NOAA Technical Memorandum NOS NGS 26

MOTORIZED LEVELING AT THE NATIONAL GEODETIC SURVEY

Rockville, Md.
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NOAA geodetic publications

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Specifications To Support Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys. Federal Geodetic Control Committee, Department of Commerce, NOAA, NOS, 1975, reprinted annually, 30 pp (PB261037). (A single free copy can be obtained from the National Geodetic Survey, OA/C18x2, NOS/NOAA, Rockville, MD 20852.)

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Heinz Poetzschke

National Geodetic Survey
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MOTORIZED LEVELING AT THE NATIONAL GEODETIC SURVEY

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ABSTRACT. Since the early 1900's, various forms of motorized leveling modes have been attempted to speed up leveling operations. Because leveling has to be performed in the highly turbulent and fast changing layers of air near the ground, faster progress in leveling is a desirable goal. This will help to minimize the effects of refraction. Also, in motorized leveling heavier equipment can be used than in conventional leveling and, therefore, greater stability is induced in the setup of instrument and rods. A short review of the existing systems of motorized leveling is given, and the operational system of the National Geodetic Survey is described. The results show the improvements achieved with the NGS system.

INTRODUCTION

The term "motorized leveling" is defined as a leveling procedure in which vehicles are an integral part of the entire leveling instrumentation system and are not merely used for transportation to and from the work site. This definition implies that the leveling rods are carried by separate vehicles that also serve to stabilize the leveling rod during observing, while the leveling instrument, the observer, the recorder, and the necessary accessories are carried by another vehicle. Ideally, neither observer nor rod personnel should leave their vehicles to perform their operational tasks.

Leveling and the treatment of the results obtained constitute one of the most complex problems in geodesy. Not only does this work suffer from a lack of redundancy but observations must be performed in the first 2 meters of the atmosphere, which is subject to constant change from turbulence. It is a well-known fact that the first 2 meters of the atmosphere above the ground show a temperature gradient that is about four to seven times greater than that experienced from 2 to 6 meters above ground. The magnitude of the gradient varies with the amount of insolation as a function of cloud cover, diurnal change of the Sun's position, and ground cover which also affects the water vapor content in the air and acts as an insulator. Other contributing factors are the moisture content of the soil and, to a much lesser degree, wind and humidity. All these factors contribute to the undesirable, but almost ever present, refraction phenomenon which adversely affects leveling operations (Geiger 1975).

One way to minimize, if not eliminate, refraction effects would be to raise the height of the line of sight so far above ground as to avoid the first 2 meters of the atmosphere. However, this cannot be accomplished with classical leveling techniques because in this mode the height of the line of sight depends on the height of the observer.

The motorized leveling mode provides an opportunity to overcome the handicap of an observer-dependent height of the line of sight because the observer can be positioned at any height above ground, within practical limits. Only an appropriate structural design of the observing vehicle is necessary to fulfill this requirement. Another advantage of an elevated line of sight is that the length of the sighting distance is more uniform. Smaller obstructions that previously interfered with the line of sight no longer pose an obstacle.

One of the major benefits of motorized leveling is that it lessens field personnel fatigue. This benefit is often underestimated or overlooked, but experience shows that the motorized leveling mode results obtained late in the workday are as reliable as those taken in the early hours, and the number of rejections is reduced considerably.

As early as 1916, the U.S. Coast and Geodetic Survey (now the National Ocean Survey) tried a motorized leveling procedure by using "motor velocipede cars" when the leveling moved along railroad tracks. In the 1916 annual report of the U.S. Coast and Geodetic Survey (1916) we read: "Formerly, the tripod was set upon the ballast of the railroad track, while now it is set rigidly upon a motor velocipede car. The level is placed upon the tripod at the beginning of a day's work and remains there until the day's work is completed. The observing is not now such a strain upon the observer and greater progress can be made. Another innovation was the use of a listing adding machine on which to record the rod readings." (See fig. 1.) This method was used for more than three decades. Since the early 1950's, motorized leveling has been used in its modern form. One of the first users was the Geodetic Survey of Canada. The Canadian rod personnel employed separate vehicles for lower-order leveling work.

