequent computer runs for X = 7- and 10-ft., a saw-tooth simulated ground surface profile was imposed (average ground slope remained at **0%**), and again the laser-receiver position at X = 10-ft. provided better grade control (**Fig. 23**). The variable, $\mathbf{Z_p}$ shown in Figs. 22 and 23, represents the small upward & downward movement of the laser-beam receiver-unit to maintain the projected laser-beam centered vertically on the receiver-unit mounted on the plow beam.

Expansion of ARS Research Project Plan for Advanced Laser Grade-Control System:

With the success of the original prototype laser-beam grade-control system, the ARS project was expanded to conduct two additional phases. Those involved creating a laser-beam or laser-plane reference above the field to be drained so that the laser transmitter did not need to be moved and set up and aligned with each drainline. Two approaches were considered, one was to optically spread the laser-beam to project a **"pie-slice" laser-plane**, and the other was to rotate the laser-beam on its tripod mount, much like a lighthouse beacon, to create a **circular laser-plane reference** over a large area of the field. The optical laser pie-slice was field tested, but the distance the laser-controlled plow could operate from the laser transmitter was too limited for practical applications. The circular laser-plane phase was not developed by ARS because our team learned that concurrent research and development work was underway in industry (details below).

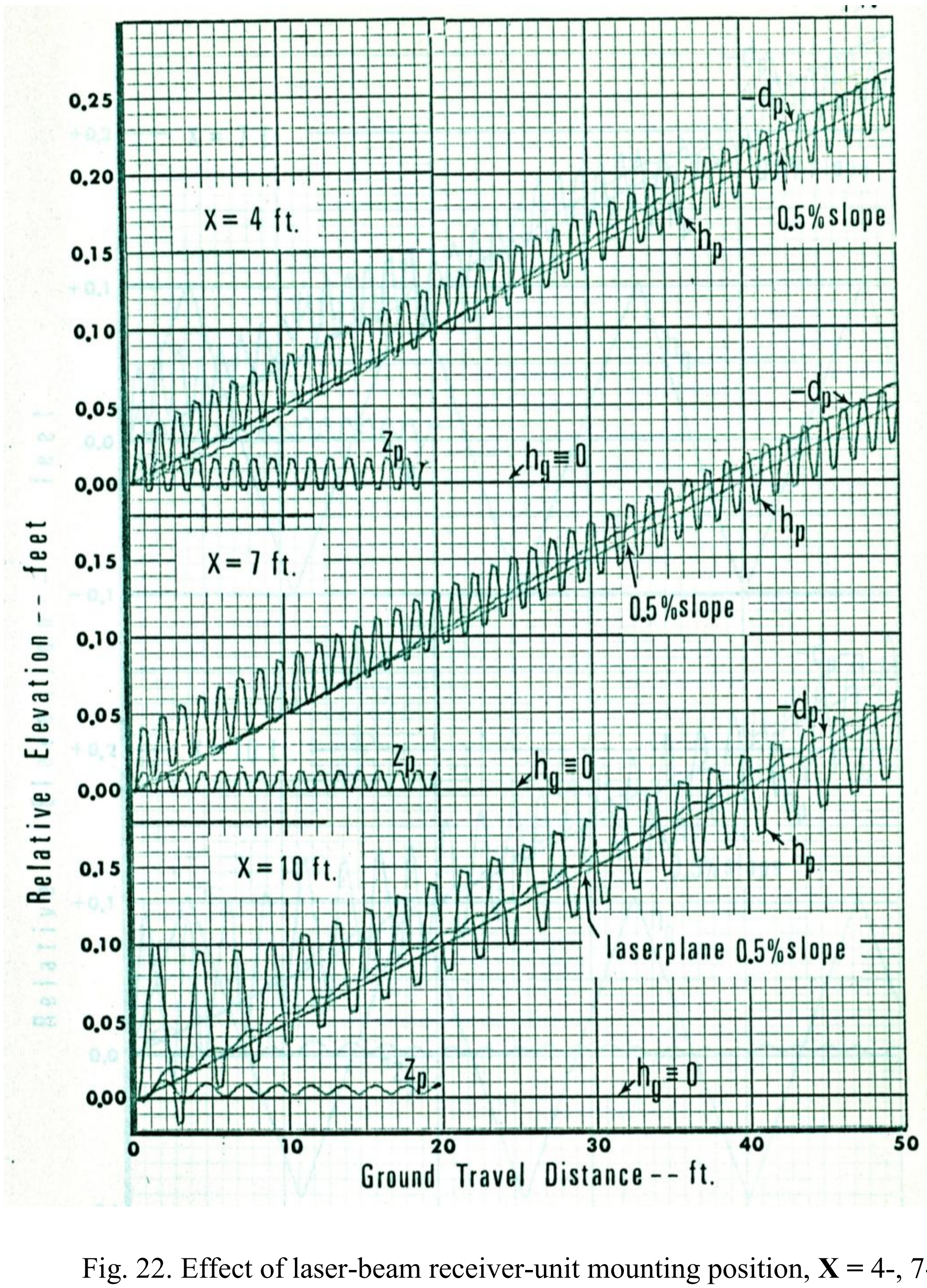

Fig. 22. Effect of laser-beam receiver-unit mounting position, **X** = 4-, 7-, 10-ft., on the floating-beam of the research drainage plow; a "bang-bang" control mode was used, and the laser-beam reference grade was set at 0.5**%**. The simulated ground surface was horizontal. (**Z_p** is motion of receiver-unit).

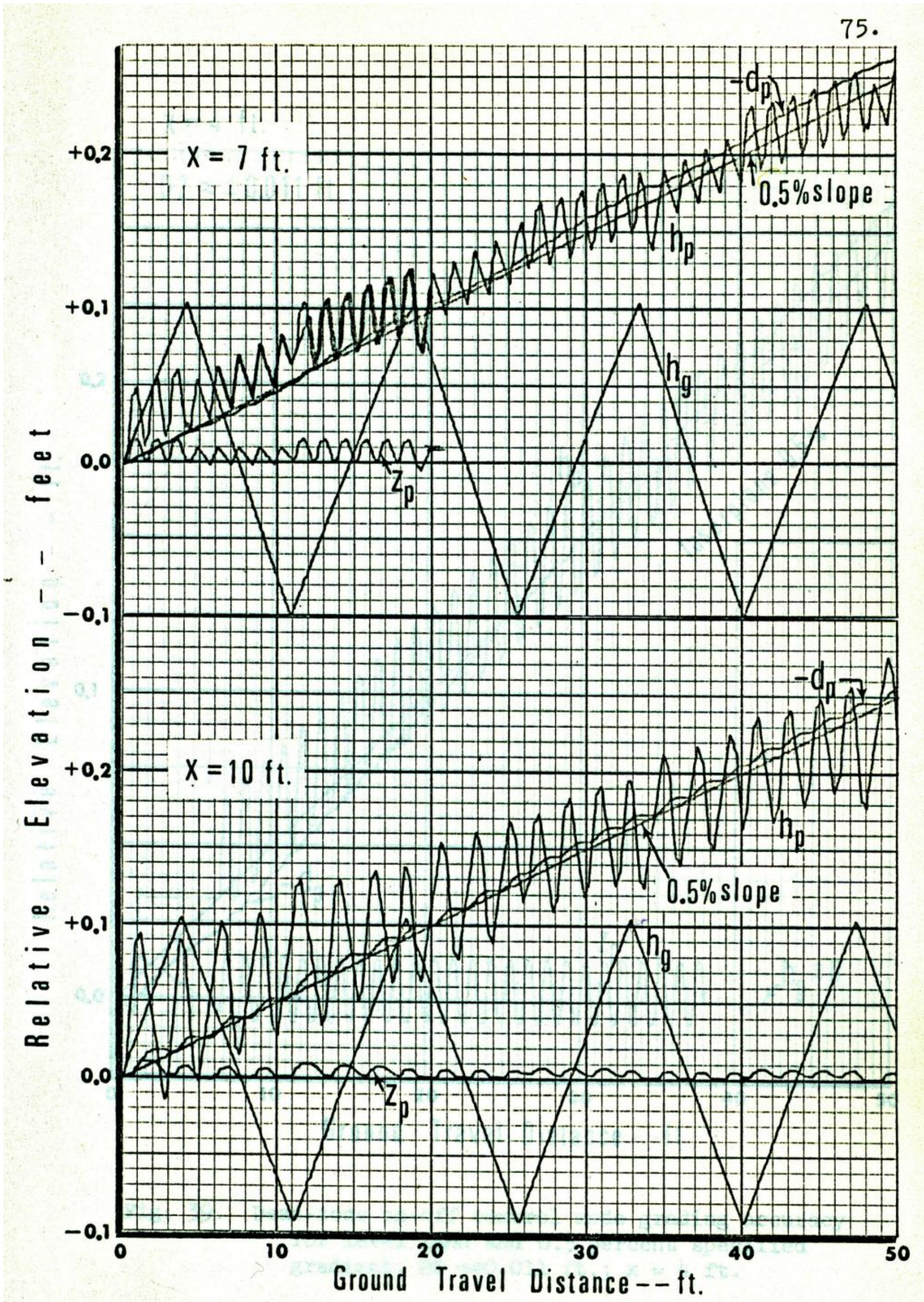

Fig. 23. Grade-control accuracy for two laser-beam receiver mounting positions on the plow beam and with a "bang-bang" control mode at a specified drain grade of 0**.**5**%**. The simulated ground surface was a *"saw-tooth"* profile (the average land slope was **0%**). (**Z_p** is vertical motion of receiver-unit).

Concurrent Industry R & D:

Mr. Robert H. Studebaker, vice-president of Process Equipment Co., Tipp City, OH, began development of a laser control device for a motor grader in 1965. This application differed from that for the drainage plow in that it was not desirable to limit the grader to straight-line travel in a construction area, such as a roadway. Thus, he developed a laser-plane rather than a laser-line reference. The prototype laser-plane reference was obtained in an ingenious way by projecting an expanded and collimated laser-beam vertically onto a rotating prism. The prism deflected the laser-beam 90 degrees, thus generating a plane reference, much like a rotating light beacon at an airport. By proper adjustment to tilt the laser transmitter mountings on the tripod mounting, a laser-plane of any desired slope could be projected over an entire field. The laser receiver or detector system, which was mounted directly on the grader blade, consisted of a 30-cm-long array of solid-state silicon cells. These photo cells were covered with a narrow band-pass optical filter which allowed only the 6328 angstroms laser light to pass through it. The cells were grouped in five sets arranged vertically and indicated “high”, “high-slow”, “on-grade”, “low-slow”, and “low” feedback corrections needed. The transverse control of the grader blade was maintained with an electronic cross-slope level sensor system. Additionally, Mr. Studebaker developed a single photocell sensor as a laser-beam detector for a sliding attachment on a surveying rod; that was the beginning of the laser-plane surveying system in which one person could survey land.

Presentations/Meetings with Contractors, Industry Reps, & Farmers on Research Progress:

Our research team was not aware of the concurrent research and development discussed in the previous section until early in January 1967 when we had just completed the first presentation and demonstration of our research prototype laser-beam depth and grade-control system for use on a drainage plow or trenching machine. That first presentation & demo was given at a winter meeting of the Ohio Land Improvement Contractors of America (OLICA) held in Worthington, OH. Norm Fausey, Ted Teach, and Glenn Schwab assisted me in that first presentation & demonstration to the group of Ohio drainage contractors. The conference room at the motel where the meeting was held was packed with attending contractors, Agricultural Extension Agents, USDA-Soil Conservation Service (SCS) technicians {that was before SCS became the Natural Resources Conservation Service (NRCS)}, and drainage industry representatives. Just as we were completing our presentation & demonstration, Mr. Robert Studebaker, vice-president of Process Equipment Co., Tipp City, OH, arrived at the Ohio LICA meeting. He had heard about our presentation at the Ohio LICA meeting on a farm radio broadcast while driving from Dayton, OH to Columbus – he diverted his travels to Worthington, which lies just north of Columbus. The Agricultural Extension Service had arranged for that radio broadcast about our demonstration of the laser-beam grade-control system at the Ohio LICA meeting in Worthington.

Studebaker’s first question addressed to me was to ask how far we had gone in our system development project. I responded that we had installed the prototype system on a floating-beam drainage plow (to install corrugated plastic drain tubing) and it worked well putting the draintube close to the desired depth and grade in preliminary field tests. It was at that Ohio LICA meeting where Studebaker first met with Fouss and Teach and they reviewed progress and compared ideas. Studebaker reported to us that he had difficulty with his prototype system’s photo-cell receiver-unit in providing acceptable grade control accuracy for the motor grader. A short time after that first meeting in Worthington, OH, Studebaker and Teach entered into a business agreement to form the **Laserplane Corporation** at Dayton, OH. The concepts for laser-beam control that were developed and tested by ARS for subsurface drainage equipment, particularly as related to mounting position for the laser-beam receiver on the drainage machine, and mode of feedback control based on laser-beam signals detected by our prototype receiver-unit and electronically processed in the controller circuit, were adopted in principle (*I believe*) for use in Laserplane's first commercial version of their system.

The initial field trials and public demonstration of the first commercially available Laserplane grade-control system were conducted cooperatively with ARS researchers at the 1968 Ohio State Farm Science Review at the OSU Airport, Don Scott Field. Attending that Farm Science Review where a few thousand farmers and many contractors who viewed the Laserplane system's performance on a rubber-tired Speicher wheel-type tile trenching machine installing corrugated plastic drainage tubing (**Fig. 24**). A key ARS administrator, Dr. C.A. Van Doren, Chief of the Corn-Belt Branch, with headquarters in St. Paul, MN, also attended that first public field demonstration. Dr. Van Doren was the regional ARS administrator responsible for our ARS location at Columbus, OH (on The Ohio State University campus). It was ironic that plow-type drainage equipment, for which the laser-beam system was originally developed, was not yet commercially available in the USA or Canada. Even though the $10,000 cost of installing a Laserplane system on a trenching machine was nearly one-third the cost of the trencher itself**,** by the fall of 1969 and early 1970 most farmers in the Midwest were demanding that their drainage systems be installed with Laserplane controlled machines. Our team heard of reports that the number of Laserplane systems sold to drainage contractors with trenching machines in 1969 and 1970 was greater than for several years after that (especially in the Midwestern States of the U.S.).

Fig. 24. First public field demo of Laserplane Grade-Control system on a Drainage Trenching Machine at the Ohio State Farm Science Review, Fall of 1968.

Continued Talks and Presentations on ARS research:

Following the 1967 Ohio LICA meeting where the ARS developed prototype laser-beam depth and grade-control system for drainage equipment was presented with emphasis on its future potential use on plow-type drainage equipment for fast installation of corrugated plastic drainage tubing, the demands for me to give presentations and/or demonstrations increased quite dramatically. Beginning in 1967 I traveled extensively, and had many visitors to my office at Ohio State, and gave talks and presentations to individuals and groups interested in the research progress we were making with our research project to develop new drainage materials and methods of installation. During 1967 and early 1968 I gave more than 100 talks and presentations, and many of those presentations were to industry groups interested in getting into the manufacturing of the corrugated plastic drainage tubing that was rapidly becoming the standard drainage material used in the U.S. and Canada. Other groups had a primary interest in the plow-type drainage installation equipment, and some of the most interested equipment industry reps were from Canada. It is noteworthy that following the demonstration of the original Laserplane system on the trenching machine at the Ohio State Farm Science Review in the fall of 1968, the inquiries and demands from drainage contractors and industry reps increased more for the latest research information on our ARS project to develop the high-speed drainage plow for installing corrugated plastic drains.

The above described events occurred during the time that I was taking graduate school courses towards my Ph.D. degree. Because of the extensive travel, it was necessary for me to restrict my course load to only one course per school quarter (Ohio State was on a Quarter System, not Semesters). I was beginning to wonder if I would be able to complete my degree requirements within the 10-year time span permitted at Ohio State for receiving the Ph.D. My slow down in course scheduling also concerned the ARS administrators in Beltsville, MD. I can recall vividly a phone call from Mr. Edminster (ARS Administrator) when he asked me about when I expected to receive my Ph.D. degree; I recall telling him that I had to slow down taking courses to handle all the requests for talks and presentations around the country. He then asked what did I need to be able to speed things up on my schooling, and I replied that I needed to stay home and not travel so much for all the presentations that were being requested. He firmly stated for me to do that, stay home, so that I could have more time to concentrate on my course work. I replied OK, but asked what we should do about all the requests for me to give the talks and presentations requested. Mr. Edminster just indicated that we could just think about that for awhile, and maybe figure something out, but I should have more time at home to focus on completing my graduate coursework. The "*thinking about it for awhile*" didn't take long, because one or two days later, **Mr. Ron Reeve**[11] in my office came to me with an idea. Ron asked if I could spare one day per month to talk and make presentations to individuals and groups that could travel to Ohio State, rather than my traveling to their location, to obtain the information on our project progress they were interested in. I agreed that would work for me. Ron continued that he, in effect, would be my *agent* and make all the arrangements with the individuals or groups who wanted to visit with me

[11] Mr. Ronald C. Reeve was the Research Investigations Leader responsible for directing the research of drainage and irrigation engineers and soil scientists in the Soil and Water Conservation Research Div., ARS, USDA, and maintained his office with our research team at The Ohio State University, Columbus. Ron was my line supervisor in ARS, and we had a great working relationship together; he always said it was fun for him to be "*along for the ride*" while we were researching and developing the new drainage materials and installation methods in our ARS project.

regarding the research progress and get up to date on the drainage materials and equipment ideas we were working on. We both kind of laughed about the arrangement, but that is what we did for about the next 14 to 18 months. Ron was successful in scheduling in groups of about 100 each month (which filled the conference lecture room #100 in Ives Hall of the Agricultural Engineering Dept. at OSU). Ron later admitted that the main problem he had to content with was that some Industry Reps who wanted to attend did not want to attend the same month that one or more of their competitors would also be attending. Almost all of those monthly events each lasted a full day to cover all the information the attendees wanted to learn about, and the Question & Answer sessions were very good for Ron Reeve, Norm Fausey, Glenn Schwab, and me, as well as the attendees too I'm sure. Also I should point out that all the day-long "seminars" (as they were often called) were scheduled on days that I did not have graduate school classes. Thus, during the latter part of 1967 and throughout 1968 I made great progress towards completing my Ph.D. course requirements.

