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

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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 lightweight 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 upgrade 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 drainpipe (fig. 2).

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

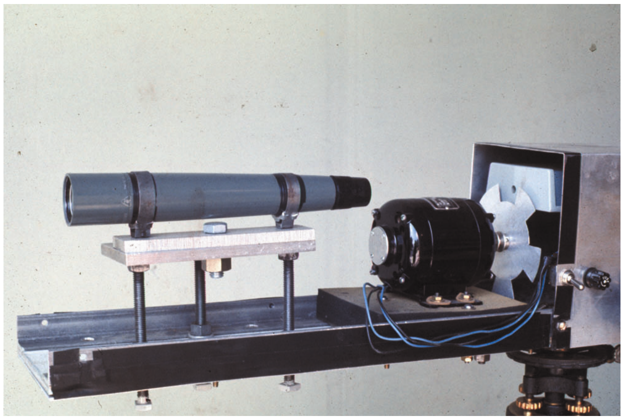

Figure 2. Prototype laser-beam transmitter to project an expanded light signal at 150 cycles/second.

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

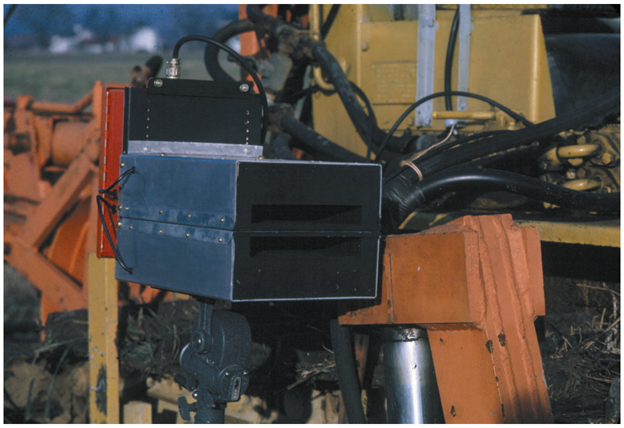

Figure 3. Laser-beam receiver unit with enclosed phototubes mounted on the draft links (beam) of the plow.

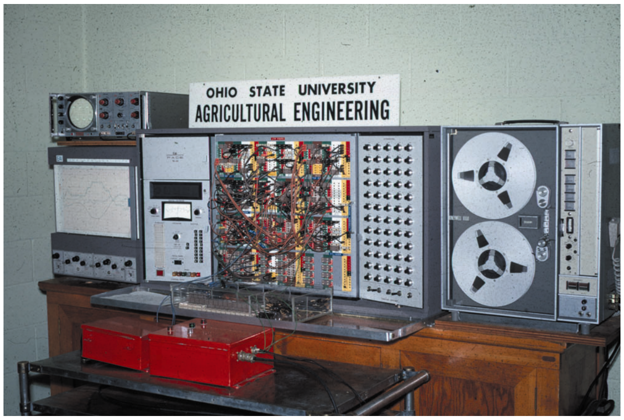

Figure 4. Electronic analog computer simulation of the laser-beam automatic grade-control system on the plow.

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.

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- 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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