Since these early attempts, considerable efforts have been made by the German Democratic Republic (GDR) under the direction and guidance of Professor H. Peschel at the Technical University of Dresden. Since 1962, German scientists, industrial designers, and field personnel researched the development of a motorized leveling system that would satisfy the most stringent requirements of precision leveling, i.e., providing results with an accuracy of 0.2 - 0.4 mm/km, and at the same time increasing productivity and improving the working conditions in the field. After 9 years of experimentation, an operational system (fig. 2) was accepted. Reports by various authors describe the system and results (Bahnert and Schöne 1962, Seltmann 1965, Hüther 1973, Peschel 1974, Steinberg 1978).

The proven economic feasibility of motorized leveling prompted other organizations to accept this method. Although the number of users in other countries is not accurately known, motorized leveling systems have been used in Czechoslovakia, Denmark, Netherlands, Norway, Poland, and Sweden. The Swedish version is an improvement on the GDR design (Becker 1977).

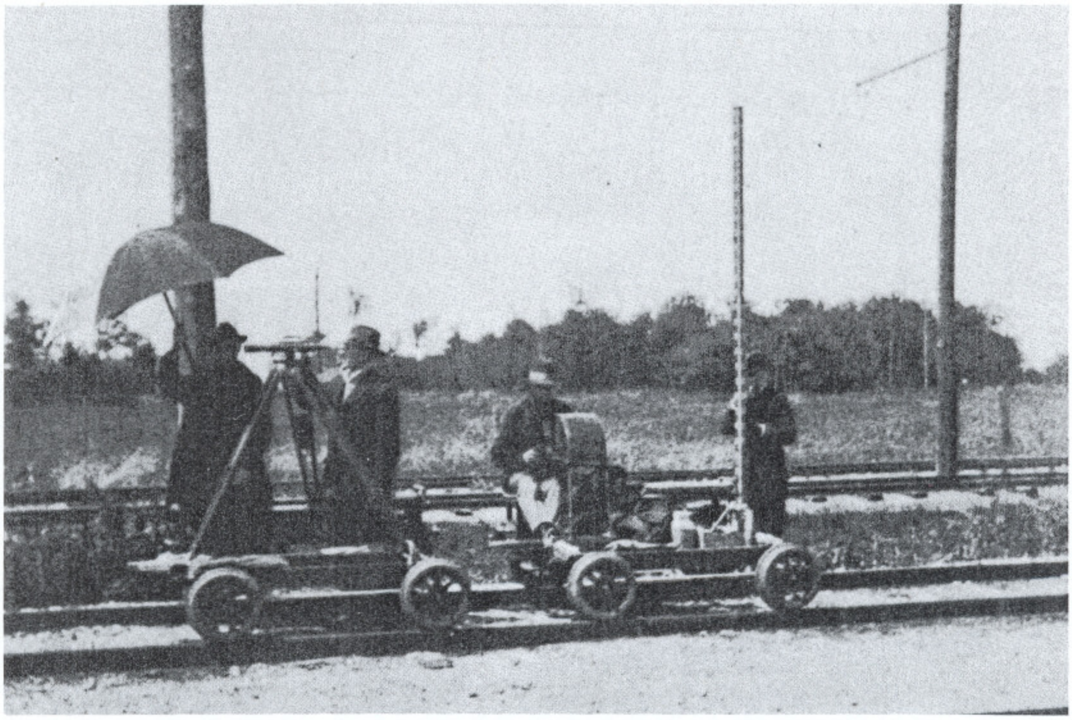

Figure 1.--Motor velocipedes used in precise leveling in 1916 and during the following three decades.