After I completed my Ph.D. degree in Agricultural Engineering at Ohio State (Mar. 1971), over about a 4-year period in the early- and mid-1970s, I was asked to present seminars on Laserplane grade-control for drainage plows during the annual National LICA Conventions that were attended by drainage contractors from all regions of the U.S., and often some from Canada. As I recall there were a few representatives from foreign manufacturers of drainage plows in attendance as well. The seminars were one-half day-long presentations with Question & Answer sessions at the end. Seminars were scheduled for two days during the annual conventions, and a morning and afternoon seminar given on each day (a total of 4 seminars). The seminars covered Laserplane grade-control accuracy and optimizing the Laserplane receiver mounting position on the drainage plow frame or linkage. I used the computer simulation technique developed in my Ph.D. research, converted to run on the digital computer and the simulation results were projected onto a large screen for illustrating the effects on grade-control accuracy for different on-machine mounting positions of the Laserplane receiver-unit. Some simulations were also given to illustrate the effects of plowing speed on grade-control accuracy, giving emphasis to determining the maximum speed that should be used to insure good grade-control accuracy. A fairly large conference room had to be arranged by LICA as there were approximately 50 to 60 attendees at each seminar. LICA and I felt the seminars were very well received and generated a great deal of interest among drainage contractors in correctly using Laserplane grade-control on their drainage plows. I believe that the discussions and demonstrations about the optimum position for mounting the Laserplane receiver-unit on the plow frame or linkage was perhaps the most used information by contractors who attended the seminars. Those contactors also talked to other contractors and the information about the proper positioning of the Laserplane receiver on a drainage plow was spread much more widely among many contractors in the U.S. and Canada, and perhaps Europe as well. As I recall, the number of new drainage plows reportedly purchased by contractors during the mid-1970s exceeded the number sold per year in the latter 1970's. The new drainage plows were manufactured in Canada, England, and Europe, as none had been manufactured in the U.S.A.

A Special Note for the Reader's consideration:

Note*:** At this point the Reader may chose to review or read the "Story behind the Story on the Development of the ARS 'Big Red' Draintube Plow with Laserplane Automatic Grade-Control System***" before proceeding with the rest of the R&D story on the laser-beam depth

& grade-control system. The field testing of the Laserplane System on the ARS Big Red Draintube Plow (*covered in the next section of this story*) was a major component of the final development phase in the ARS R&D project on innovative drainage materials and installation methods. That field testing of the Laserplane system performance on the Big Red Plow was not the 'end of the story' about the plow, however, because the plow was used for other activities into the late 1990's.

Field Testing of Laserplane Grade-Control Accuracy of ARS Draintube Plow on D-7E Cat:

As noted in the ARS Big Red Plow story, extensive grade-control field testing could not be completed in 1971 with the ARS Big Red Draintube Plow following the first field demonstrations in Illinois and Ohio because of rain delays. The D-8H Cat borrowed from the Caterpillar Tractor Co. had to be returned to the Caterpillar Proving Grounds in Peoria, IL before the full range of desired testing was completed. However, our team did summarize the early grade-control results we were able to obtain from the field testing that could be completed with the Big Red Plow on the D-8H Cat for presentation and publication at the 1972 ASAE National Drainage Symposium.[12]

In 1973 a D-7E Cat was obtained from U.S. Military Surplus Property and the Big Red Plow was modified and mounted on it. The shorter D-7E, compared to the original borrowed D-8H used in the first field demonstrations and preliminary field tests, required that the dual beams on the plow be shortened about 3.0 ft. in length. A 2nd generation design of the commercial Laserplane Grade-Control System was installed on the D-7E mounted Draintube Plow (**Fig. 25**). The improved Laserplane receiver unit was designed to automatically point the photocells in the receiver-unit towards the stationary Laserplane transmitter as the plow moved across the field.

To simplify the 1974 field testing procedure, the Laserplane System was setup such that drainlines were installed at **0%** gradient with the plow[13] for several hundred feet of travel to check depth and grade-control accuracy. All drainlines were installed at a ground speed of about 150 ft./min., considered the maximum speed for good grade-control based on earlier simulations and field testing. Referring to Fig. 6 for a definition of dimensional terms, the optimum position for mounting the Laserplane receiver on the b = 18.75-ft. long plow beam was **(b-X) = 3..0-ft.** in front of the "Big Red" plow blade on the D-7E, or at **X/b = 5/6** (approx. 0.833 to 0.84). The X/b = 5/6 position for mounting the Laserplane receiver was also the optimum position determined in the earlier preliminary tests in 1971 when the Big Red Plow (with the longer original 21.75-ft. dual beams) was mounted on the borrowed D-8H Cat (*as published in the footnote **12** reference*). It is of interest to note that the series of analog computer simulations conducted in the 1970-1971 Ph.D. project (*discussed earlier*), for different laser-receiver mounting positions, predicted about the same optimum position to mount the laser-beam receiver unit for the best grade-control accuracy.

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[12] **Fouss, J. L.**, Fausey, N. R., and Reeve, R. C. 1972. Draintube plows: Their operation and laser grade control. ASAE National Drainage Symposium. pp. 39-42, and 49. (*A reprint of this published paper is included in Appendix **V**, and is recommended reading for details on the early field testing of the floating-beam research drainage plow and the ARS Big Red Draintube Plow*).

[13] The test drainlines were installed with the plow, but corrugated drainage tubing was not installed in the drainage channels. This allowed an inverted-T-probe of known length to be inserted down into the plow-blade slit to the soil bottom of the drainage channel. The drain-bottom elevation was determined at 5-ft. intervals in the drain channel using the Laserplane surveying rod sitting on the top of the known length inverted-T-probe inserted into the plow-blade slit.

Fig. 25. ARS "Big Red" Draintube Plow with Laserplane Depth & Grade-Control System Mounted on a D-7E CAT Installing 4-in. dia. Corrugated-Wall Plastic Draintube.

Figs. 26 and **27** show selected field test results (in graphical format) with the ARS Draintube Plow on the D-7E Cat for two different positions the Laserplane receiver-unit was mounted on the plow frame (beam). The drainline bottom elevations taken at 5.0-ft. intervals plotted in Fig. 26 is for the Laserplane receiver positioned at X/**b** = 0.84 {or (**b**-X) = 3.0-ft.}, and the data plotted in Fig. 27 is for the receiver position at X/**b** = 0.28 {or (**b**-X) = 13.5-ft.}. To check and quantify the accuracy of depth and grade-control, a statistical standard deviation (S.D.)[14] was computed using the 5-ft. interval data points between the plowing depth and the desired depth of the 0% gradeline; the S.D. values are shown in the bottom right-hand corners of Figs. 26 and 27. The S.D. = $\pm$ 0.078-ft. shown in Fig. 26 for the Laserplane receiver at position (**b – X)** = 3.0-ft. provided more accurate depth and grade-control than when the Laserplane receiver was mounted at the (**b – X)** = 13.5-ft. position as shown in Fig. 27 (S.D. = $\pm$ 0.118-ft.).

In a following section of this story a method is discussed for using modern 2015 equipment and GPS 3D-positioning instrumentation to monitor & record the accuracy that the plow can install the corrugated tubing, thus eliminating the need to probe down through the plow slit and survey the plow-trench bottom to evaluate the installation accuracy for drain depth and grade.

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[14] The statistical standard deviation (S.D.) of the plowing depth was computed from elevations taken in the bottom of the plow-trench at 5-ft. intervals along the drainline path. This was considered as an average deviation. The accuracy of this below ground surveying measurement was considered to be $\pm$ 0.03-ft.

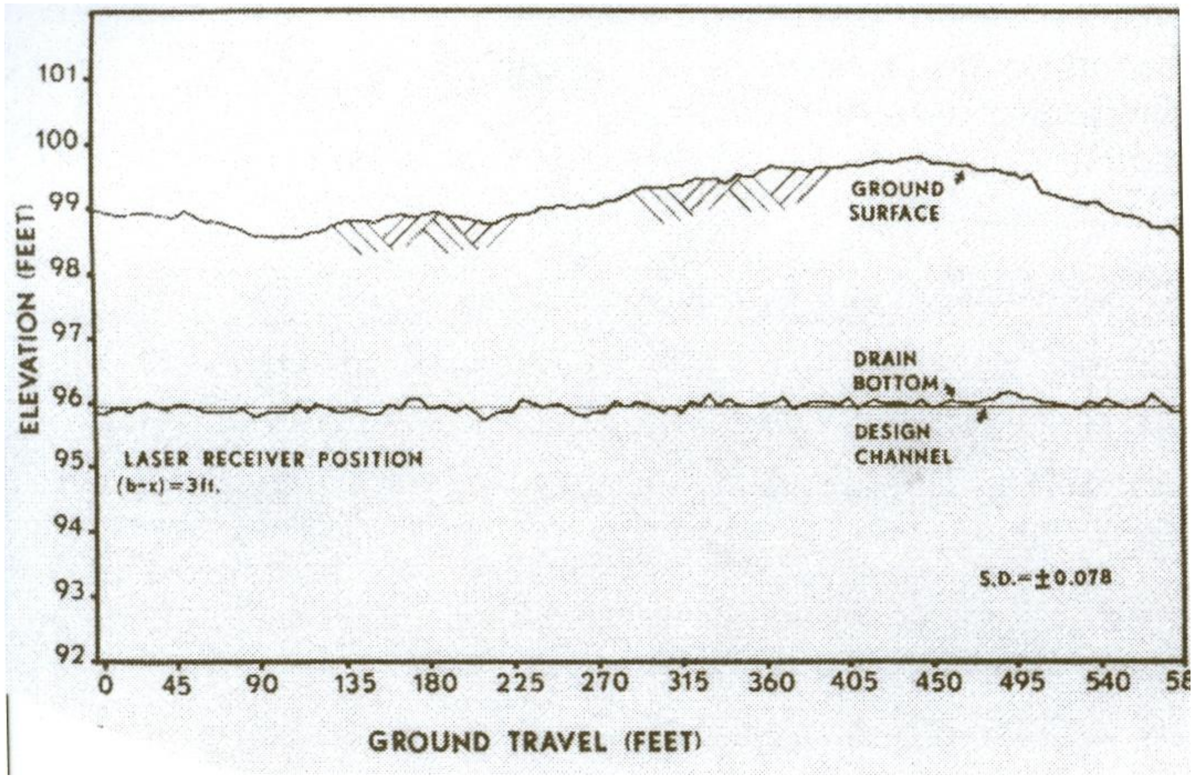

Fig. 26. Field test evaluation for ARS Plow with Laserplane Grade-Control; X/b = 0.84

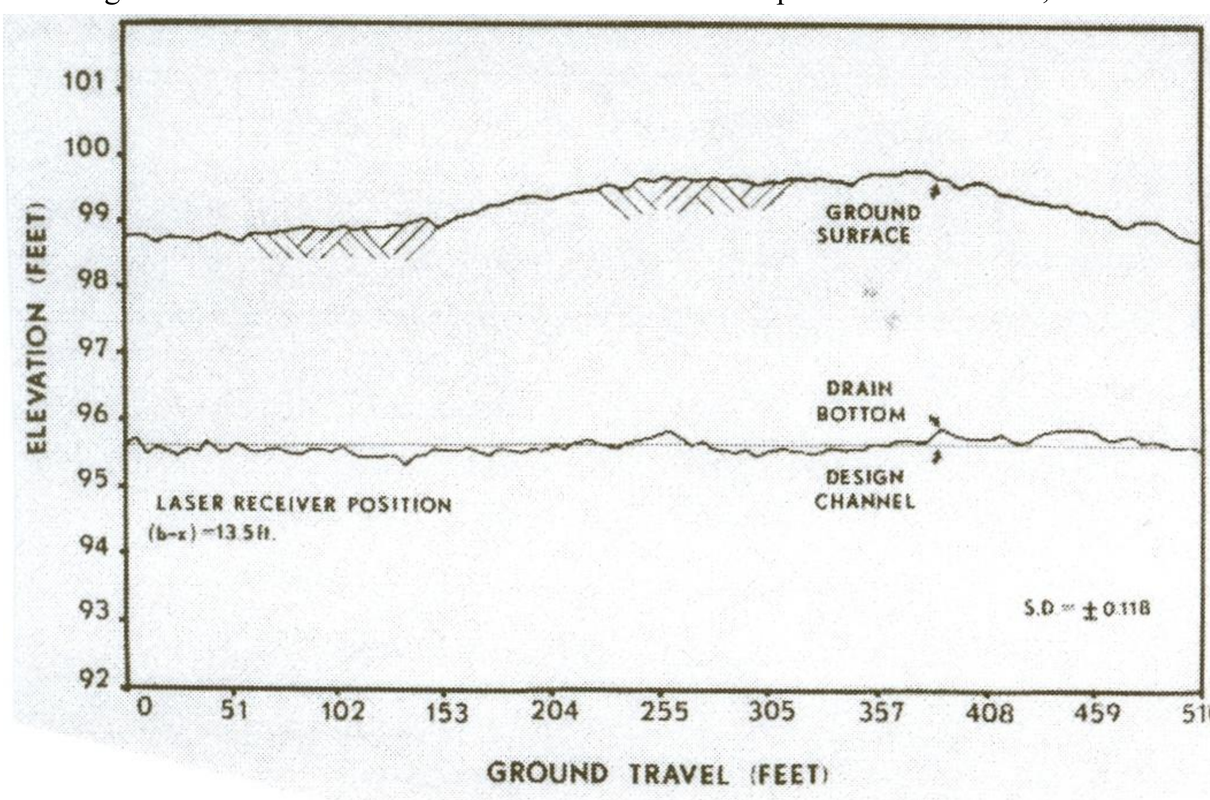

Fig. 27. Field test evaluation for ARS Plow with Laserplane Grade-Control; X/b = 0.28

More detailed results and discussion about these grade-control accuracy tests, and the effects of plowing speed, were published in the **Drainage Contractor** Magazine[15]; *a PDF printed copy of the published article is included in Appendix V* [16]

Early Acceptance of ARS-Industry Coop R&D accomplishments and recent Tech advances:

The key research and design tasks in this story about the development of the laser-beam automatic depth and grade-control system for the floating-beam drainage plow were accomplished through innovative R&D conducted cooperatively by ARS engineering scientists (James Fouss and Norman Fausey) and a key industry representative (Ted Teach) who had expertise in electronics and trencher-type drainage equipment. Mr. Teach's contribution to the project was brought about because the ARS scientists had contracted with him (as the successful bidder) to develop improved electronic circuits[17] for the laser-beam receiver-unit and the feedback control circuit for the drainage plow depth and grade-control system. Although a number of press releases, popular publication articles, and a technical outlook publication had been issued by the ARS scientists about the laser-beam grade-control development project, it was only after the initial technical presentation and demonstration of the prototype laser-beam system to Ohio drainage contactors at a Land Improvement Contractor's conference in early-1967 that industrial interest and action picked up. As noted in an early section of this story, it was immediately following this contractor's conference where Fouss and Teach met Mr. Robert Studebaker who had conducted some concurrent research with a prototype laserplane system for a motor patrol grader. It was soon after that meeting the business partnership was formed between Robert Studebaker and Ted Teach, and the company founded, Laserplane Corp., was the beginning of the laser grade-control industry. The specific ideas and concepts developed in the cooperative ARS and Industry cooperative R&D project that were adopted and used in the future commercial products developed and sold to contractors was covered in an earlier section of this story. Also discussed and illustrated in a section of this story, the first public demonstration of a commercial Laserplane system operating on a wheel-type tile trenching machine was in the fall of 1968 at the Ohio State Farm Science Review (see Fig. 24).

The additional thoughts and observations expressed below are related to what I recall knowing something about from the late 1960s and early 1970s, and are not documented anywhere else to my knowledge. The dates I have expressed here are likely close to when events occurred, but may not be exact. With the successful field demonstrated performance of the Laserplane system on a tile trenching machine in 1968, drainage contractor interest picked up significantly,

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[15] **Fouss, J. L.** 1978. Watch your drainage plow speed and laser receiver position. Agri.-Book Publication, Drainage Contractor 4 (1): 100-101. (*Reprint in Appendix V*).[16]

[16] The author draws to the reader's attention that the original article referenced in footnote #15 was published in **Drainage Contractor** with an error made in the article's magazine layout. The graphs used for Figs. 2 and 3 were reversed in position within the layout, and thus were placed with the wrong figure title. For the **reprint** included in Appendix **V** of this story, the two graphs were repositioned so that each would be over the correct figure title.

[17] The research prototype circuits assembled by the ARS scientists functioned well enough to confirm that the design concept for the envisioned laser-beam automatic depth and grade-control system on the drainage plow functioned as hoped and expected. However, it was realized that improvements in the system electronic circuits would likely significantly improve the response characteristics of the system for controlling depth and grade on the drainage plow.

and also their interest in plow-type installation equipment increased because of the potential for higher speed installation of subsurface drainage corrugated plastic tubing. It was soon apparent that Canadian and European industry had taken notice as new models of drainage plows became available for contractors by the early 1970's; but, still no plows were developed by U.S. industry. By 1971 most tile trenching machines were equipped, or were being equipped, with Laserplane grade-control systems, and drainage plows were beginning to enter the market place at an increasing pace. By 1972, all plows and almost all high-speed trenchers sold were equipped with laser automatic grade-control as standard equipment. The laser-beam or Laserplane grade-control systems were also adopted by drainage contractors in European countries for new drainage-plow equipment by the early 1970s. Following the successful field demonstrations in 1971 of larger drainage plows capable of 6-ft. plowing depth and good grade-control accuracy (e.g., the ARS Big Red Draintube Plow, and one or two foreign plows), most plow manufacturers began offering plows of different sizes and maximum plowing depth capability to meet a range of drain installation requirements. By the year 2000 contractors began requesting that plows be developed to install larger diameter corrugated-wall drainpipe, e.g., 8- to 15-in., and perhaps larger. Larger plows were developed by Canadian and The Netherlands manufacturers and perhaps one or two firms in Europe to meet that growing market demand by contractors. I have been impressed with the success of the larger plows and the ability to plow-in large-diameter corrugated-wall plastic pipe. Many contractors still use trenching machines, especially the chain-type trenchers, for the installation of large-diameter drain pipes or collector mains on their drainage jobs. All modern drainage machines are equipped with Laserplane or RTK-GPS depth and grade-control systems.

The laser-beam system for alignment and/or guidance was adapted by industry worldwide for many other applications, such as land surveying, open ditch excavation, land grading, rice paddy construction, pipeline construction, tunnel excavation, building construction & alignment, and other engineering and construction projects, including several military applications. The night-time operation of the laser-beam (Laserplane) system in many of these applications was also noteworthy, especially in night-time land leveling of level basin land areas for rice production in the Western U.S. states. These world-wide applications of the laser-beam technology were documented in a special report for the World Bank by Dr. Marvin Jensen, ARS National Program Leader. The report to the World Bank illustrated the wide ranging benefits of agricultural research, and high-lighted the very large economic benefits in the area of laser-controlled precision land leveling for irrigated agriculture world-wide in terms of reducing the large volumes of irrigation water required, and the associated economic savings in the costs for crop production on irrigated agricultural lands. Many, if not most, of these applications for the laser-beam and laserplane systems are being upgraded, I'm sure, to the modern RTK-GPS systems (this modern system upgrade is discussed in more detail below). I have not covered in this story the integrated systems now available for computer software to design projects and then install the projects with automatically controlled equipment in accordance to the computer generated designs for subsurface and surface drainage systems. Similar computer software for design and integrated control of construction equipment are also used widely in civil, industrial, and military projects.

Summary Comments

The laser-beam automatic grade-control system developed and demonstrated by ARS researchers and industry cooperators provided the technology to improve installation speed and accuracy for modern corrugated-wall plastic tubing with high-speed plow-type and chain-type-trenching equipment for agricultural subsurface drainage systems. After the initial technology transfer to industry in 1967, only about 2 years were required until the first commercial Laserplane equipment was available and in use by Midwestern U.S. drainage contractors. Over the next 20-25 years, continued developmental research by industry, at times in cooperation with federal and state government researchers, resulted in significant improvements and innovations, plus expanded applications worldwide to many agricultural, civil, construction, and military tasks. The laser-beam and Laserplane system was considered and became known as the **engineering standard** method for alignment and guidance applications beginning in the early 1970s. This engineering standard remained in effect for about the next 25 to 30 years at which time new satellite-based technology that provided precision geographical 3D positioning (i.e., RTK-GPS) was developed that began replacing it as the engineering standard.