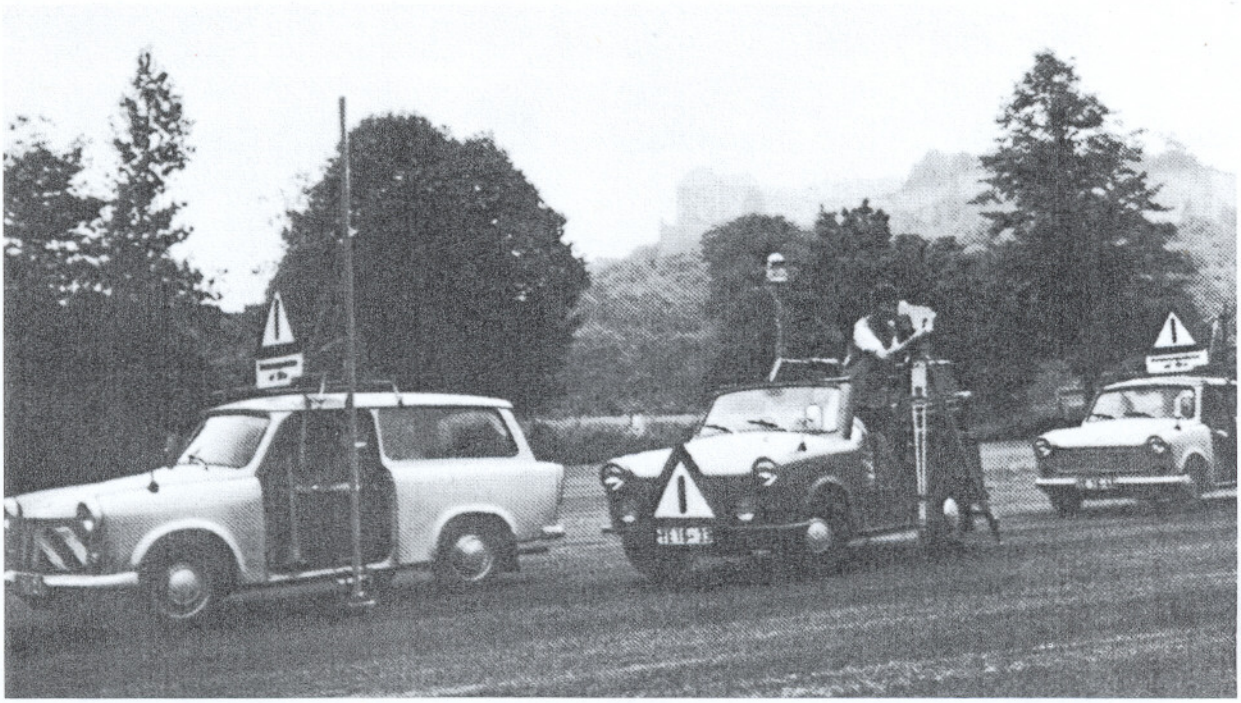

Figure 2.--Motorized leveling in progress with the use of three subcompact cars. (Credit: Jenoptik, Jena, German Democractic Republic)

In the Federal Republic of Germany, Wesemann (1978; Witte 1979) has been using a different approach since 1977. Two electrically powered motorbikes replace the conventional car and serve as rod vehicles. (See fig. 3.) The rods are not permanently attached to the vehicles but, rather, only stored. The rodman must dismount from the bike to set up the leveling rod on the turning point. This obviously slows down the flow of operations. Also, a trailer is necessary to transport the bikes to and from the work area. The trailer is towed by the observer vehicle and remains hooked-up when possible. Other more efficient types of vehicles are being considered. Nevertheless, the present system has proven its worth by providing twice the daily production rate as compared to traditional leveling methods while still maintaining an accuracy of s = ± 0.5 mm/km.

Figure 3.--Motorized leveling being performed by means of one compact car and two electric motorbikes. (Courtesy: Dr.-Ing. H. Wesemann, Federal Republic of Germany)

In the United States, the Thomas Engineering Company began using a motorized mode for its leveling operations in the late 1950's. Leveling equipment is moved by trucks between setups to perform third- and lower-order leveling surveys depending on the project requirements (Watts 1978).

Another method of "motorized leveling" was developed by the Finnish Geodetic Institute. The pedal power of bicycles replaces motor power for movement along roads. Handcars are employed on lines along railways. Four or five vehicles of either kind are used to move equipment and personnel between setups (Takalo 1978).

THE NGS SYSTEM

After thoroughly researching the various motorized leveling modes available, the National Geodetic Survey undertook the development of a motorized leveling system for typical field conditions in the United States, based on reasonable costs.