RTK-GPS Precision X,Y,Z Positioning System Replaces Laserplane System for Drain Plows

Let me cover first a bit of personal background on our thinking in the early stages of the ARS research project to develop the laser-beam automatic depth and grade-control system for the drainage plow. When we made the early determination that an on-plow sensor was needed for detecting an off-plow elevation referencing source, such as a wire stretched to grade or a narrow light-beam projected to grade, Satellite-based GPS was early in its development and only a few satellites were in orbit. The GPS system available at the time was restricted for use only by Intelligence Agencies and the U.S. Military. When our staff discussed the idea that it would be nice if we could use an accurate Space Age GPS system for the off-plow elevation reference, we recognized that even in military applications at the time it was probably not really accurate enough for our needs to control depth and grade on the drainage plow. I joked with the staff about it at the time and stated that even with the Military's GPS we might come fairly close to being on the right farm, but not necessarily the right field or the right place in a field to install a subsurface drain for the farmer. And I knew the GPS elevation coordinate (*for controlling plowing depth*) was not very accurate at all. The whole idea was thus a "***dream***" for the future. That future dream started coming true during about the last decade of the 1990's, and was more fully developed in the early years after 2000. The enhanced "dream" systems available by 2015 had features and capabilities well beyond the 1990-2000 Era systems and have had a larger impact on the way surface and subsurface drainage equipment is automatically controlled than the original laser-beam and Laserplane systems. The modern day Satellite-based RTK-GPS 3D-positioning and control technology now used for both steering (X & Y positioning) and control of the Z-coordinate (elevation) for drain depth on drainage equipment and the cut/fill depth on land grading equipment is described and discussed below.

The laser-beam and Laserplane industry changed a lot from 1982 into the early years of the 2000's. In 1982, the Laserplane Corp. was acquired by Spectra-Physics, a company with expertise in laser-beam systems technology. During the 1990's, Trimble pioneered Real Time Kinetic (RTK) technology to rapidly correct Satellite GPS detected coordinate data to achieve centimeter-level accuracy for 2D and 3D positioning in real time. Then in 2000, Trimble acquired the Spectra Precision Group, and became one of the major sources for laser-based and satellite-based positioning and control systems. Trimble vastly expanded its scope of technologies after 2000 by the acquisitions of many firms with related technologies, including software technologies used to process rapidly the acquired data from satellite-based positioning systems.

RTK satellite navigation is the technique used to accomplish precision positioning via signals received from multiple Global Navigation Satellite System (GNSS) constellations such as, the United States' **GPS**, Russian Federation's **GLONASS**, the European Union's **Galileo**, and China's **Compass** systems. [18] Real-Time Kinematic (RTK) GPS systems can provide centimeter-level positioning accuracy by eliminating errors that occur in positioning based only on signals from the satellites being tracked by the GPS system. For an RTK-GPS precision positioning system [e.g., to control travel direction and plowing depth (elevation) on a drainage plow], requires an RTK-GPS receiver mounted on the frame of the drainage plow and a source of position corrections signals from an RTK-GPS receiver located at a known geographic location Base Station or Network of Base Stations. A Base Station is an RTK-GPS receiver placed at a known (and fixed) geographic position (X, Y, Z) and it tracks the same GNSS satellites that are tracked by the RTK-GPS receiver mounted on the drainage plow; *both receivers track the same satellites at the same time*. Errors in the GPS system are monitored at the known location Base Station, and a series of position corrections are computed via the RTK technology. The Base Station receiver sends correction signals via a radio link to the receiver on the drainage plow, where the signals are used to correct the real time position data for the receiver on the moving plow.[19] The corrected real time position data in the receiver mounted on the plow provides feedback control input to the depth and grade-control system on the drainage plow. The feedback control hydraulically adjusts the plow hitch point (or plow linkage system) to maintain the drainpipe depth and grade at the subsurface drainage system design values. The RTK receiver at the Base Station is capable of computing up to 20 position corrections per second, which may be averaged for a second or more and sent as position correction signals to maintain real time precision position data in the moving plow mounted receiver. This rapid updating of real time position data in the plow mounted receiver is fast enough for the automatic depth and grade-control system to insure the drainpipe is installed in the soil very close to the design depth and grade for the subsurface drainage system. If the automatic feedback control system on the tractor and plow is also configured to steer the equipment across the field, the position correction signals will insure the path the subsurface drain follows the drainage system layout design as well.

The laser-beam and Laserplane technology of the 1970's up to about 2000 began being replaced for many applications after the year 2000 with enhanced Satellite-based RTK-GPS systems providing precision 3D-positioning (X,Y,Z) technology. The RTK-GPS systems provided precision positioning and control for the horizontal movement or steering (X & Y) and vertical elevation or operating depth (Z) for applications in land surveying, depth & grade-control of drainage equipment, and 3D control of soil cut & fill on land grading and earth moving equipment.

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[18] By 2013 the U.S. GPS and Russian GLONASS were the GNSS systems most used in Agricultural applications. The accuracy of RTK-GPS positioning systems have improved as the number of satellites in orbit increased.

[19] Both the Base Station receiver and receivers on moving field equipment require ***clear*** line-of-sight to the sky for receiving satellite signals. The RTK receiver Base Station on larger farms can be located as far as 8 miles from field sites without line-of-sight obstructions such as hilly terrain or numerous trees. A higher power radio transmitter may be needed on larger farms where longer range transmissions of correction signal are required. RTK-GPS receivers can be mounted on multiple machines or equipment operating within range of a single Base Station RTK-GPS receiver. A more powerful radio transmitter (e.g., 35 watt long range radio) can transmit up to 15 km (9 mi.) radius from the base station. The extra radio power can penetrate the signal through tree lines and provides coverage in undulating terrain.

Grade-Control Testing/Certification Programs for Drainage Plows using RTK-GPS:

Drainage plows with different designs and draft linkage configurations (e.g., long floating-beam, hinged-beam, 3-point hitch, etc.) should undergo field testing to confirm the optimum position for mounting the Laserplane or RTK-GPS receivers on the plow frame or linkage for the best depth and grade-control accuracy. The recommended optimum mounting position for the on-plow receiver, as reported in this **story** about the laser-beam depth and grade-control system development, could be used as an initial receiver mounting position to be tested on other plows. As of mid-2015, I have not seen in publications or advertisements the results of such grade-control testing for the several types of drainage plows available to contractors in the U.S. and Canada, nor in European countries. There have been some advertisements stating that the firm's plows are "*certified to maintain grade*," but test results are not shown in the ads.

I have made (and published[20]) my recommendation for a method to test the accuracy that a drainage plow installs subsurface drains to design depth and grade by mounting a **second** receiver, preferably an RTK-GPS receiver, on the **pipe-feeder boot** attached behind the drainage plow blade. The second receiver would monitor and record the RTK corrected GPS coordinates (X, Y, and Z-h, where "h" is the height at which the second receiver is mounted above the bottom of the tube feeder boot) at the bottom of the drain tube as it emerges from the tube feeder and is installed in the open channel in the soil created by the plow.[21] The coordinate data recorded by the second receiver would more accurately define the final X, Y, and Z-h locations along the line of the installed drain tube than a recording of coordinates from the conventional depth and grade-controlling receiver (either a Laserplane or RTK-GPS receiver) mounted on a forward reaching cantilever arm attached to the plow blade. For innovatively advanced drainage plows, the **Z-h** data versus ground-travel could be displayed graphically to the plow operator on a flat-screen monitor, along with other plow and tractor performance information. Such testing of the plow's performance could also determine the maximum ground speed that would provide good depth and grade-control with the plow's controlling receiver mounted in the ***optimum*** position on the plow frame or linkage.

Since the mid-1970s, the province of Ontario, Canada has had a drainage plow testing and certification program. As far as I have been able to determine, they have tested only a limited number of drainage plows. Ontario's program was based on specifications and standards stated in the Agricultural Tile Drainage Installation Act originally passed in 1973. The accuracy of the drain installed during the plow testing was determined by digging to uncover the drainpipe so that its bottom elevation could be surveyed every few meters along its path. The Canadian act included a provision for training and licensing of drainage contractors and was administered by the Ontario Ministry of Agriculture and Food and Ministry of Rural Affairs. As of 2015, a drainage plow testing and certification program had not been developed in the U.S.

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[20] Fouss, James L., Ph.D., P.E. 2014. **Setting Standards:** "Accountability for depth and grade-control accuracy", **Drainage Contractor** magazine, p. 14, Nov. 2014 issue (published in Ontario, Canada). [*reprint in Appendix V*]

[21] At the time of this reporting (July 2015), I was actively coordinating with Trimble, Inc. and a drainage contractor in Indiana (with an Inter-Link drainplow) to conduct a preliminary field test for this method of checking (testing) depth and grade-control for installing corrugated plastic drain tubing.

Recent innovative designs for self-contained drainage plows have become available and their acceptance by contractors has significantly increased in the U.S., Canada, and Europe. Most of the modern plows are very powerful and capable of operating at greater depths, and can install drainage pipe faster than earlier plow models. However, earlier regulations in Canada did not set limits on the maximum speed the plows should be operated in order to ensure subsurface drains were installed accurately to design depth and grade.

I am not suggesting beginning a Government regulated program in the U.S. for testing and certifying drainage plows using the method I recommended and outlined above. It is my thought that plow manufacturers and/or drainage contractors should voluntarily conduct the tests and provide the results in advertisements or reports in contractor organization (e.g., LICA) newsletters or publications, etc. Such reporting of drainage plow performance results should be made available to all farmers having drainage systems installed on their farms with plow-type equipment. I will be providing additional published articles on this matter in the months and years ahead as I coordinate with drainage plow manufacturers, drainage contractors, and the RTK-GPS control system industries to hopefully organize and implement a way of accomplishing this goal for the benefit of the drainage industry, contractors, and farmers.

# # # # #

JLFouss; 07/02/2015.

APPENDIX I

List of References:

Fouss, James L. 1971. Dynamic Response of Automatically Controlled Mole-Drain Plow. Unpublished Ph.D. Dissertation, Department of Agricultural Engineering, The Ohio State University, Columbus, OH; 133 pp. (*see PDF of the full dissertation on CD in Appendix IV*)

Fouss, J. L. and Hamdy, M. Y. 1972. Simulation of a laser beam automatic depth control. TRANS. of the ASAE 15(4): 692-695. (*Reprint in Appendix V*)

Fouss, J. L., N. R. Fausey, and R. C. Reeve. 1972. Draintube plows: Their operation and laser grade control. Proceedings of the ASAE National Drainage Symposium. pp. 39-42, and 49. Available from ASABE, 2950 Niles Rd., St. Joseph, MI 49085. (*Reprint in Appendix V*)

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Fouss, J.L. and Fausey, N.R. “Researchers Fouss and Fausey Develop Laser Grade-Control System That Transforms Drainage and Irrigation Technology,” published by the Council for Agricultural Science and Technology (CAST), NewsCAST “Success Stories in Agriculture” 31 (01): 15-18, July 1, 2004. (*Reprint in Appendix II*)

Fouss, J.L. and Fausey, N.R. Research and Development of Laser-Beam Automatic Grade-Control System on High-Speed Subsurface Drainage Equipment. TRANS. of the ASABE. 50 (5): 1663-1667. 2007. (*Reprint in Appendix II*)

ARS research for development of the Laser-Beam Grade-Control System for High-Speed Drainage Equipment was Honored by ASABE with a Historical Landmark Plaque; plaque and accompanying research story was dedicated and mounted in The Food Agricultural, and Biological Engineering Dept., The Ohio State University, Columbus, OH, May 2007. (*Note: Fig. 1 shows the ASABE Plaque*)

List of published Magazine Articles:

Fouss, J. L. 1978. Watch your drainage plow speed and laser receiver position. Agri.-Book Publication, Drainage Contractor 4 (1): 100-101. (*Reprint in Appendix V*).

Fouss, James L., Ph.D., P.E. 2014. **Setting Standards:** “Accountability for depth and grade-control accuracy”, **Drainage Contractor** magazine, p. 14, Nov. 2014 issue (published in Ontario, Canada). (*Reprint in Appendix V*)

APPENDIX II

(Reprints of these two published articles included on the following pages)

(1) Fouss, J.L. and Fausey, N.R. "Researchers Fouss and Fausey Develop Laser Grade-Control System That Transforms Drainage and Irrigation Technology," published by the Council for Agricultural Science and Technology (CAST), NewsCAST "Success Stories in Agriculture" 31 (01): 15-18, July 1, 2004. (*The Council reviewed about 200 ARS research projects, and selected this accomplishment as the first of only four "**success stories**" published to document and demonstrate for the U.S. Congress that research dollars pay off.*)

(2) Fouss, J.L. and Fausey, N.R. Research and Development of Laser-Beam Automatic Grade-Control System on High-Speed Subsurface Drainage Equipment. TRANS. of the ASABE. 50 (5): 1663-1667. 2007. (*The Senior Author and Co-Author were invited by the American Society of Agricultural and Biological Engineers (ASABE) to author this article for publication in a special Centennial Issue of the **Transactions of ASABE**.*)

Success Stories  in Agriculture

Researchers Fouss and Fausey Develop Laser Grade-Control System That Transforms Drainage and Irrigation Technology

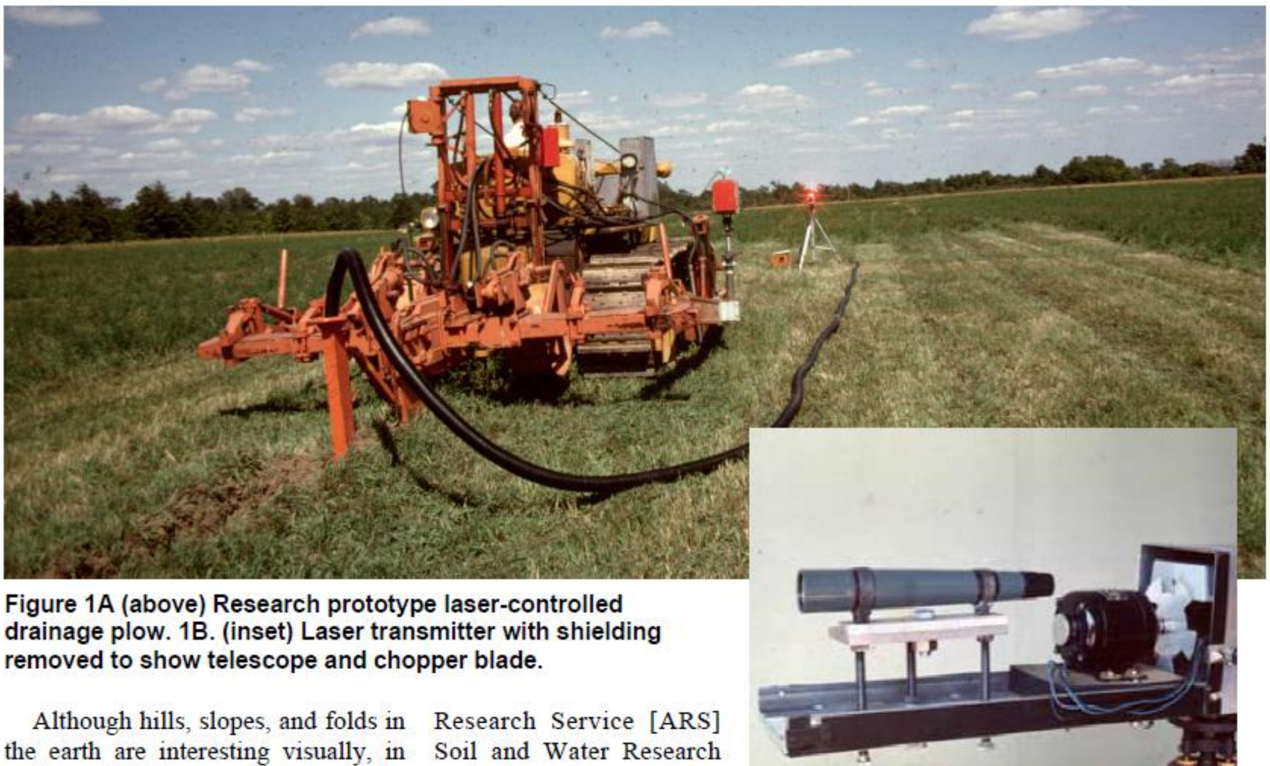


Figure 1A (above) Research prototype laser-controlled drainage plow. 1B. (inset) Laser transmitter with shielding removed to show telescope and chopper blade.

Although hills, slopes, and folds in the earth are interesting visually, in cultivated fields these features can be problematic for farmers. Uneven land surfaces, bound by the laws of gravity, often pull water away from where it's needed most. As a result, some crops languish from excess water, others shrivel for a lack of it, and runoff and erosion are commonplace.

James E. Fouss (currently a supervisory agricultural engineer and research leader at the Agricultural Research Service [ARS] Soil and Water Research Unit in Baton Rouge, Louisiana) and Norman R. Fausey (currently a supervisory soil scientist and research leader at the ARS Soil Drainage Research Unit in Columbus, Ohio) found a way, almost three decades ago, to use emerging technology to solve the problem of uneven field surfaces associated with installing subsurface drainage on agricultural lands. Their creation—the laser beam automatic grade-control system—has provided the most efficient way to install drain tubing in agricultural fields rapidly and accurately with modern equipment. About a decade later, other ARS researchers spearheaded studies to apply the commercialized "laserplane" system technology to the field of agricultural

In recent months, a CAST committee made up of five members of the Board of Directors and chaired by Dr. William Sandine has identified a number of "research success stories" that succinctly convey the value of agricultural research to our readers. The first story appears here; others will follow in subsequent issues of NewsCAST.

Figure 2. Laser-controlled ARS draintube plow.

cropland leveling and surface irrigation (see Textbox 1).

Why Use Lasers for Drainage?

The idea for a laser beam-controlled plow came to Fouss and Fausey while they were employed in the Agricultural Engineering Department at the Ohio State University, Columbus, in 1964–1965 testing the installation of subsurface drains with experimental plow-type equipment. They were using ARS-developed lightweight corrugated plastic drainage tubing that had replaced the heavy, rigid drain tile materials of clay and concrete. But they saw quickly that drainage machine operators would not be able to control accurately the depth and grade for installing tubing at the plow's speeds of 100–150 feet per minute. The solution? Some form of automated depth and grade control. Traditionally, operators just "eye-balled" the sighting bar to bring it in line with crossbars aligned across the field to determine whether to raise or lower the digging mechanism. Requiring the constant attention of the operator, this practice could control trenching machines effectively, but only at speeds of 10–30 feet per minute.