At present, NGS applies a half-motorized procedure. The field truck stands close to the instrument waiting for the rearward rodman to complete the necessary tasks. The rear rodman (with necessary equipment) steps on the rear bumper, while the observer stands with the leveling instrument on a step at the side of the truck. The truck then proceeds to the next setup point, where the observer and the rodman get off the truck. The observer sets up the instrument in the traditional manner, while the rodman walks to the next forward turning point, which has already been marked by the pacer. It is obvious that time could be saved by providing a motorized vehicle for the rodman and the equipment and having the observer/recorder stay on the vehicle.

The Observer Vehicle

In contrast to the European countries, logistical problems encountered in the United States affect design and development plans. The work area may often be 80 to 100 km away from suitable lodgings and supply facilities. Therefore, travel to and from the work site often becomes a significant portion of the total workday. One of the stringent considerations for motorized leveling then is to provide an efficient means for transporting personnel and equipment to the work site. This can be resolved either by using three compact motor cars--as done by the German Democratic Republic, Sweden, and elsewhere--or one car and two motor bikes and a trailer. The first solution was considered by NGS but abandoned as a result of technical considerations and financial constraints. The second solution was unappealing because handling a trailer is too cumbersome. Also, electrically powered motorbikes are not readily available in this country and their slow rate of speed is a disadvantage in emergency situations.

Therefore, the NGS plan concentrated on using a pickup truck and two motorbikes of special design, manufactured by Rokon, Inc. of Keene, New Hampshire. (See fig. 4.)

The pickup truck accommodates the observer and the instrument (Ni 002, Jenoptik, Jena), the recorder who acts as driver, all field equipment, the motorbikes, and, of course, the rodman while traveling to and from the work area. (See fig. 5.) The pickup truck was modified to serve as the observer vehicle.

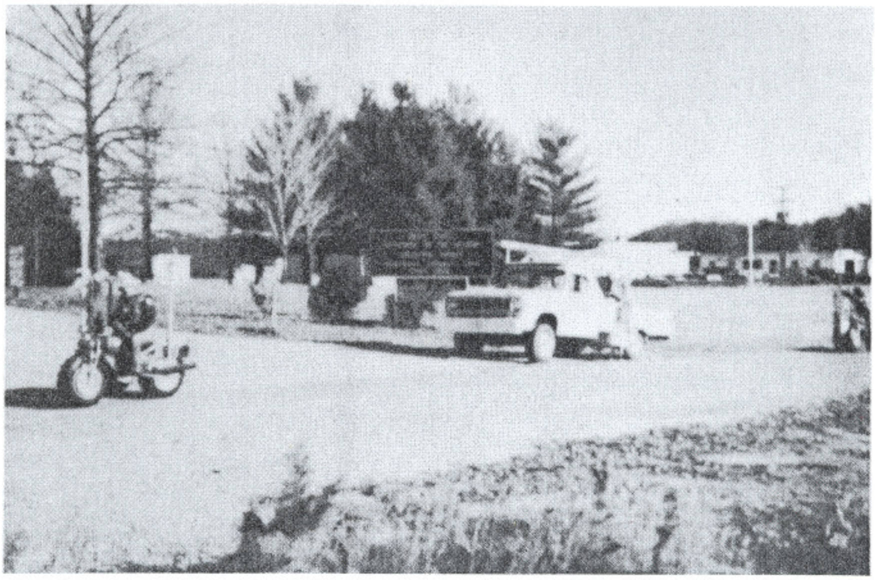

Figure 4.--Motorized leveling equipment of NOS National Geodetic Survey, using one pickup truck and two all-terrain motorbikes with sidecar attachment.