The research prototype laser beam system was designed and developed to meet the specific needs of high-speed drainage plow equipment used to install corrugated plastic drain tubing (Figure 1A). The prototype system, assembled and tested between 1965 and 1967 by Fouss and Fausey, consisted of a transmitter—a 0.3-milliwatt-output helium–neon gas laser, a 10-power telescope to expand and collimate the small-diameter laser beam to about 1/2-inch diameter, and an electric motor-driven slotted disc to

Textbox 1. Additional Early Researchers

- T. W. Edminister, Administrator, USDA–ARS (deceased)
- Cecil H. Wadleigh, Director, Soil and Water Conservation Research Division, USDA–ARS (deceased)
- Jan van Schilfgaarde, Director, Soil and Water Conservation Research Division, USDA–ARS (retired)
- Ronald C. Reeve, Research Investigations Leader, Soil and Water, USDA–ARS (retired)
- Glenn O. Schwab, Professor, Agricultural Engineering Department, The Ohio State University (deceased)
- Cornelius A. Van Doren, Chief, Corn Belt Branch, USDA–ARS (retired)
- Ted L. Teach, President, Laserplane Corporation (retired)

"chop" the beam at a frequency of 150 times per second (Figure 1B). This battery-powered laser transmitter was mounted on a tripod at the upgrade end of the proposed drain line. The desired grade or slope was set into the transmitter, projecting the laser beam parallel to and above the proposed drainpipe.

As the laser beam-adapted plow moved forward, any deviation from the desired grade caused the receiver unit mounted on the plow's frame to move up or down, which then would cause an imbalance in the electrical bridge circuit. Once the imbalance reached a preset level, a control circuit activated an electric valve to hydraulically move the plow's hitch-point up, or down, until the laser receiver was again "on grade." According to field tests, the laser receiver could be maintained within about 3/4 inch of the desired grade line, at ground speeds up to 100 feet per minute.

Textbox 2. Uses of the Laser Grade-Control System

- Land surveying and grading
- Increased water conservation
- Erosion control
- Overall farm efficiency for irrigated agriculture
- Highway and building construction and alignment
- Tunnel and open ditch excavation
- Rice paddy and levee construction
- Pipeline construction
- Military applications

Going to the Marketplace

Following a 1967 demonstration of the ARS prototype laser beam automatic grade-control system to Ohio land drainage contractors, Fouss met with individuals who, soon afterward, became founders of the Laserplane Corporation, located in Dayton, Ohio. Many of the concepts for the laser beam control, developed and tested by the ARS, were adopted for use in the development of a commercial version of the laserplane system for drainage equipment.

At the 1968 Ohio State Farm Science Review in Columbus, Ohio, the first commercially available Laserplane Grade-Control System was revealed in field trials and demonstrations. These trials were conducted cooperatively by ARS researchers and Laserplane engineers. Here, a few thousand farmers and as many as 100 drainage contractors

Figure 3. Visitors to the 1971 Ohio State Farm Science Review.

viewed the system's performance on a wheel-type tile trenching machine installing corrugated plastic drain tubing. By the fall of 1970, many farmers in the Midwest were demanding the laser beam-controlled machine to install their drainage systems. And by early 1971, many tile trenching machines were equipped with laserplane grade control.

Making a Good Thing Even Better

Researchers at the ARS designed a larger drainage plow and tested its capability and grade-control accuracy for installing corrugated plastic drains. This larger plow was equipped with the commercial Laserplane Grade-Control System and was demonstrated at field shows in Illinois and Ohio in 1971 (Figure 2). A new drainage plow imported from England—equipped with laserplane control—also was seen at the Ohio State Farm Science Review that year (Figure 3). Even larger crowds attended these events.

Testing of this larger plow allowed ARS researchers to ascertain the accuracy of the grade control and to confirm the optimum mounting position for the laser receiver on the drainage plow frame. Fouss and Fausey also found that ground speeds for the plow—of up to 100 feet per minute—provided the best grade-control accuracy. These findings soon became important guidelines for the industry.

After 1971, all plows and nearly all high-speed trenchers sold in the United States were equipped with laser automatic grade control as standard equipment. By the early 1970s, the laserplane grade-control system was adopted for most drainage machines—both trenchers and plows—in several European countries.

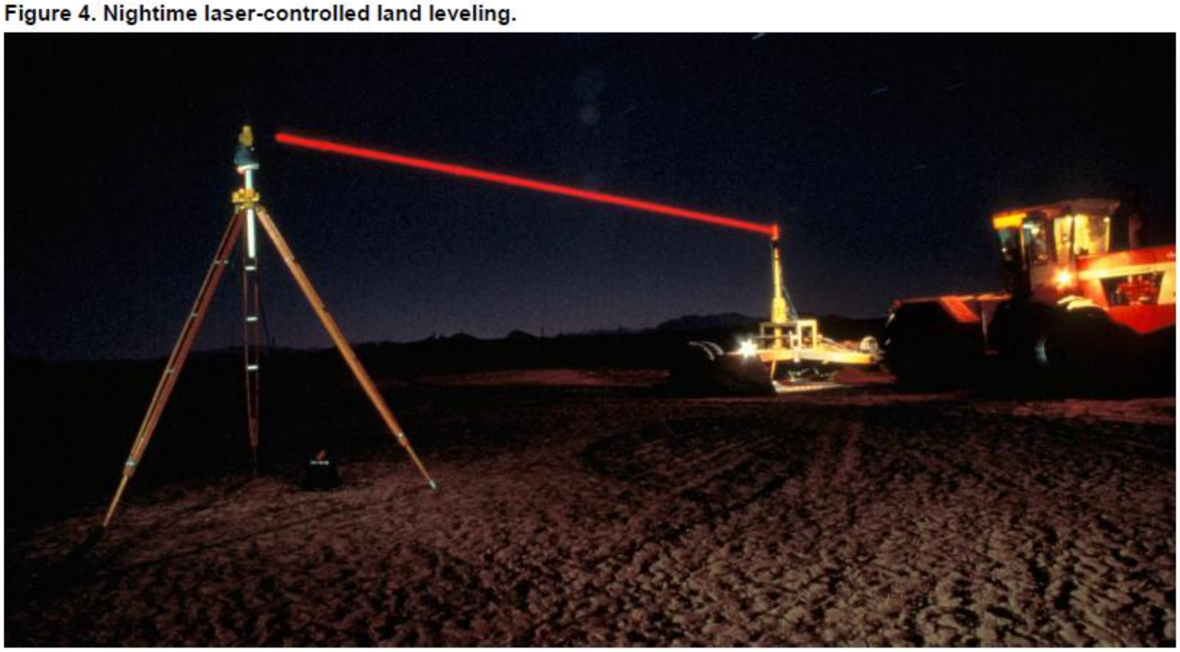
Worldwide Use Nets Big Dividends

Since its inception and development, the laserplane system has been adopted by agriculture and industry worldwide to improve land-grading operations for surface irrigation (see Textbox 2). The adoption of this technology has led to significant increases in surface irrigation efficiency and a great decrease in irrigation costs through savings in the volume of water needed to be pumped and the cost of energy needed for pumping. Nighttime operation of the laser system allows operators to take advantage of good weather conditions and lower temperatures, both of which can improve grade-control accuracy (Figure 4). Improved surface irrigation also has brought about increased crop productivity and uniformity on irrigated lands.

* * * * *

Additional contributors to this story include **Allen R. Dedrick**, Associate Deputy Administrator, Natural Resources & Sustainable Agricultural Systems, National Program Staff, USDA–ARS; **Marvin E. Jensen**, National Program Leader, Irrigation and Drainage, National Program Staff, USDA–ARS (retired); and **Dale A. Bucks**, Senior National Program Leader, Water Quality & Management, National Program Staff, USDA–ARS. Write-up, in part, courtesy of **Erin Kendrick-Peabody**, writer/public affairs specialist, USDA–ARS.

Figure 4. Nightime laser-controlled land leveling.



RESEARCH AND DEVELOPMENT OF LASER-BEAM AUTOMATIC GRADE-CONTROL SYSTEM ON HIGH-SPEED SUBSURFACE DRAINAGE EQUIPMENT

J. L. Fouss, N. R. Fausey

ABSTRACT. *Subsurface drainage methods and materials technologies were modernized more through innovative research and development between 1960 and 1975 than during the previous 100 years. Original research conducted by ASABE Member agricultural engineers who were employed by the USDA Agricultural Research Service (ARS) and worked cooperatively with other ARS scientists and technicians plus scientists at The Ohio State University developed the prototype materials and equipment to test the new drainage technology. High-speed installation of plastic subsurface drains with plow-type equipment was made possible and practical in the late 1960s with the adoption of coilable corrugated-wall polyethylene plastic tubing. However, manual control of depth and grade by the operator of the drain plow at speeds of 35 to 50 m/min was not sufficiently accurate or practical. A laser-beam automatic grade-control system was designed and developed to meet the specific requirements of high-speed plow-type draintube installation equipment. The first use of the laser in agriculture was reported to be in the installation of plastic drain tubing with plow and/or trencher equipment. Through cooperative field trial demonstration projects with university extension specialists and industry representatives, the new technology was transferred to industry for final development and marketing. A laser-plane system, rather than the laser-line prototype tested, was developed by the industry cooperators to project a beacon of laser light (a laser plane) over an entire field. Laser-plane technology subsequently applied in precision land grading for surface irrigation vastly improved irrigation efficiency and saved untold millions of acre-feet of irrigation water worldwide. From this agricultural engineering beginning, laser technology expanded rapidly into many engineering agricultural and non-agricultural fields, including surveying, land leveling and grading, construction (highways and buildings), and military tasks. The laser-beam and laser-plane systems are considered the engineering standard method today for alignment and guidance applications.*

Keywords. *Automatic, Corrugated, Drain, Drainage, Grade control, Irrigation, Laser, Laser beam , Laser plane, Plastic, Plow, Subsurface, Surface, Technology, Trencher, Tubing.*

This article describes pioneering research conducted in the 1960-1975 period, during which drainage methods and materials technology advanced more than during the entire previous century (Fouss and Reeve, 1987). ASABE Members James L. Fouss and Norman R. Fausey, employed by the USDA Agricultural Research Service (ARS) and stationed in the Department of Agricultural Engineering at The Ohio State University, Columbus, Ohio, conducted the research and development work cooperatively with agricultural engineers and soil scientists at The Ohio State University and with several industry representatives.

The research led to the replacement of the slow trench-installation of rigid clay and concrete drain tile with light-weight corrugated-wall polyethylene plastic drain tubing installed with plow-type or high-speed trenchers controlled by a laser-beam grade-control system. The laser grade-control system was required on the high-speed drainage plow equipment to ensure accuracy of the drain installation to specified depth and gradient. This research and development project involved both computer modeling and simulation and field testing of the system performance to optimize various parameters, such as the best position to mount the laser-receiver unit on the frame of the drainage machine to obtain the best accuracy in automated control of depth and grade for the drain being installed (Fouss, 1971). Following the research and development work, the performance of the laser grade-control system was demonstrated through extensive field trials conducted in cooperation with extension specialists and industry representatives for the benefit of drainage contractors and farmers, and to transfer the technology to industry for development and marketing. As with any technological development, the first 20 years of use for the new materials, equipment, and methods included further important improvements and innovations, but these are not discussed in this article.

BACKGROUND

High-speed installation of subsurface drains with plow-type equipment was made possible and practical in the U.S.

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by the late 1960s with the adoption and modification of coilable corrugated-wall plastic drainage tubing developed in Germany during the mid-1960s. The modifications required for use in the U.S. involved producing the drain tubing from high-density polyethylene (HDPE) plastic rather than the polyvinyl chloride (PVC) used in Europe, and designing deeper and wider spacings (pitch) between corrugations to compensate for the lower strength of HDPE plastic compared to PVC (Fouss, 1973); in the 1960s, HDPE was significantly lower in cost in the U.S. than PVC.

Manual control by the machine operator of depth and grade for the drainage plow was not sufficiently accurate or realistically practical at the 35 to 50 m/min ground speeds typical with the plow equipment. Therefore, the plow-in method of drain installation required the development of some type of automated depth and grade control. Traditionally, depth/grade control on slow-moving trenching machines was accomplished visually by the operator, hydraulically raising or lowering the digging mechanism to bring a sighting bar in line with crossbars on targets aligned across the field. During drain installation, the depth/grade control of the trencher required almost constant attention by the operator, but was accurate for trenching speeds of only 3 to 9 m/min. Another technique commonly used for trenchers was to stretch a string or wire line parallel to the desired trench bottom. The trencher operator visually maintained a reference bar or pointer attached to the digging frame at the same level as the stretched line. For higher-speed machines the stretched wire might have served as a reference for suitable electronic sensors to automate depth and grade control. However, the time, labor, and expense required for stretching and presetting the elevations of the wire grade-line for each drainage pipe installed would have been excessive. A pendulum leveling device (like that used on a self-leveling combine) was field evaluated for automated grade control on the drainage plow, but accuracy was poor and the idea was thus abandoned (Fouss et al., 1964).

Development of Laser-Beam Automatic Grade-Control System

The research prototype laser-beam automatic grade-control system was designed and developed to meet the specific requirements of the high-speed drainage plow equipment used to install corrugated plastic drain tubing (Fouss, 1968). The drainage plow, rather than the trencher, was selected for this development because it was envisioned that the plow-in method of drain installation would be adopted as the preferred equipment in the future if an accurate and efficient method of depth and grade control could be achieved. The prototype system was designed, assembled, and field tested between 1965 and 1967 (fig. 1). The laser-beam transmitter consisted of a 0.3 mW output helium-neon gas laser that emitted 6,328 Angstrom wavelength laser light, a 10× telescope to expand and re-collimate the small-diameter laser-beam to about 0.5 inch diameter, and an electric motor-driven slotted disc to "chop" the beam at a frequency of 150 times (cycles) per second. This battery-powered laser transmitter was mounted on a tripod at the up-grade end of the proposed drain line. The desired grade (slope) was set into the transmitter, projecting the laser-beam parallel to and at a fixed distance above the proposed drain-pipe (fig. 2).

Figure 1. USDA-ARS prototype draintube plow with laser-beam automatic grade-control system.

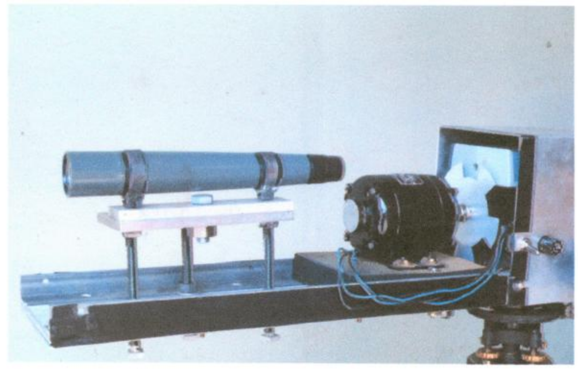

Figure 2. Prototype laser-beam transmitter to project an expanded light signal at 150 cycles/second.

The research prototype laser-beam receiver consisted of two horizontal rows of phototubes closely spaced and placed in a housing designed to block as much of the ambient sunlight as possible (fig. 3). Phototubes were used in the prototype because commercially available solid-state photocells that functioned well with the helium-neon laser light were not yet commercially available. The receiver was mounted on the draft links of the floating-beam type plow frame between the hitch point on the crawler tractor and the plow blade/point (see fig. 1). The optimum position for mounting the laser-receiver on the plow frame (draft links) was determined by using an analog computer simulation technique (Fouss, 1971; Fouss and Hamdy, 1972), which significantly reduced the number of field test trials needed (fig. 4). The field tests confirmed the computer simulation result that the optimum receiver mounting position was forward of the plow blade about 1/5 of the plow beam (draft links) length. Electrical signals from the receiver phototubes consisted of a DC component, primarily from the ambient light, and an AC component generated by the intercepted 150 cycles per second chopped laser-beam from the transmitter. The signal processing circuit was designed and fabricated for ARS under a USDA contract to a private firm, Control Systems Company of Urbana, Ohio; Ted L. Teach, co-owner. The electrical output from the phototubes was coupled via a capacitor to an amplifier, and the AC portions were amplified. An electronic filter attenuated all but the 150 cycles per second components of the

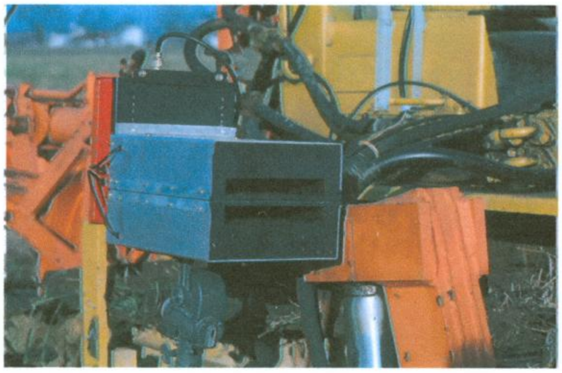

Figure 3. Laser-beam receiver unit with enclosed phototubes mounted on the draft links (beam) of the plow.

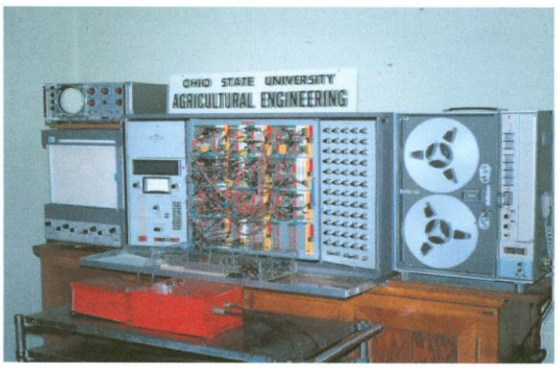

Figure 4. Electronic analog computer simulation of the laser-beam automatic grade-control system on the plow.

signal. An electrical bridge circuit detected the difference in signal levels of the top and bottom rows of phototubes and the polarity (+ or –) of the difference. The + or – differences in signal levels indicated whether the receiver was above (+) or below (–) the on-grade projected laser-beam.

The plow blade/point was set on-grade at the start of each drain line, with the intercepted laser-beam centered between the top and bottom rows of phototubes. As the plow traveled forward, any deviation from desired grade would move the receiver unit up or down, which would cause an unbalance in the electrical bridge circuit. Once the imbalance reached a preset (adjustable) level, a control circuit activated an electric solenoid valve to hydraulically move the plow's draft-link hitch-point up or down (feedback control) until the laser receiver was again on grade. Field tests showed that the laser receiver could be maintained within about ±10 to ±13 mm of the desired gradeline. Because the plow blade and drain-tube "feeder" were located behind the receiver on the floating-beam plow, the fluctuations in grade (or depth) for the installed drainpipe were even less than this.

With the success of the original prototype system, the ARS project was expanded to conduct two additional phases. These involved creating a laser-beam or laser-plane reference above the field to be drained so that the laser transmitter did not need to be moved and set up for each drain line. Two approaches were considered: one was to optically spread the laser-beam to project a "pie slice" laser plane, and the other was to rotate the laser-beam on its tripod mount, much like a lighthouse beacon, to create a circular laser-plane reference over a large area of the field. The optical laser "pie slice" was tested, but ARS did not develop a laser-plane configuration, as concurrent work was underway in industry (details below).