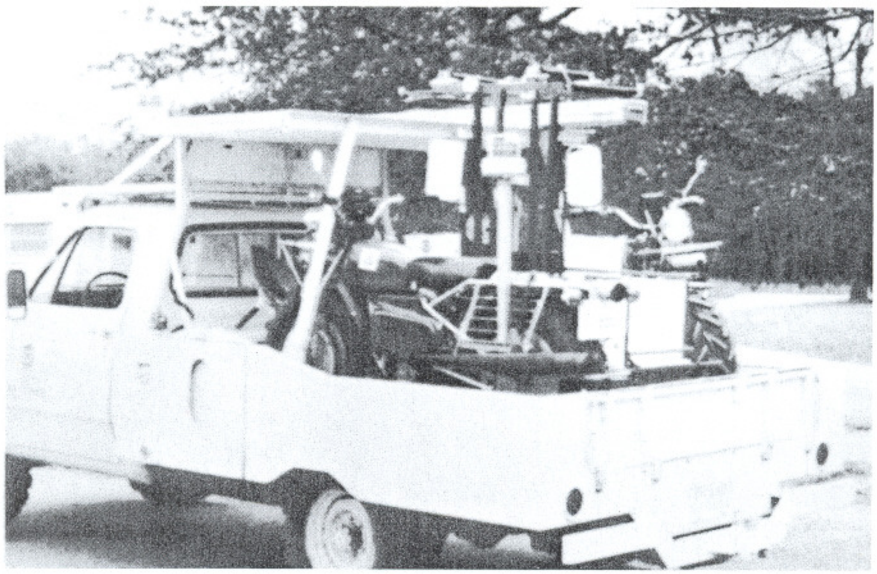

Figure 5.--Observer vehicle with motorbikes, loaded for traveling.

The truck bed was redesigned to hold the two motorbikes. One fold-down observer pit on either side of the truck was arranged to allow the observer to observe from either side of the truck, depending on road conditions. Provisions were made for mounting an instrument lift on either side as needed. The instrument lift raises the tripod and instrument off the ground when the vehicle moves and lowers the instrument onto the ground when the setup point is being established. (See fig. 6.) An opening, cut into one portion of the fold-down pit, accommodates one tripod leg.

A swivel seat was installed for the observer's use during observations. A sliding roof protects the instrument and observer against adverse weather.

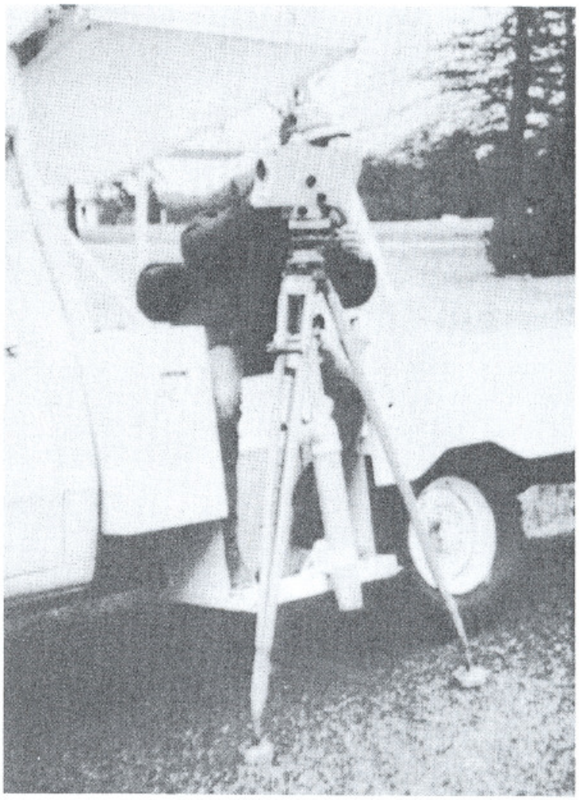

Figure 6.--Observer with instrument. Instrument lift is visible between tripod legs.

The standard field data recording equipment is mounted in the cab of the truck for convenience and storage. A special trip meter ("Twinmaster" model with two counters, manufactured by the Haldex Company, Sweden) is mounted on the dashboard to facilitate balancing of sight distances. It is easily visible and readable by the driver-recorder.

The Rod Vehicle

The Rokon Mototractor was considered to be durable and suitable for NGS field work (fig. 7), but the following modifications were necessary before it could be used as the rod vehicle:

1. Replacement of the original pull starter with an electric starter.

2. Replacement of the original battery with a standard 12-volt car battery, and the addition of a voltage regulator.

3. Installation of a carrier which carries the leveling rod in a horizontal position during travel between turning points, and supports and stabilizes it during observation.