ARS continued the research by conducting mathematical modeling of the laser-controlled plow and simulating its performance on the electronic analog computer for various field and soil conditions that would normally be expected in actual installations (Fouss, 1971). Results of these simulation studies and confirming field tests provided guidance to industry and drainage contractors on the proper and optimum mounting position for the laser-receiver unit on plows and high-speed trenching equipment. Mounting the laser-receiver at the optimum position on the drain machine was critical to achieving good grade-control accuracy when installing drains, especially with the high-speed plow. The field tests also confirmed that plow-in speeds less than about 40 m/min provided the best accuracy under most conditions.

Concurrent Industry Research and Development

In 1965, Robert H. Studebaker, vice-president of Process Equipment Co., Tipp City, Ohio, began development of a laser control device for a motor grader. This application was different from that for the plow in that it was not desirable to limit the grader to straight-line travel along curved highways being constructed or in a field to be graded. Thus, a laser-plane rather than a laser-line reference was needed. The prototype plane reference was obtained by projecting an expanded and re-collimated laser-beam vertically onto a rotating prism. The prism deflected the beam 90°, thus generating a plane reference, much like a rotating light beacon. By proper adjustment of the mountings of the laser transmitter on the tripod, a laser-plane of any desired slope could be projected over the field. The receiver or detector system, which was mounted directly on the grader blade, consisted of a 300 mm long array of solid-state silicon cells. These photocells were covered with a narrow bandpass optical filter that only the 6,328 Angstrom laser light could pass through. The cells were grouped in five sets to indicate high, high-slow, on-grade, low-slow, and low feedback corrections. The transverse control of the grader blade was maintained with an electronic cross-slope level sensor system. Additionally, Studebaker developed a single photocell sensor as a laser-beam detector for a sliding attachment on a surveying rod; this was the beginning of the laser-plane surveying system in which one person could survey land.

Technology Transfer

Immediately following a seminar and demonstration of the ARS-developed prototype laser-beam automatic grade-control system to Ohio land drainage contractors at their annual conference in Worthington, Ohio, in early 1967, Studebaker met with Fouss and Teach to review progress and compare ideas. Soon thereafter, Studebaker and Teach entered into an agreement to form the Laserplane Corporation, which was located at Dayton, Ohio; Teach was named president of the new firm. The concepts for laser-beam control that were developed and tested by ARS and OSU for subsurface drainage equipment, particularly as related to mounting position for the laser-beam receiver and mode of feedback control, were adopted with some modification for use in their development of a commercial version of the system for drainage equipment. The initial field trials and demonstration of the first commercially available Laserplane grade control system were conducted cooperatively with ARS researchers at the September 1968 Ohio State Farm Science Review near the OSU Airport in Columbus, Ohio. At this field show, a few thousand farmers and perhaps as many as 100 drainage contractors viewed the system's performance on a wheel-type tile trenching machine installing corrugated plastic drain tubing. It was ironic that plow-type drainage equipment, for which the laser-beam system was originally developed, was not yet commercially available in the U.S. or Canada. By the fall of 1970, most farmers in the Midwestern states of the U.S. were demanding that their drainage systems be installed with laser-beam controlled machines. By early 1971, most tile trenching machines were equipped with laser-plane grade control, and plow-type equipment was beginning to make its presence in the market place (Fouss and Reeve, 1987).

The ARS researchers designed and had industry fabricate (under USDA contract) a larger drainage plow to test its capability and grade-control accuracy when installing corrugated plastic drains at a maximum depth of 1.8 m (Fouss, 1971). It should be pointed out that the ARS researchers were not authorized to purchase an early model drainage plow available in Europe for further ARS testing. The European plows at the time, however, were smaller than needed for the continuing ARS and OSU research, and had limited (less than 1 m) installation depth capability. The larger ARS-fabricated plow was equipped with the commercial Laserplane grade-control system, and it was demonstrated at two field shows: (1) a drainage field show held in Monticello, Illinois, in August 1971, and (2) the September 1971 Ohio State Farm Science Review (fig. 5). A new drainage plow imported from England, and equipped with laser-plane control, was also demonstrated at the 1971 OSU Farm Science Review. Even larger crowds attended these field shows than the earlier 1968 demo on the trenching machine (fig. 6).

Testing of this larger plow by ARS and OSU researchers continued for several months after the Ohio State Farm Science Review field demonstrations to document the grade control accuracy and to confirm the optimum mounting position for the laser receiver on the plow frame (Fouss et al., 1971). These additional tests also confirmed that ground speeds for the plow that were less than 40 m/min provided good grade control accuracy, but speeds greater than this could result in poor grade control accuracy. These were important guidelines for the new industry. After 1971, all plows and almost all high-speed trenchers sold in the U.S. were equipped with laser automatic grade control as standard equipment. In European countries by the early 1970s, the laser-plane grade-control system was adopted for most of their drainage machines, both trenchers and plows.

Figure 5. ARS experimental draintube plow with Laserplane automatic grade-control system installing 100 mm drain.

Figure 6. Demonstration of ARS draintube plow at the 1971 Ohio State Farm Science Review for farmers.

Worldwide Applications of Laser Alignment/Guidance Technology

The laser-beam and laser-plane systems for alignment and/or guidance were adapted worldwide by agriculture and industry to many other applications, such as land surveying, land grading (for surface irrigation and surface drainage), rice paddy construction, open-ditch excavation, pipeline construction, tunnel excavation, building construction/alignment, highways, other engineering and construction work, and military applications. The eventual worldwide application of laser control technology that improved land grading operations for surface irrigation resulted in significant increases in surface irrigation efficiency, a great reduction in irrigation costs through savings in the volume of water that needed to be pumped, and savings in the cost of energy (e.g., electrical power) for pumping. The improved surface irrigation also resulted in both increased and more uniform crop yields from irrigated farmland. Many of these applications are now considered standard practice. The night-time operation of the laser system in many of these applications is also noteworthy, and sometimes preferred, such as land grading during the night to take advantage of good weather conditions.

Summary

The laser-beam automatic grade-control system was developed and demonstrated by ARS researchers (ASABE Members) in cooperation with their university and industry partners (many of whom were also ASABE Members) to provide the technology to improve the speed and accuracy for installation of modern corrugated-wall plastic drain tubing with high-speed equipment for agricultural subsurface drainage systems. After initial ARS technology transfer to industry in 1966-1967, only about two years were required until the first commercial laser grade-control equipment was available and in use by drainage contractors. Over the next 20 years, continued developmental research by industry, at times in cooperation with government researchers, resulted in significant improvements and innovations, plus very important expanded applications worldwide to many agricultural, construction, industry, and military tasks. The economic returns from applying this technology worldwide have been tremendous. The laser-beam and laser-plane systems are considered the engineering standard method today for almost all alignment and guidance applications.

Acknowledgements

The authors wish to acknowledge the contributions and express thanks for the support of the following individuals throughout the research and development project for the laser-beam automatic grade-control system: T. W. Edminister, Administrator, USDA-ARS (deceased); Glenn O. Schwab, Professor, Department of Agricultural Engineering, The Ohio State University (deceased); Ronald C. Reeve, Research Investigations Leader, Soil and Water, USDA-ARS (retired); M. Y. Hamdy, Professor, Department of Agricultural Engineering, The Ohio State University (retired); Cecil H. Wadleigh, Director, Soil and Water Conservation Research Division, USDA-ARS (deceased); Jan van Schilfgaarde, Director, Soil and Water Conservation Research Division, USDA-ARS (retired); Cornelius A. Van Doren, Chief, Corn Belt Branch, USDA-ARS (deceased); Ted L. Teach, President, Laserplane Corporation (retired); Robert Studebaker of Laserplane Corporation (deceased); "Jack" Diamond of Caterpillar Tractor Co.; and Marvin E. Jensen, National Program Leader, Irrigation and Drainage, National Program Staff, USDA-ARS (retired).

The authors also wish to express thanks and appreciation for the following two special recognitions of this research:

- The laser grade-control research and development was selected and recognized as a pioneering research project in the first article of a series of "Research Success Stories" to illustrate the value of agricultural research that was published by the Council for Agricultural Science and Technology (CAST) in the Spring 2004 issue of *NewsCAST* (Vol. 31, No. 1, pp. 15-18).
- The development of the "Laser-Beam Automatic Grade-Control System" was designated as the 48th ASABE Historic Landmark on May 3, 2007, at the Department of Food, Agricultural, and Biological Engineering of The Ohio State University.

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Fouss, J. L., N. R. Fausey, and R. C. Reeve. 1971. Draintube plows: Their operation and laser grade control. In *Proc. ASAE National Drainage Symposium*, 39-42, 49. St. Joseph, Mich.: ASAE.

APPENDIX III

Related Short-Story #1 (Re: Concerning advice sent (mailed) by Mr. Edminster in the early-1960's suggesting that I should **not** use a Laser-Beam for a grade-control reference because it would be too expensive.)

In the fall of 1971, prior to the reorganization of ARS from Divisions to Areas, I was invited by Mr. Edminster to attend a meeting held at Pine Mtn., GA and he asked that I make a presentation entitled, "**Drainage Mechanization *Dream* Accomplished**." As I recall, this was one of the final meetings, if not the final meeting, for the leaders and some attending invited scientists (like me) of the Soil and Water Conservation Research Division (SWC). My presentation, illustrated with many color slides, reported on the completion of the research project Mr. Edminster had assigned to me in 1960 at Columbus, OH with the objective to develop Materials and Equipment to install plastic tubing for subsurface agricultural drainage. The final research development accomplished the rapid and accurate installation of corrugated-wall polyethylene plastic drainage tubing with plow-type equipment (not a trencher) that was controlled for depth and drain gradient with an automated laser-beam system to operate the hydraulic depth regulation system on the plow. The presentation also covered observations and results from two successful field demonstrations of the new drainage technology at industry and university sponsored field shows for farmers, drainage contractors, and other research and extension professionals.

Following my presentation, two key questions were asked of me and Mr. Edminster; one directed to me by the Branch Chief in Texas, Dr. Rex Johnston, and the second directed to Mr. Edminster by Dr. Sterling Hendricks, one of ARS's Pioneering Scientists. Dr. Johnston stood up and asked in a fairly loud voice, "What did you say?" Actually, he kind of startled me because he asked the question so quickly and loudly. He asked me to repeat what I had said at the end of my talk. I then indicated that as ARS scientists we had taken the drainage technology development project as far as we should go as a Government research agency, and it was now up to industry and drainage contractors to commercialize it. I then added that it was time for me to move onto other research. At that point, Dr. Johnston stood up on his chair, overlooking the group, and stated that he thought that this was a ***first*** in ARS. He stated that, "most of us here, myself included, are trying to figure out how to make our job on our current project or assignment last until we can retire, but this young man wants another job!!" There was a lot of laughter, but I do not recall laughing myself (ha). Mr. Edminster then asked if there were any other questions for Jim. Dr. Sterling Hendricks (one of ARS's pioneering scientists) stood up and asked a question of Mr. Edminster, saying, "I don't have a question for Jim, but do have one for you Mr. Edminster." He said that he wondered if Mr. Edminister "was going to have to fire this young man for success, as I understand it Jim was told that he should not use the laser because it was too expensive?" Dr. Hendricks had evidently heard of Mr. Edminster's message to me several years before. Mr. Edminster did not respond directly to Dr. Hendricks, but turned his attention to the entire group and asked, "Are there any more questions for Jim?" As there were no more questions, the program as planned was continued. Those moments following my presentation have stuck with me for years.

[I will add here that Dr. Hendricks and I had a very good relationship with each other, and he provided extremely valuable advice to me earlier in my research career. I have always considered him one of my more important mentors during the early years of my ARS career. One bit of advice he gave me was that I should not do too much literature research before trying out a new idea, because I might end up talking myself out of trying it. He noted to me that how different scientists implemented an idea was often the factor of why it didn't work for some and did for others. As I recall, he was also a believer in serendipity in research accomplishments and success.]

Side-Story #2 (Re: Loaned laboratory Laser unit from the Battelle Memorial Laboratory)

After we had the laboratory Laser unit for our testing set up about two weeks in the basement of the Agricultural Engineering building, we were visited by an OSU Police Officer. He was looking for a lost or stolen laser unit from the Battelle Memorial Laboratory. My associate at Battelle had evidently not told anyone in his laboratory that he had loaned the unit to me before he traveled to Europe, and thus the police considered that we had stolen it in his absence. Because we had the laser set up and kind of hidden in the dark basement of the Ag. Engr. Bldg., it made it even more suspicious to the officer. The Battelle associate was not easy to make contact with in Europe, and it took a while for the Physics Dept. at Battelle to contact him and receive communications back that he had in fact loaned the laser unit to me while he was out of the country. Thus, we got to keep the unit to continue our testing.

I will add here that this was the first of about four times during our work on the ARS drainage technology project at OSU that we had some run-in with the OSU Campus Police concerning various issues or complaints. By about the third occasion the Police got to know us and had learned what our project was all about and thus became much more understanding and accommodating in a manner to help us out. We even became friends with one of the Police Officers who had only one arm, which was huge and very strong. Specific details of other events will be covered in other sections, or side-stories, in this write-up.

Related Side-Story #3 (*about the interruption of the night-time laser receiver early testing underneath Ohio Stadium*.)

A few days before we were planning on conducting the sensitivity tests for the prototype laser-beam receiver unit, I contacted the Chief of Police at the OSU Police Station and advised him what we were going to do one or two nights later that week. He didn't seem to want any details but acknowledged my call; I asked him to advise the night-time patrol officer of our plans to be under the Ohio Stadium, and he indicated he would take care of it. On the first night we set up for our sensitivity testing under the Stadium, Norm and I had completed a few sensitivity tests with the prototype laser receiver unit and reviewed the results. We were satisfied that the receiver was quite sensitive to relatively small vertical movements (displacements) of the projected laser beam above and below the center-line (gap between the horizontal rows of phototubes) of the receiver unit. We decided upon the next test with a smaller gap between the phototubes, and I think we had completed that adjustment on the receiver unit. I then went to my station at the receiver unit and Norm returned to be at the laser-beam projection unit. We had just started the next test sequence when all at once an OSU police car came roaring through Gate #9 entrance into the Ohio Stadium area where we were working. The police car came to a short sliding stop that stirred up the dust that was on the concrete floor of the Stadium. As the laser-beam was projected through the area where the dust was stirred up, the projected laser beam was reflected off the dust particles in the air and a red-line appeared through the space near the OSU police car. By this time both Norm and I were running from our positions during the laser testing toward the police car. The police officer opened his driver's side door quickly, and I noticed that his driver's side door window was down and the dusty laser red-line projected directly through the open car door window. As the policeman was exiting his car quickly he noted the red-line projected through his open window and quickly jumped back into the car seat. At that point I was essentially next to the car and it struck me funny and I laughed a bit. It was a bad time for me to laugh, because the police officer did not think there was anything funny about it.[22] We tried to explain to the officer (who only had one arm; *a very large one*) that we had permission from the Police Chief to work there at night, but the officer wasn't listening. He grabbed me by the shoulder with his very strong lone arm and pushed me into the back seat of his cruiser (with a wire-cage separation from the front seat), and started off toward the Campus Police Station. Norm followed in the Government pickup truck. When we were all in the police station, with the help of other officers at the station we finally got the officer who found us at the Stadium to settle down enough to ask him to call the Chief of Police. By that time, however, it was pretty evident that the Chief had not informed anyone at the station of our work plans in the Stadium area that evening. The call to the Chief was made and he confirmed our request to him, but he could not remember my name for sure, however he came close enough to my name that the office staff knew we were the ones he had talked with. At that point all was forgiven, and we shook the hand of the officer we had encountered at the Stadium. After that the one-armed officer would stop by the Agr. Engr. Dept. and have a friendly talk with us from time-to-time, especially when we were working outside of the building. While the loaded semi-trailer was still parked at the curb outside Ives Hall, we completed the assembly of the laser grade-control system on the Caterpillar tractor and mounted plow.

We had the D-7 Cat and mounted plow loaded on our low-boy tractor-trailer truck parked along the street curb right outside of Ives Hall. Our rig took up 3 parking spaces and that caused two or three reports to the police department over the next 2 or 3 months about our excessive use of parking typically used by faculty and staff members. The one-armed policeman got us out of those jams on each occasion. However, the parked equipment caused one last parking/traffic problem on Campus. When it was time to move the truck and haul the Cat and Plow to the field for testing we had more trouble. The truck axle broke as we pulled out of the 3 parking places, and the truck sat in the middle of the street over the next 4 days until repairs were completed and we could continue with moving the equipment. The one-armed policeman helped in that situation too.

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[22] It should be added at this point that this interruption was soon after the popular James Bond movie "***Gold Finger***" was shown only a few weeks before. That was the movie with a scene where an the attempt was made to cut James Bond in two halves with a Ruby Laser Beam as he was strapped to a steel plate. The Ruby Laser cut through the steel plate, but James Bond was freed from his bindings before the cutting laser reached him. The very high energy Ruby Laser could cut steel with its brilliant red beam, but the red beam helium neon gas laser beam was a very low-energy system. It is not known if the OSU police officer might have made a flash connection to that James Bond movie scene.

APPENDIX IV

(*Reference for my Ph.D. dissertation that is included as a PDF file on the CD attached below*.)

Fouss, James L. 1971. Dynamic Response of Automatically Controlled Mole-Drain Plow. Unpublished Ph.D. Dissertation, Department of Agricultural Engineering, The Ohio State University, Columbus, OH; 133 pp.

APPENDIX V

(*Reprints of these four publications included on the following pages)*

Fouss, J. L. and Hamdy, M. Y. 1972. Simulation of a laser beam automatic depth control. TRANS. of the ASAE 15(4): 692-695.

Fouss, J. L., N. R. Fausey, and R. C. Reeve. 1972. Draintube plows: Their operation and laser grade control. Proceedings of the ASAE National Drainage Symposium. pp. 39-42, and 49. Available from ASABE, 2950 Niles Rd., St. Joseph, MI 49085.

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Fouss, James L., Ph.D., P.E. 2014. **Setting Standards:** “Accountability for depth and grade-control accuracy”, **Drainage Contractor** magazine, p. 14, Nov. 2014 issue (published in Ontario, Canada).

Simulation of a Laser Beam Automatic Depth Control

J. L. Fouss and M. Y. Hamdy
MEMBER ASAE MEMBER ASAE

PRESENT grading methods using sight-bars, stretched wires, etc., are slow, costly, and unsatisfactory for high speed drainage equipment. A laser beam automatic depth control system was developed specifically to meet the requirements of this equipment. It was successfully tested on a plow-type machine, called a "draintube plow", for installing corrugated plastic drainage tubing (Fouss, 1968 and Fouss and Reeve, 1968). Laser control systems are now commercially available and are being used on tile trenching machines (Studebaker, 1971). Through proper design and adaptation, laser control systems can be used for both elevation and guidance control on several types of machines such as those used in earth moving, land leveling, ditching and road grading, not only for agricultural purposes, but for civil and military projects as well.

The purpose of this paper is to report on a design procedure which utilizes analog computer simulation to adapt a laser control system to various kinds of machines. As an example, the design, adaptation, and adjustment of the laser control system for the draintube plow machine will be discussed.

DESCRIPTION OF CONTROL SYSTEM

The automatic grade control system uses a laser beam projected from a portable, tripod-mounted source as an elevation reference and a machine-mounted receiver (Fig. 1). The laser beam is projected above and parallel to the proposed drain line toward the drainage machine and the receiver output is sensitive to deviations from the beam. An on-board controller unit detects changes in the receiver output and energizes the solenoid of a hydraulic valve. The valve activates a hydraulic cylinder to correct the hitch point elevation, thereby controlling the plow depth automatically.

The laser is basically a light amplifier emitting a well-collimated light beam that can serve as an elevation reference line from which the operating depth of the drainage machine is controlled (Fouss and Reeve, 1968). Since the effective range of this reference line exceeds 1,000 ft under most conditions, its use eliminates the need for setting a multitude of sight-bars, or stretching a guide wire supported at 50 to 100 ft intervals.

The laser unit used in the research was a compact, lightweight, helium-neon gas type with a light beam output of 0.3 milliwatt at 6328 A deg wave length. The laser beam was "chopped" mechanically by a motor-driven, slotted disc at a frequency of 150 Hz so that the receiver can distinguish it from extraneous light. The beam was also projected through a 10-power telescope to increase its diameter and to reduce its divergence. The light intensity was distributed across the diameter of the laser beam in a Guassian wave-front.

Consideration was given to the use of a laserplane type reference created by either optically spreading the beam of light (a pie-shaped plane) or by rotating the laser source (much like a light house beacon), but this was determined not necessary for early experimental work.* A laserplane system is now available commercially, however, and is in use on several kinds of drainage and earth moving machines (Studebaker, 1971).

Receiver

The receiver consisted of two horizontal rows of phototubes closely spaced one above the other in a multibaffled shadow box to reduce the effect of sunlight, and two follower amplifiers (Fig. 2). Each row had 7 phototubes connected in series with a 90-volt battery and a 1 M ohm resistor. The voltage drop across the resistor was amplified by a follower amplifier and used to drive the controller. The receiver could be positioned on the plow frame anywhere between the hitch point and the plow blade. Assuming that the plow would operate very close to the design depth, the change in receiver elevation would be a fraction

*SWC, ARS, USDA, research project outline: "Light beam activated automatic grade-control device for drainage machines"; Work Project/Work Unit No. SWC-020-eCol-2, Code No. Col-65-7a; 1965, Columbus, Ohio.

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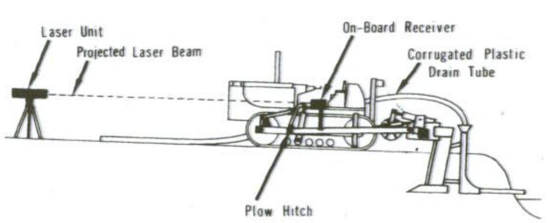

FIG. 1 Schematic of the laser beam automatic depth and grade control system for a draintube plow.

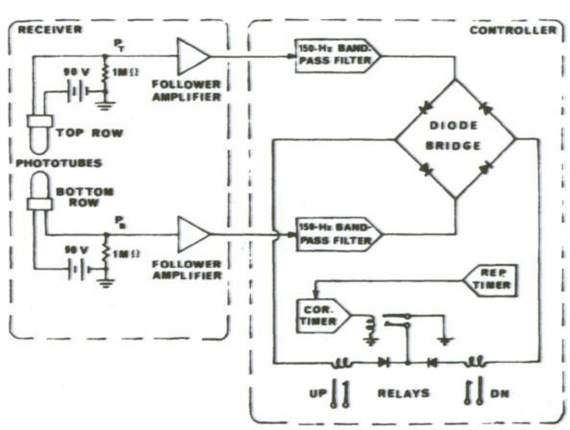

FIG. 2 Receiver and controller circuit diagrams.

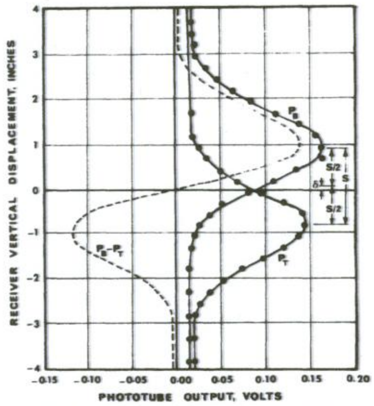

FIG. 3 Variation of phototube outputs with vertical displacement.

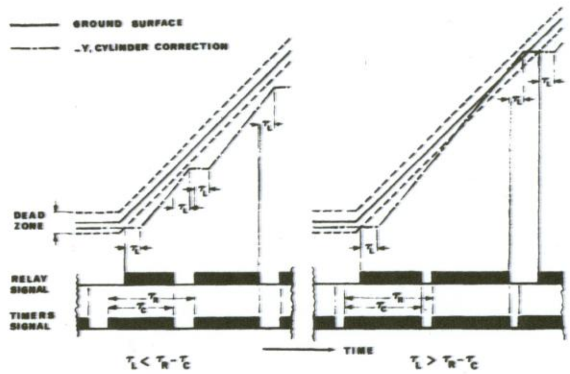

FIG. 4 The effect of the controller setting on the cylinder correction.

L_R of the change in hitch elevation, where L_R is the distance of the receiver from the blade relative to the frame length. A more detailed description of the receiver and specifications for the phototubes are given by Fouss and Reeve (1968).

The receiver elevation was adjusted relative to the beam until the outputs of both rows of phototubes were equal. The output of the top row, P_T, and bottom row, P_B, were then measured through a vertical displacement of ± 4 in. (Fig. 3). The two outputs are not identical and the receiver geometrical center (half the distance S between peaks) deviates a distance δ from its null point (where the two outputs are equal). The difference between the two outputs, $P_B - P_T$, which the diode bridge of the controller detected, is essentially linear and very sensitive to the receiver motion relative to the beam over a fairly wide range around the null. The hydraulic system would bring the receiver null point to coincide with the beam center-line, that is, bring it to zero elevation.

Controller

The controller unit consisted of electronic filters, a diode bridge, timers and relays (Fig. 2). A band-pass filter was used for each receiver row to filter out all signals except those with a frequency in a narrow band around 150 Hz, thereby causing the system to ignore light sources other than the 150 Hz chopped laser beam. The polarity of the voltage difference, which indicates the direction in which the receiver was off-center, was discriminated by the diode bridge circuit. Subsequently, the bridge would activate the proper up or down relay to energize the solenoid of the hydraulic valve. The dead-zone of the diode circuit was adjustable by changing the gains of the follower amplifiers. The receiver was adjusted to a ± 1/4 to ± 3/8 in. deadzone.

The controller had replication and correction timers which acted as a synchronizing clock to control its mode of operation. The replication timer determined the period τ_R of a replicated cycle at the start of which the controller would be set and able to energize the hydraulic valve solenoid. The correction timer determined the portion τ_C of the replication period during which the controller could energize the solenoid, and beyond which it would be disabled until the start of the following replication cycle. The controller circuitry was designed such that once a relay was closed, it remained closed until the end of τ_C and then would open for the remainder of τ_R regardless of the receiver elevation after closure. The replication period τ_R could be adjusted to any length greater than 0.002 sec, and the correction period τ_C could be adjusted to any portion of τ_R. The controller operation will be illustrated after the hydraulic components are discussed.

Hydraulic Components

The hydraulic system consisted of a solenoid valve and a double acting cylinder to control the hitch elevation. An adjustable flow-divider valve was used on the high pressure pipeline feeding the cylinder side containing the piston rod. It was adjusted to reduce the oil flow into that side to make the piston velocity equal in both directions. The piston velocity was essentially a step function with a time lag $\tau_L \approx 0.15$ sec behind the controller signal; the durations of its acceleration and deceleration were extremely short.

The operation of the controller logic and the hydraulic system is illustrated in Fig. 4 for two cases: τ_L less than and greater than $\tau_R - \tau_C$. The first case shows the disruption in the cylinder motion when the controller was disabled even though the error persisted. The second case shows that the hydraulic valve was not allowed sufficient time to close and when the error persisted, the piston motion was not disrupted while the controller was disabled. Both cases could be called "sampled-digital" control modes, indicating that the error signal is "sampled" by the controller before energizing the valve solenoid. As τ_C approaches τ_R, a pure "on-off" control mode is approximated and eventually approached if τ_R becomes infinitesimal.

COMPUTER SIMULATION

An attempt was made to simulate the entire control system (receiver, controller, hydraulic valve, and cylinder) on a fully expanded EAI TR-48 analog computer (Electronic Associates, Inc.)† The computer, however, did not have enough logic capacity to simulate the controller. There was also some concern that the nonlinear characteristics of the available logic (dead-zone, hysteresis, etc.) may not match those of the controller.

The approach was modified to incorporate the controller itself into the circuit to provide the needed logic. This necessitated the addition of the follower amplifiers to drive the controller since the computer did not generate enough current to drive it. The use of the controller and follower amplifiers as

†Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by USDA.

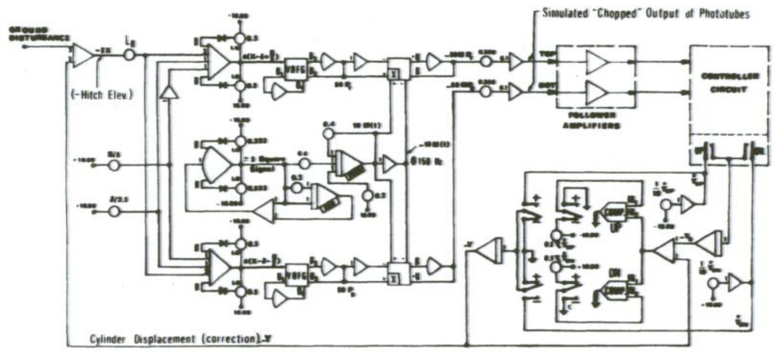

FIG. 5 Analog computer circuit and hybrid components.

"hybrid" components of the analog circuit also meant using their actual characteristics in the program which would have been very difficult to simulate. The computer circuit (Fig. 5) had to be programmed for real time operation because of the presence of the hybrid components. The analog sections which simulated the phototubes and the valve and cylinder will be discussed in some detail.

Phototube Simulation

The output of each row of phototubes (Fig. 3) was generated by a 19-segment VDFG (variable diode function generator) as a function of the row elevation measured at the point producing the peak output. Defining the receiver null point elevation x, the elevation of the top and bottom rows would be $(x - \delta + \frac{S}{2})$ and $(x - \delta - \frac{S}{2})$, respectively. Each row elevation was computed by a separate amplifier and used to drive the corresponding VDFG. The δ and S signals were generated by one potentiometer each for both amplifiers for convenience.

The row elevation amplifiers had a gain of two to magnify the input to the VDFG's around the peak elevation and were soft-limited at about ± 10 v to prevent overloading. The VDFG's were set to take advantage of these variable gains. The break points were taken on each side of the peak elevation at ¼-in. intervals, which gave excellent accuracy in a ± 2½-in. range around it. The soft limits extended the usefulness of the VDFG's to at least ± 5 in. around the peak elevation with reasonable accuracy (the row outputs changed very little beyond ± 2½ in.), thereby covering the full range shown in Fig. 3.

The outputs of both rows were modulated by the "chopped" laser beam at a 150 Hz frequency. The outputs at a fixed receiver elevation were observed on a scope to study the chopping effect. The modulating function M(t) was found to resemble a square on-off periodic function with first order transitions caused by the gradual covering/uncovering of the beam source. A 150-Hz, ± 5-v square wave generator was, therefore, included in the computer program and its output was passed through a first order filter. The generator used an integrator with a gain of 600 which later had to be reduced slightly to correct for the wave imperfections due to the hard limiting diodes. The filter used an integrator which was biased to produce a signal between 0 and 10 v (instead of ± 5 v) and its gain was adjusted until its output matched those of the receiver rows (at a gain of 2,000).

The VDFG's outputs were modulated by multiplying them by the filter output. The miltipliers' outputs were properly scaled down to drive the follower amplifiers. The controller was tested and found to respond to the simulated phototube outputs.

Valve and Cylinder Simulation

The up and down switches in the controller were used in the computer circuit to obtain the up and down piston velocity signals, respectively. It is not necessary for the up and down piston velocities to be the same in order to accomplish the simulation. Their combined output was integrated to provide the hypothetical piston displacement y_h which would have been obtained if the hydraulic system had no time lag τ_L. The difference between y_h and the actual piston displacement y was used to operate the up and down double-pole, double-throw, relay comparators (shown in their "open" position in Fig. 5). Each comparator was biased through one of its switches such that, assuming that the piston was not moving (y = constant), the up or down comparator would "close" at τ_L behind the controller up or down relay, respectively. Once it was closed, the bias was removed and it could not open until $y = y_h$ which occurred only at τ_L after y_h had stopped changing, that is, at τ_L after the controller relay had opened.

The comparators operated identically to, and with a time lag τ_L behind, the controller switches, and, therefore, were synchronized with the piston motion. Their second switches were used to conduct the appropriate up or down piston velocity into an integrator to compute the piston displacement y and provide the correction in the hitch elevation. The hitch elevation is simply the tractor deviation from the ground datum less the piston displacement. The tractor deviations were assumed to follow the ground surface irregularities.

COMPUTER ANALYSIS

The computer simulation was based on "standardized" ground surface profiles consisting of step, ramp, saw-tooth, and sinusoidal functions and their combinations. It was felt that if the control system displayed good performance and stability with these inputs, its performance should be acceptable for the irregular and random inputs typical for the actual ground surface profile.

The computer analysis was checked against the observed response of the actual control system to step and ramp inputs and by its hunting characteristics at zero input while the tractor was not moving. A step input was obtained in the field by deactivating the control system, displacing the receiver vertically by the desired step, and then reactivating the control system. The ramp input was obtained by steadily moving the receiver vertically at a prescribed rate using a hand crank and screw mechanism. The observed response agreed very closely with that determined by computer simulation. In addition, the observed and simulated hunting cycle at zero input had both the same amplitude and frequency.

Since the controller timers were independent of, and not synchronized with, the computer circuit, simulation runs could not be repeated. Therefore, all computed information needed to evaluate the system performance had to be recorded simultaneously for each run. A Honeywell, 7-channel, FM magnetic tape recorder (Model 8107) was used to record this information and to play it back later, one channel at-a-time, for observation and plotting.

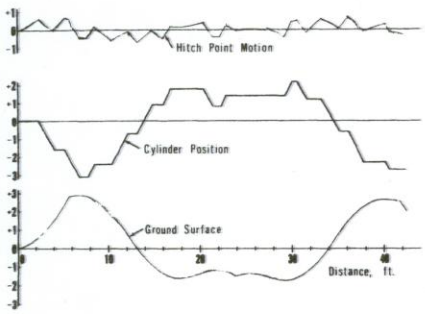

FIG. 6 Sample of computed results for 2½ ips cylinder velocity.

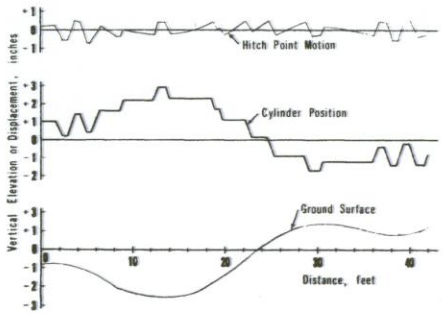

FIG. 7 Sample of computed results for 3 ips cylinder velocity.

No attempt will be made here to present the results for all combinations of variables and parameters covered in this study. Only sample results will be presented to illustrate the value of computer simulation in analyzing and adjusting a control system. The results of two simulation runs using hydraulic piston speeds of 2½ and 3 in. per sec are shown in Figs. 6 and 7, respectively. The values of other pertinent parameters used in both runs are given in Table 1. All parameters were set by potentiometers in the computer circuit except the dead-zone (set by the gains of the follower amplifiers) and the replication and correction periods (set by potentiometers in the controller timers circuit).

Comparison of the simulation results of Figs. 6 and 7 reveals that the higher piston speed improves the control system accuracy in maintaining the hitch point position near zero elevation. This was found true for several types of ground surface inputs. The hitch motion did not "overshoot" the zero elevation with each corrective motion and was above or below it for prolonged periods. The double-step correction occurred in both Figs. 6 and 7 and the hitch point was maintained to within about ± 3/4 in. of the zero elevation. This agreed well with field observations where the auto-control maintained the hitch within ± 1.0 in. of the zero elevation for several ground surface conditions.

DISCUSSION

The computer simulation of the automatic depth control system offers an excellent method to analyze and adjust the system for optimum performance. To accomplish this using field tests alone would be difficult, expensive, and time consuming because of the random variation in field conditions and the numerous combinations of system parameters. The computer simulation does not eliminate the need for field evaluation, but can significantly reduce the number of parameter combinations that need to be tested under natural field conditions.

The simulation results revealed that the "sampled digital" control mode with $\tau_L > (\tau_R - \tau_C)$ tended to improve the system performance over that obtained with a pure on-off control mode when the receiver dead-zone was $\geqq \pm$ ¼ in. and the piston speed was $\geqq \pm 3.0$ in. per sec. For many inputs, particularly those changing slowly or gradually, the pure on-off control mode may not provide sufficient "overshoot" and the hitch elevation would be above or below the zero elevation for prolonged travel distances. The pure on-off mode gave a performance comparable to the sampled-digital mode only when the hydraulic gain was increased considerably, which often resulted in high amplitude hitch point "hunting". On the other hand, the simulation showed that for a receiver with a narrow dead-zone (e.g., $\leqq \pm$ 1/16 in.), the pure on-off control mode was satisfactory and the hydraulic gain could be adjusted to give acceptable hunting characteristics. The use of a proportional control mode would be hard to accomplish with the fixed discharge oil pump and may not improve performance; in fact, for some inputs it may result in a larger displacement of the hitch point from the zero elevation.

TABLE 1. PERTINENT PARAMETER VALUES

Parameter	Value
L_R	1.00
S	1.50 inch
δ	0.00 inch
τ_L	0.15 sec
τ_C	0.60 sec (approx)
τ_R	0.70 sec (approx)
Dead-Zone	± 0.25 inch (approx)

In general, for the on-off type control mode, optimum performance occurred when the control system caused the laser receiver to "hunt" about the beam center-line for a zero input. For the draintube plow, a "hunting" cycle with a frequency of about 1 Hz and an amplitude of 1 in. (measured at the hitch point) provided a good compromise of sensitivity and stability over several types of ground surfaces.

In the study reported here, the system performance was evaluated on the basis of the accuracy of maintaining the plow hitch near the zero elevation. The plowing depth was assumed to follow the hitch elevation with a time lag behind it. In later studies (not reported here) by Fouss, et al. (1971), the dynamics of the plow were modeled and included in the simulation, thus providing a means to optimize the position for mounting the laser receiver on the frame of the plow.

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DRAINTUBE PLOWS: Their Operation and Laser Grade Control

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"PLOWING-IN" corrugated plastic drainage tubing with plow-type equipment automatically controlled by a laser beam grading system, is a modern subdrainage method beginning to be used in several areas of the United States and Canada. The idea of installing drains with equipment called "Draintube Plows", is not new as discussed by Dr. van Schilfgaarde in his paper at this Symposium, regarding "Drainage—Yesterday . . .". The engineer's viewpoint has long been one of speeding up the installation of drains by eliminating the slow trenching and backfilling operations—most approaches taken have involved some adaptation of the "mole drainage plow".* The "plowing-in" of drains became practical, from a materials handling standpoint, with the introduction of coilable, corrugated-wall plastic drain tubing. In this method, the drainage tubing is merely "fed" into the ground through a slit opening created by passage of a blade through the soil, thus eliminating the conventional trenching. Soil erupted by the plow blade can be pressed down easily and rapidly by running a track of the crawler tractor over the slit opening after installation, thus eliminating backfilling. The high speed of installation is the major advantage of the "plow in" method; drain installation at a rate of 70 to 150 fpm ground speed, or 1,500 to 4,000 ft of drain laid per working hour, are typical with the latest equipment.