4. Installation of a suspension system used to set the turtle at the turning point on the ground and also lift it for travel (fig. 8).

5. Installation of a Twinmaster trip meter for measuring distances between turning points.

6. Installation of turn and warning signals.

Items 1, 2, 5, and 6 above did not create any difficult problems, but items 3 and 4 required some design changes before a satisfactory solution was found.

The carrier (item 3) must provide freedom of movement about all three principal axes and rotation of 180° about the vertical axis so that a leveling rod can be properly set up and used. The carrier must also serve as a firm storage medium when the leveling rod is transferred between turning points in a horizontal position.

It was necessary to find a way to enable the rodman to set the turtle without leaving the vehicle. With the suspension system developed by NGS, a hand lever operates the device to which the turtle is connected with cables, so that no rigid connection exists while the turtle rests on the ground. A tamper is used to set the turtle firmly with a few strikes. (See fig. 9.)

The leveling rods can easily be detached from their holders. A second turtle is carried on the bike if the need arises for operations where motorized leveling is not possible.

Procedure and Operation

The observational procedure was not changed. The standard sequence of reading the leveling rods--backward-forward, forward-backward--was used with stadia readings included as a check for the sighting distances.

After performing the initial setup in a section (fig. 10), the following sequence is observed to prepare the vehicles for subsequent setups:

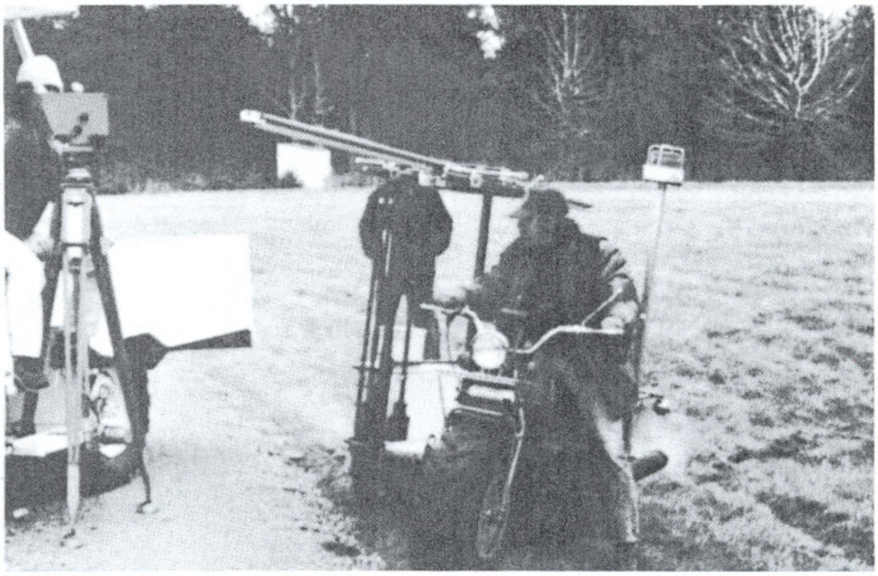

Figure 7.--Rod vehicle with rod mount.