This paper describes the operational and/or performance characteristics of Draintube Plow equipment; criteria for mounting and/or adapting laser grade control equipment; efficient field work procedures; and areas requiring further equipment development work.

TYPES OF DRAINAGE PLOWS

Several different plow-type drainage machines have been developed but, basically, they fall into two groups as to the method of depth control, (a) depth-gage wheel, and (b) long floating-beam. The depth wheel type is best suited where the land slope is uniform and constant depth plowing can be used, such as on much of the irrigated lands of the Western United States. On irregular ground surfaces, it would be very difficult to accurately control the depth wheels fast enough to maintain grade in the drainage channel, especially at normal ground speeds of 70 to 150 fpm. Willardson (1970) discussed the use of a large depth-gage wheel controlled plow for installing corrugated plastic drains in the Imperial Valley, California. Further attention will not be given here to the depth-wheel type plow.

The long floating-beam type plow is well suited for operation on the irregular ground surfaces commonly encountered on most of our cropland. The floating-beam principle of operation is illustrated in Fig. 1. For the case shown in the schematic, a steady-state plowing depth is assumed and the hitch height is held constant above the average ground surface datum during forward motion. The counteracting rotational moments about the hitch pin (a pivot point) due to the plow weight (mg) and soil resistance (R) balance each other and the plow is said to operate with a "floating-beam action." Step changes in the vertical position of the hitch relative to the ground surface reference are not immediately reflected in the plowing depth. The plow blade adjusts or "floats" to a new equilibrium depth as the tractor moves forward; as much as 5 beam-lengths of ground travel may be required for the blade to reach a new equilibrium depth after a step-change in hitch height. This characteristic time-lag in response permits the use of conventional automatic feedback control of the plow's hitch height to maintain a desired drain channel gradient.

Fouss (1971) studied the basic response characteristics of a long floating-beam pole plow.† He found that in a silt loam soil, changes in plowing depth in response to changes in hitch height were approximately linear, but not directly proportional: for example, a ± 1-in. vertical displacement of the hitch (held constant after change) resulted in a ∓ 1.25-in. change in plowing depth (difference between steady state plowing depths). This characteristic response will occur for all drainage plows and is governed somewhat by plow blade design, but is influenced more by the changes in soil resistance on the moving blade as plowing depth changes. In general, the draft on a soil cutting blade can be expressed as a power function of depth; experience indicates that the draft function for many soils varies with the 2.0 to 3.0 power of depth. Again considering rotational moments about the plow hitch pin (pivot), one sees that the constant moment due to the plow weight is opposed by a soil resistance force mo-

†A portion of this study involved the mathematical modeling and analog computer simulation of the dynamic response of a floating-beam mole plow; these results will be published in a future paper.

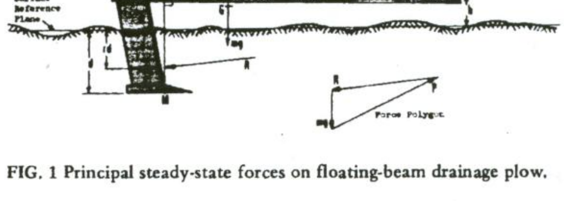

FIG. 1 Principal steady-state forces on floating-beam drainage plow.

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*A summary of drainage mechanization research will be available in the ASA Monograph 14, Drainage for Agriculture, Chapter IV: "Drain tube materials and installation," by J. L. Fouss (in preparation).

ment that varies nonlinearly with plowing depth. Thus, the "floating" adjustments in plowing depth are greater than changes in hitch height. Therefore, for a wide range of topography, accurate grade control for the long floating-beam plow *cannot* be achieved by controlling the hitch such that it travels on a line parallel to the desired drain gradient, as assumed in earlier work (Fouss and Fausey, 1967; Fouss and Reeve, 1968; and Fouss, 1968). Proper control of the hitch motion for accurate grade control is discussed later.

DESIGNS OF FLOATING-BEAM DRAINTUBE PLOWS

A few crawler tractor drawn drainage plows developed and operational by the early 1970's, for the installation of corrugated plastic tubing, utilized the floating-beam principle. One of these plows, manufactured in England and called the "Badger Minor"‡, was patterned after a unique design developed by Ede (1961, 1965) in England. Actually this plow might be said to operate with a "floating blade" action. The blade and tractor are connected by a pair of rollers which run in a curved track that is mounted on the rear of the tractor. The center-of-curvature of this roller track acts as a virtual hitch point which coincides approximately with the center of the crawler tracks. The plow blade is thus nearly isolated from most pitching movements of the tractor. Depth and gradient are controlled by raising and lowering the imaginary hitch point; this is accomplished by hydraulically moving the roller track frame relative to the tractor mount. Thus the Badger Minor plow operates, in principle, as a long, floating-beam plow; other features of this plow are discussed by Prof. Irwin in his paper at this Symposium. A similar drainage implement called the "Zor Plow", developed in Canada, uses two nonparallel, "floating" links instead of the roller track to make the connection with the blade.

The draintube plow prototype shown in Figs. 2 and 3 was designed and developed by the authors§ under a USDA, ARS, SWC research project conducted cooperatively with The Ohio State University and the Ohio Agricultural Research and Development Center. The plow was fabricated under Government contract by the Process Equipment Company of Tipp City, Ohio. The basic plow design consists of a tool-bar mounted blade, through which 4-in. diameter corrugated plastic tubing can be installed to a 6-ft maximum depth in a medium clay soil. This requires a crawler tractor capable of developing at least 60,000 lb of drawbar pull; performance of the grade control system and ground-speed control are improved if the tractor is equipped with a torque converter type transmission. The twin draft links connected to the tool-bar ends serve as the long, floating-beam (split beam): each beam is hitched to the tractor at the rear side of the bulldozer blade. The draft links, or twin beams, were arched and extended above the crawler tracks so that the tool-bar length (width of plow frame) could be kept at 11 ft maximum to facilitate transporting the equipment. The two hitch points are spherical pivots, and the tool-bar to draft link connections each provide a vertical axis of pivot. Thus, the tool-bar and split-beam assembly can "swing" in a horizontal plane to permit steering the tractor or to lay curved drain lines, and in addition permits the plow blade to be maneuvered around buried stones. The plow's operating depth is regulated by raising or lowering the hitch points with the dozer blade; the same hydraulic cylinders used to position the dozer blade (above the ground level) thus provide depth control for the plow. The large hydraulic cylinder on the rear of the tractor is used only to lift the plow out of the ground and transport it; in plowing position this cylinder is put into a "floating" mode, that is, it carries no weight. Because of the downward pull component, having the hitch points forward of the tractor improves traction efficiency and dynamic stability of the crawler tractor. For the prototype plow, the hitch is about 24 ft forward of the plow blade, and can be positioned from 2 to 6 ft above the ground surface with the dozer blade. For any given height of the plow hitch above the ground, the plowing depth can be adjusted to the desired level by changing the angle between the tool-bar and draft links; large turnbuckle screws are provided to make this adjustment (see Figs. 2 and 3).

The structural members of the plow frame were designed with large cross-sections to create rigidity: springiness of the frame would cause severe problems in controlling plowing depth and thus drain gradient. The plow was constructed of T-1 type steel to provide high ultimate strength. The plow blade was designed to reduce soil resistance (draft) by applying the following concepts: (a) the upward sloping leading edge of the blade causes lifting of the soil as the blade passes through it, thus reducing soil cutting force; and (b) the thicker leading edge of the balde moves the soil aside sufficiently to reduce frictional drag on the relatively large surface area on the sides of the blade shank. The enlarged leading edge encompasses the corrugated tube feeding-guide (see Fig. 2). The use of a vibrating blade was not considered for this plow.// For drains larger than 4 inches in diameter, a separate tube-feeding tool can be attached behind the present blade. Corrugated tubing 5 and 6 inches in diameter probably can be satisfactorily installed in this manner, but installation of larger sizes is questionable.

Two smaller versions of this ARS plow design are envisioned, namely, a

‡Trade and company names are included in this paper for the benefit of the reader and do not imply endorsement or preferential treatment of the product listed by USDA.

§The authors wish to acknowledge the assistance of Mr. Zigbigniew Stolarczyk and Mr. Dennis Bassett who prepared the engineering design drawings, and special appreciation and thanks to Dr. Glenn Schwab for assistance and encouragement throughout the project. Furthermore, the authors gratefully acknowledge the loan of a large crawler tractor from The Caterpillar Tractor Co. for testing and evaluation of the prototype plow.

//A vibratory-type plow does reduce draft requirements, but not necessarily total horse power demands when the power unit to drive the vibrator is considered in the total. In many areas of the U.S., the smaller tractor used on a vibratory plow can be transported over highways without special permits and thus may prove quite advantageous.

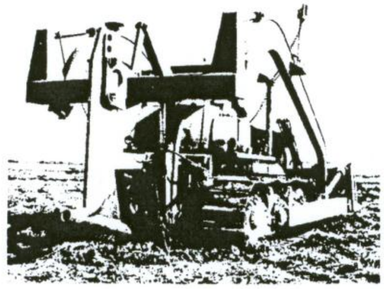

FIG. 2 ARS Draintube Plow in transport position.

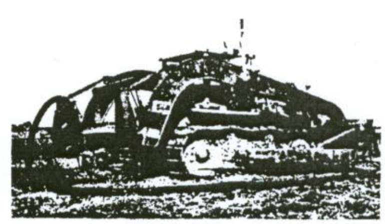

FIG. 3 ARS Draintube Plow in operating position.

medium depth plow (4- to 5-ft depth capability), and a shallow depth plow (3-ft maximum depth). These plows, of course, would be pulled by smaller crawler tractors than used on the prototype. The medium depth plow design would be used mainly in the Midwest, whereas the prototype plow developed for the design testing program would be used mostly in the Great Plains states and western regions where deep drainage is needed in conjunction with irrigated lands. The shallow depth plow might be considered still experimental, in that its use to install small diameter, shallow, and closely spaced corrugated plastic drain-tubes looks promising for subdrainage of heavy clay and/or fragipan soils.

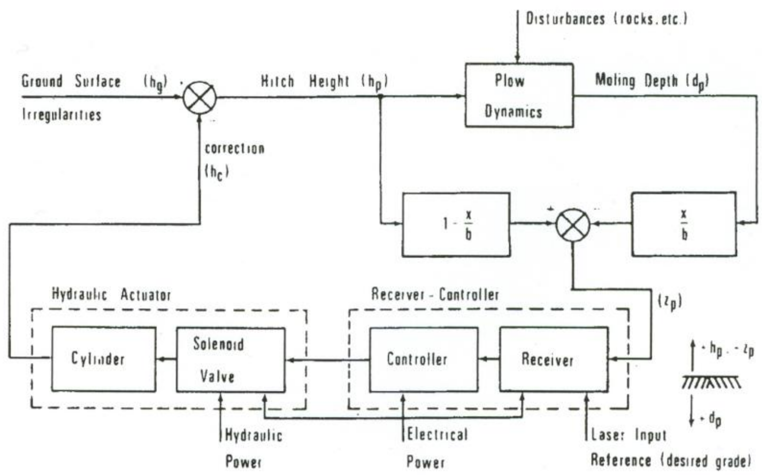

FIG. 4 Block diagram of plow and laser depth-and-grade feedback control system.

ADAPTING LASER AUTOMATIC DEPTH AND GRADE CONTROL SYSTEMS

The successful operation of high-speed plow-type drainage equipment is dependent upon the ability to control and maintain the gradient of the drain-tube installed (Fouss, 1965). One of the first experimental laser beam automatic grade control systems was designed to meet the requirements for the draintube plow equipment (Fouss and Fausey, 1967; and Fouss, 1968). Commercial versions of laser beam grading systems became available, however, before operational drainage plows and the new automatic systems soon were accepted and used by contractors on conventional trenching machines.

The basic principle of automatic depth and grade control for a draintube plow using a projected laser beam datum (grading reference), and an on-board laser tracking-receiver which automatically controls plowing depth via hydraulics, has been previously reported (Fouss, 1968). The same principle of auto-control applies to the conventional wheel-type trenching machine that is equipped with a "shoe". However, the difference in normal ground speed between the trencher and plow (i.e., 15-25 ft per min and 70-150 ft per min, respectively) makes it necessary to consider the machines independently when adapting or mounting a laser system for automatic grade control. Here the draintube plow will be discussed in considerable detail to illustrate the importance of various factors and system parameters considered in the control system adaptation.

The prototype ARS draintube plow (Figs. 2 and 3) was equipped with a "laserplane" type of automatic grade control system produced by the Laserplane Corp. of Dayton, Ohio (Studebaker, 1971). In this system, an elevation reference plane is generated above the working surface by rapidly rotating (5 cps) the projected laser beam (much like a lighthouse beacon), where one axis in the plane is aligned parallel to the desired drain gradient, and the cross-axis is aligned either horizontal or parallel to the general land slope. The effective range of the rotating "laser beacon" is at least 1,000 ft, and thus the laser elevation reference plane covers a large field area with each setup of the laser transmitter (e.g., a field within a 75 to 100-acre circular area).

The laser tracking-receiver, mounted on the plow frame (Fig. 3), consists of a vertical array of closely spaced photocells, which are connected to a logic and controller circuit. The controller in turn operates the tractor's hydraulics to raise or lower the plow hitch (by moving the dozer blade up or down) to provide the corrective feedback control motion, and thus automatically maintains the receiver nearly centered on the laserplane reference. The laser receiver unit is very sensitive and can electronically detect the center of the 1-in. thick (approximate) laserplane reference within a "dead zone" of about ±1/16 in. However, the proper use of this electronic detection signal in the feedback control system is most important to achieve stable and yet accurate automatic grade control.

The draintube plow and laserplane (or laser beam) feedback control system can be represented in block diagram form as shown in Fig. 4, where b is the plow's beam length (Fig. 1), and x is the distance rearward from the hitch to the laser receiver unit mounted on the plow beam (Fig. 3); symbols for other variables are identified in Fig. 4. For the "Laserplane" system, the receiver-controller output is digital; either an up-, down-, or no-correction "signal" is generated every 200 msec. (i.e.. for each rotation of the "laser beacon"). The solenoid valve and hydraulic cylinder (which cause the hitch to move up or down) are thus operated in an on-off (or step-wise) manner by the digital output of the controller unit. Since the sole-

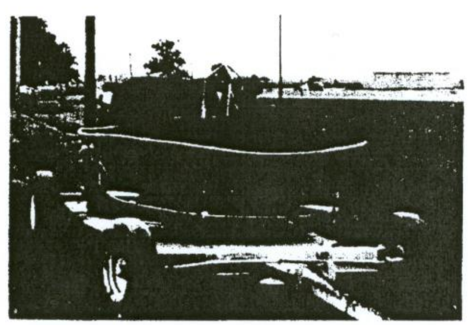

FIG. 5 Wagon-mounted uncoiling mechanism for corrugated plastic drain tubing.

noid valve opens and closes with a characteristic time-delay relative to the inputs from the controller, the duration that the controller unit "holds" the valve open (for an up- or down-correction) is important to system performance. For the prototype draintube plow, the controller was factory adjusted such that up- or down-correction signals were held "on" for 180 msec. out of 200 msec.** The time-delay of response for the solenoid valve was greater than 20 msec., therefore, the automatic system operated essentially as a pure "on-off" feedback control. The hydraulic flow rate from the pump was adjusted so that the hitch height would limit-cycle ("hunt") with an amplitude of 1 to 1-1/4 in. and at a frequency of 1/2 to 1 cps. Because of the long time-lag in response of the floating-beam plow to change plowing depth, the up-and-down cyclic motion of the hitch point at this amplitude and frequency does not cause significant variations in the drain channel gradient. This approximate "on-off" mode of control was predicted to be satisfactory for use on the draintube plow by Fouss and Hamdy (1970) from analog computer simulation studies of the feedback control system, and later by Fouss (1971) where the plow dynamic (Fig. 4) effects were also included in the simulation.

The above discussion relates to sensitivity and stability of the feedback control system, but possessing these two characteristics does not guarantee accuracy of grade control for the draintube plow, or any other drainage machine for that matter. Undoubtedly, one of the more critical factors relating to grade control accuracy is being able to determine the optimum position for mounting the receiver unit on the drainage machine's frame (i.e., the x/b ration in Fig. 4). Referring to Fig. 4 one can see that, for a receiver positioned directly over the hitch (i.e., x/b = 0) deviations of the hitch height are detected directly (1:1) by the receiver, but variations or changes in plowing depth are not detected; this receiver position (x = 0) maintains the hitch point such that it travels on a path (line) parallel to the desired drain grade, but this does not provide positive grade control because the plowing depth is not 'directly' related to hitch height. Where the receiver is positioned directly above the plow blade (i.e., x/b = 1), variations in hitch height are not detectable until the plow blade actually varies from its desired depth, thus resulting in significant fluctuations in the plowing depth and the drain channel gradient. Thus, a compromising (or optimum) receiver position is somewhere between the hitch and blade. Based on computer simulation results, Fouss (1971) proposed that $x/b \approx 5/6$ as a "general guideline" for good automatic grade control of a long floating-beam draintube plow. We conducted several field tests with the prototype draintube plow (Figs. 2 and 3) for the cases $x/b \approx 1/2, 2/3, 3/4$, and $5/6$. The results confirmed that values in the range, $3/4 < x/b \lesssim 5/6$, provided the best grade control accuracy.

The accuracy of grade control was checked and recorded in the field by use of a movie camera equipped with a telescopic lens. The camera, mounted on a sturdy tripod, was set up directly behind the plow with the line-of-sight pointing in the direction of travel and also aligned parallel to the projected "laserplane" reference. A reference mark was made or noted on the plow blade which laid on the line-of-sight (i.e., cross-hairs in the telescopic lens). If the plow blade stayed "on grade" as travel across the field progressed, the reference mark on the blade remained aligned with the line-of-sight. In subsequent reviewing of the movie film, a horizontal center-line across the projection screen (not on film) served as a line-of-sight datum.

To summarize the above results, both depth and grade are positively controlled only if the laser receiver is positioned closer to the plow blade than to the forward hitch point of the plow beam. This is particularly true if different soil types are encountered along the path of a drain line. To explain in more detail the type of grade control error which results from the laser receiver being too far forward of the plow blade, the following example is given. Consider a drain being installed where the land is flat (no slope), except possibly for a few minor ground surface irregularities. Thus for a drain to be laid at a grade, the plowing depth must decrease as the tractor moves across the field (assuming direction of ground travel is up-grade). The normal procedure under these conditions is to set the laser transmitter to project one axis of the laserplane parallel to the desired gradient for the drain line. The field studies showed that the resulting drain gradient was steeper than the slope at which the laserplane was projected.†† This type of response in the plowing depth (which is similar to the relationship between hitch height and plowing depth) occurs because the laser receiver is too far forward and a 'direct' relationship does not exist between height to the receiver above the ground surface and plowing depth.

For the desired mounting position, that is $x/b \approx 5/6$, a "mounting arm" can be extended almost directly forward of the plow blade from the tool-bar (i.e., the receiver mast would extend above the tractor cab from the rear), thereby essentially eliminating any depth and grade errors resulting from sideward "tip" of the plow frame when the off-center experimental mounting positions were used (Fig. 3).

FIELD WORK PROCEDURES

One practice of handling the corrugated plastic drainage material in the field is to place the coiled tubing on a spindle mounted on the drainage machine from which it uncoils and feeds directly into the plow's hollow-bladed installation tool. More than one coil of the plastic tubing can be carried on the machine, and as one coil is nearly installed, forward travel is stopped to permit coupling to the next roll so installation can continue. Another practice for field handling is to uncoil the tubing and lay it offset but parallel to the proposed drain line, as shown in Fig. 3. Several types of uncoiling mechanisms have been devised to speed up this operation; one of the more successful ones in use is shown in Fig. 5. With such a mechanized uncoiling device, one man can keep tubing laid out on the ground ahead of the drainage machine.

Our experience with the prototype draintube plow led us to recommend that the tubing be laid out on the ground in advance; this results in a much more efficient field operation of the high-speed plow equipment because it is not necessary to stop for coupling on each new roll of tubing. Considering an average ground speed of 125 fpm with the drainage plow, one roll of tubing (each about 250 ft in length) is installed about every 2 min of ground travel. For installations made during extremely hot weather (e.g., 90 F and up), however, feeding directly from the

**Note: The controller can be factory adjusted to provide *two* durations of correction to obtain minor and major feedback motions; for some kinds of machines this is desirable or even necessary.

††Note: This characteristic response was predicted in computer simulation studies by Fouss (1971).

(continued on page 49)

DRAINTUBE PLOWS

(continued from page 42)

coil may be desirable to prevent excessive stretch of the plastic tubing; this could keep the tubing cooler since its exposure to sunlight rays prior to installation would be reduced. The tube guides and feeding devices should be designed to reduce frictional drag on the tubing as much as possible. In any event, the percentage stretch of the corrugated tubing installed with a high-speed draintube plow can be less than that occurring with slower moving trenching machines (assuming the same frictional drag factor) because the tubing is under a "stretch load" a shorter period of time during the placement operation. [Reference discussion on stretch versus time by Drablos and Schwab in their paper presented at this Symposium.] To prevent excessive initial deflection of the tubing once it is in the "mole channel", several minutes should be allowed to elapse before the installation slit is closed by compaction (especially on hot days).

A drain line is easily started and connected with the main or collector drain if a back hoe is used to excavate a short (4-5 ft) starting trench. If the starting trench is not provided next to the main, then the plow point can be started into the ground 15-20 ft on the other side of the main and allowed to "float" down to a depth just above the main as the plow approaches the intended intersection; hand excavation can be used if necessary to remove the loosened soil to make the "Tee" connection between the main and lateral.

Future reports will cover such additional items as calibration and operation of laser receiver-controller equipment, operation in rocky soils (which has not presented severe problems), making proper tube couplings, and, the economics of operating the plow-type drainage equipment. Because of the high installation rates, large jobs must be available for the contractor to profitably operate the new equipment.

ADDITIONAL EQUIPMENT DEVELOPMENT NEEDED

The principal features of the draintube plow equipment that needs further design and development work pertain to special applications, such as, installation of larger size tubing (up to 6-in. diameter at least); simultaneous installation of the corrugated tubing with a gravel envelope (as used in the Western U.S.), and using a vibratory leading edge on the plow blade to reduce draft.

With the recent interest expressed by industrial firms and drainage contractors, it seems certain that draintube plows patterned after the design discussed here will soon be commercially available.

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(Figs 2 & 3 corrected)

Watch your drainage plow speed

Plowing-in corrugated plastic drainage tubing with a trenchless system which is automatically controlled by a laser beam grading system is a modern method of subsurface drainage installation that is receiving rapid acceptance throughout the world. Most draintube plows today are based upon the principle of a long floating-beam to assist in grade control; the floating-beam is a physical beam (figure 1) or an 'imaginary' beam depending upon plow design. The design or shape of the plow blade or shank and the structural features of the plow govern to a large extent the draft required to operate the unit. Undoubtedly, the more critical factors relating to grade control accuracy are the ability to determine the optimum position for mounting the laser receiver unit on the draintube plow frame, and in determining the maximum ground speed permissable to maintain grade control accuracy as frequent grade control corrections or adjustments are made by the automatic laser system. Most draintube plows today can accurately install corrugated plastic drains to grade if properly adjusted and operated.

I will concentrate my discussion upon three fundamental principles related to operation and grade control:

(a) Basic response characteristics
(b) Laser receiver position
(c) Ground speed

Basic response characteristics

In studies of the basic response characteristics of a long floating-beam plow (Fouss, 1971 and Fouss, et al., 1971) it was shown that in a silt-loam soil, changes in plowing depth in response to changes in hitch height were approximately linear, but not directly proportional: For example, a 1 inch vertical displacement of the hitch (held constant after change) resulted in a 1.25 inch change in plowing depth (after the plow had regained a steady state). This characteristic response occurs for all drainage plows and is governed somewhat by plow blade design but is influenced more by changes in soil resistance on the moving blade as plowing depth changes. Due to changes in soil consistency within the path of a plow blade operating at a given depth, the plowing depth may change due to the change in forces on the blade and where the hitch point height is not changed. Therefore, for a wide range of topography and changing soil types in the field, accurate grade control for the long floating-beam plow cannot be achieved by controlling the hitch such as it travels on a line parallel to the desired drain gradient.

Laser receiver position

The plow dynamics relationships also indicate the characteristic time lag of response, in that if the hitch height is changed one unit, the moling depth will change to a new equilibrium value but only after several feet of ground travel; for some plows a 1 inch change in hitch height will result in a new equilibrium moling depth only after about 50 to 70 feet of ground travel has occured. This latter time delay factor implies that in order to return the plowing depth to a corrected or desired level for grade control, it is necessary to over-correct the hitch height in order to speed up the dynamics of a plow depth change.

For a receiver position directly over the hitch, deviations of the hitch height are detected directly (1:1) by the receiver, but variations or changes in plowing depth are not detected; this receiver position ($x = 0$) maintains the hitch point such that it travels on a path parallel to the desired drain grade, but this does not provide positive grade control because the plowing depth is not directly related to hitch height, it also depends on blade altitude. Where the laser receiver is positioned directly above the plow blade (i.e., $x = b$), variations in hitch height are not detectable until the plow blade actually varies from its desired depth of operation, thus resulting in significant fluctuations in the plowing depth and the drain channel gradients due to the sluggish dynamics of the long-beam plow.

Therefore, a compromising receiver position is somewhere between the hitch and blade of the plow. Based on computer simulation results and field testing it was proposed that a value of $x/b = 0.833$ be used as a general 'guideline' for 'good' automatic grade control with a long-floating beam draintube plow (re: Fouss, 1971). Figures 2 and 3 show field test results for the ARS plow for the cases x/b of 0.28 and 0.84, respectively; it is noted through the standard deviation ** of the moling depth from the desired depth that the laser receiver position of $x/b = 0.84$ improved grade control accuracy. These tests were conducted at a ground speed of approximately 150 ft per min (a moderately high speed) using a laser system (for details of the system characteristics, see Fouss, et al., 1971). Grade control accuracy as expressed in terms of standard deviation from desired depth was noticeably improved by decreasing forward ground speed (but detailed test data is not available for direct comparison with the results shown).

Figure 4 illustrates a problem condition where the laser receiver indicates that the plow is operating on grade but in fact the drain is being laid above the desired grade line (the deviation from grade sketched in figure 4 is exaggerated in scale); this condition occurs when the plow encounters soil requiring greater draft and therefore a greater suck angle on the plow point in order to maintain depth. The laser grade control system causes the hitch to be lowered until the receiver is again within the laser beam, but the attitude of the entire machine is such that the drain is installed at the wrong depth. The further the laser receiver is ahead of the plowing blade, the worse this condition becomes. Attempts are being made to use a combination of depth control and slope control (or attitude control) system to correct this problem, but

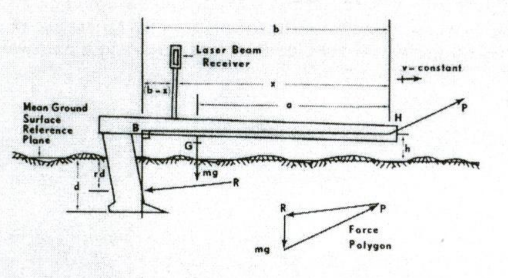

fig. 1.

Principal steady-state forces and geometrical relationships of laser controlled floating-beam draintube plow.

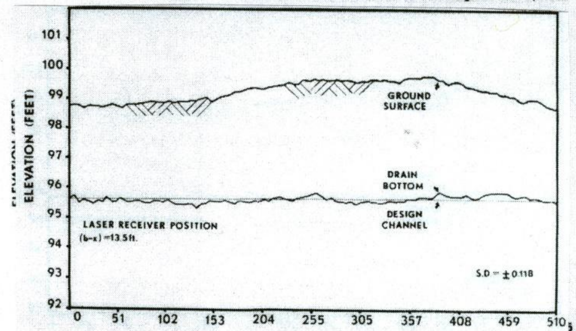

fig. 2.

Field test evaluation for ARS plow with laser grade controls x/b = 0.28.

and laser receiver position

by James L. Fouss

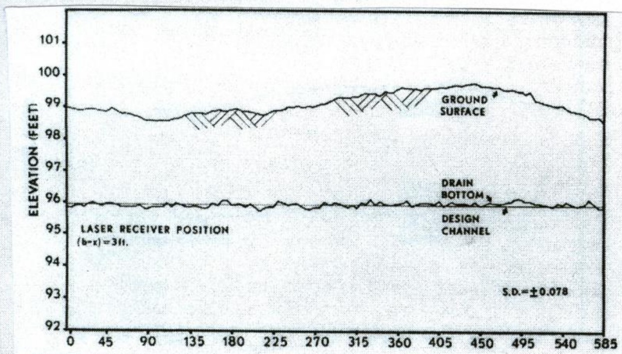

fig. 3.

Field test evaluation for ARS plow with laser grade controls x/b = 0.84.

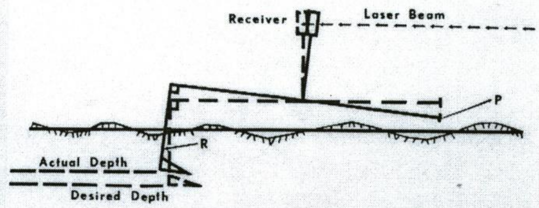

fig. 4.

Poor grade control can result from improper laser receiver position on a draintube plow when encountering increasing draft conditions.

in some cases it will require that force be used to either cause the plow to penetrate to the deeper depth in the harder soil or in the case of soft soil to hold it out of the ground, and therefore depth fluctuations could increase in magnitude if ground speed is not reduced significantly. Of course, in a condition in which the plow tends to settle to a deeper depth because of the soft soil condition, the reverse of the situation described in Figure 4 occurs; that is, the hitch is in an elevated position, the laser receiver is right on beam, but the plow depth is such that the tube is installed too deep. Thus, the selection of the optimum position for the laser receiver is paramount for good grade control accuracy under a wide range of soil conditions.

Ground speed

The effects of excessive ground speed can exaggerate the effects of improper or slightly less than optimum positions for the laser receiver. If the plow tends to drift off grade, then the faster the plow is moving, the further it will drift off grade before it is corrected back to the desired grade line. Therefore, it is recommended that ground speed always be reduced when large numbers or frequent corrections in grade are being made with the laser system, for example in very uneven ground, such that laser grade control corrections are not constantly over-compensating or getting behind. Many contractors know that performance can be improved at any given ground speed by increasing the rate of hydraulic cylinder movement to make the corrections, and this is true for some soil conditions, however, as the plowing speed slows down, the high speed hydraulics tend to cause the control system to 'hunt' rapidly. In effect then we may need a 'gain control' on the hydraulics to compensate for this, provided that we don't over-do the job by trying to maintain an extremely high ground speed.

I have noted a practice among contractors to move the laser receiver further ahead, thus 'settling down' the grade control system. This works by appearance but in fact can cause the plow to drift at a low frequency above and below the desired grade line (see Figure 3). One of the simplest ways of checking this on any given machine, and especially a plow (since the bottom of the plow trench is not readily available), is to set the laser grade control up on a completely horizontal line and drive the plow along a predetermined path (it is not necessary to lay pipe for this test). After the plow has travelled several feet (say, 75 to 100 feet), one can set up a conventional surveyor's level behind the machine and aim at a spot on the plow blade to coincide with the cross-hairs of the level as the machine is driven away — this observation gives you a direct indication of the vertical deviations from grade line of the plow blade. This type of test or quick check on every machine is recommended from time to time, especially as new soil types are encountered. ■

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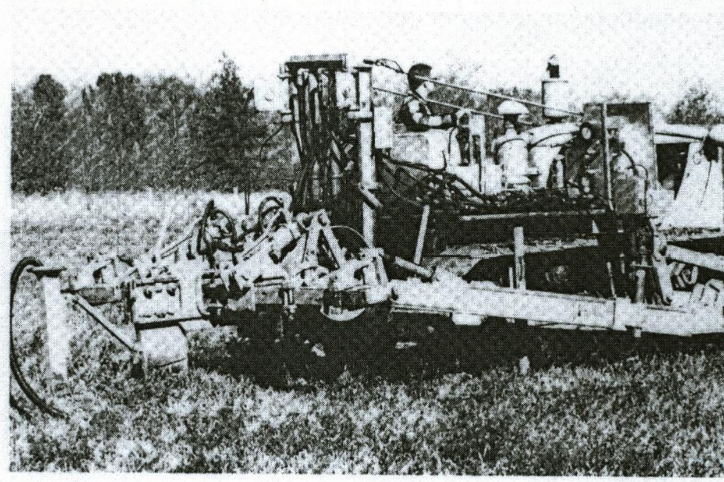
***The statistical standard deviation of the moling depth was computed from elevations taken in the bottom of the plow trench at 5 foot intervals along the drain; this can be thought of as an average deviation. The accuracy of this below ground level surveying measurement was considered to be - 3/8 inch (or - 0.03 ft.).*



USDA-ARS tool-bar mounted, floating-beam mole plow adapted to install corrugated plastic drainage tubing.

1978 Drainage Contractor magazine

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Setting Standards

"Accountability for depth and grade-control accuracy", by James L. Fouss, Ph.D., P.E.

Since the mid-1970s, the province of Ontario has had a plow testing and certification program and is currently updating the program. With the significant increase in plow-installed subsurface drainage over the last several years in both the U.S. and Canada, it seems that it is time that a drainage plow testing and certification program be considered for development in the United States. Corrugated plastic (HDPE) subsurface drain tubing installed with plow-type equipment has increased dramatically since the early 1970s, in both Canada and the United States. All of the early drainage plows were equipped with laser-based automatic depth and grade-control systems. Older systems have now been upgraded on many plows, and some trenchers, with the modern satellite-based 3-D GPS depth and grade-control system.

More recently, innovative designs for self-contained drainage plows have become available and their acceptance by contractors has significantly increased in the U.S. and Canada. Most of the modern plows are very powerful and capable of operating at greater depths, and can install drainage pipe faster than earlier plows. However, current regulations in Canada do not set limits on the maximum speed the plows should be operated at in order to ensure drain tubes are installed accurately at design depth and grade. Although the U.S. has current subsurface drainage design and installation specifications and standards though the American Society of Agricultural and Biological Engineers, the American Society of Civil Engineers, and the Natural Resources Conservation Service of the United States Department of Agriculture, there are no drainage plow performance regulations in place in the U.S.

Ontario's program is based on specifications and standards stated in the Agricultural Tile Drainage Installation Act originally passed in 1973. The act includes a provision for training and licensing of drainage contractors that is administered by the Ontario Ministry of Agriculture and Food and Ministry of Rural Affairs. A similar testing and certification program is not available in the United States.

The advanced features provided by the GPSRTK systems, including automatic steering of the plow or trencher, should be considered and included in the plow-testing standard. The GPS-RTK system now available may allow higher ground speeds with modern plows, if the machine hydraulics responds quickly enough to the control system feedback signals at the higher speeds to maintain design drain depth and grade. Mounting a second satellite GPS-RTK receiver directly above the drainage tube feeder boot attached to the plow blade may provide the enhanced accuracy needed to establish guidelines for a plow-testing program. The second receiver would monitor and record the GPS co-ordinates (X, Y, and Z-h, where "h" is the height at which the second receiver is mounted above the bottom of the tube feeder boot) at the bottom of the drain tube as it emerges from the tube feeder boot and is installed in the soil channel created by the plow. The co-ordinate data recorded by the second receiver would more accurately define the final X, Y, and Z-h locations along the line of the installed drain tube than a recording of co-ordinates from the controlling receiver mounted on a forward reaching cantilever arm attached to the plow blade. For advanced drainage plows, the Z-h data versus ground travel could be displayed graphically to the plow operator, along with other performance information.

Without regulated programs, it is the contractor's responsibility to find solutions ensuring accuracy and quality of installation.

Prior Grade-Control Performance Tests on Pull-Behind Drainage Plows

In 2000 & 2001, C. J. Knueven, a graduate student at The Ohio State University in the Agricultural and Biological Engineering Dept., conducted field tests on a Pull-Behind Drainage Plow (manufactured by the Liebrecht Co.) to evaluate to determine the depth and grade-control accuracy possible with the Laserplane controlled plow for several experimental conditions. This work was jointly supervised by Dr. Larry Brown (OSU) and Dr. Norman Fausey (ARS-USDA) at Ohio State. The depth and grade-control for the Pull-Behind Drainage Plow was monitored and recorded by mounting a second Laserplane-GPS Receiver (a GeoStar System) on the blade or pipe feeder boot of the Laserplane controlled plow as corrugated plastic drainage tubing was installed. The GeoStar System manufactured by Spectra-Precision (prior to its acquisition by Trimble, Inc.) was composed of an analog Laserplane Receiver Mast that had a “shuttle” sensor that moved electronically vertically up & down to maintain it in centered contact with the rotating Laserplane light-beam projected above the field. The GeoStar System used geographic position correction signals from the U.S. Coast Guard to obtain accurate X & Y satellite positioning coordinates. Research reports on the field test results are included in the technical papers referenced below; only one of the papers was published by ASABE.

The RTK-GPS receiver system described on the previous pages of this Story is a technologically advance precision positioning system; it can operate from signals from multiple satellites to accurately determine the X, Y, & Z coordinates of the receiver location in rapid sequence as the drainage plow moves across the field. As noted in the previous article, it is recommended that this second receiver be mounted on the pipe-feeder “boot” behind the drainage plow blade for monitoring (and recording) the data to determine the depth and grade-control coordinates for the installed drainage tubing, thus providing a means to evaluate depth and grade-control accuracy for the drainage plow used.

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