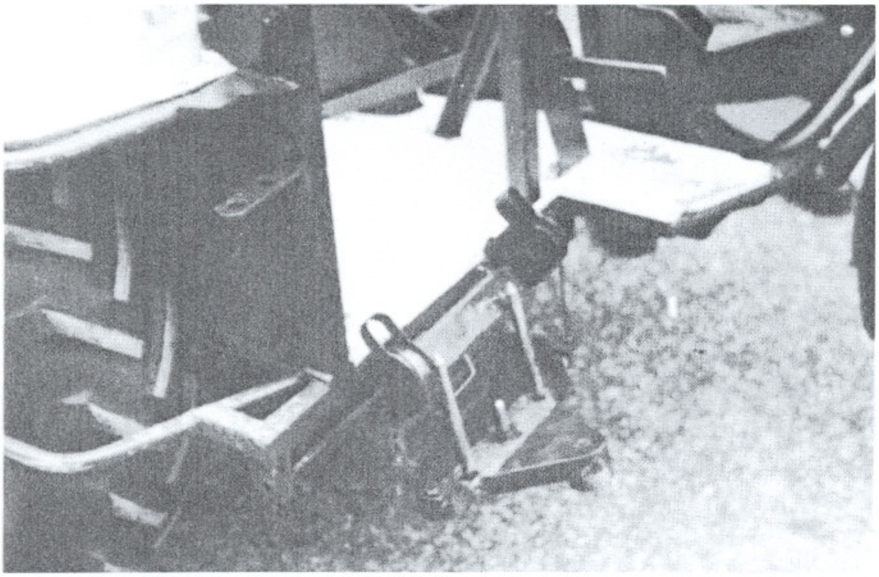

Figure 8.--Rod vehicle showing turtle suspension system.

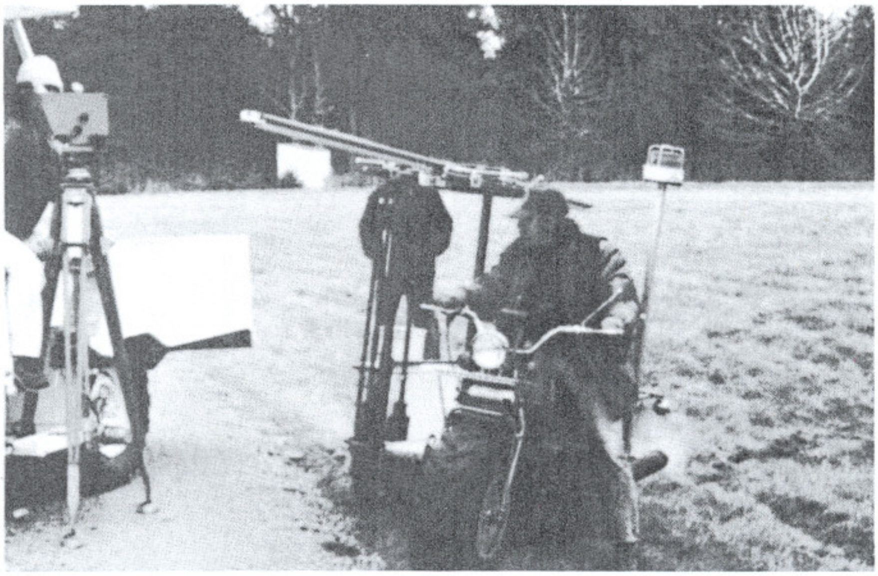

Figure 7.--Rod vehicle with rod mount.

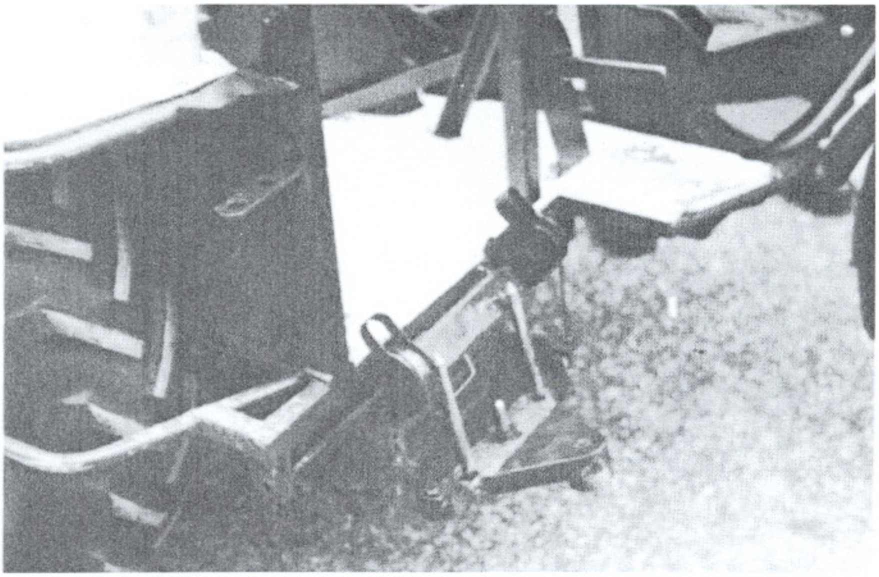

Figure 8.--Rod vehicle showing turtle suspension system.

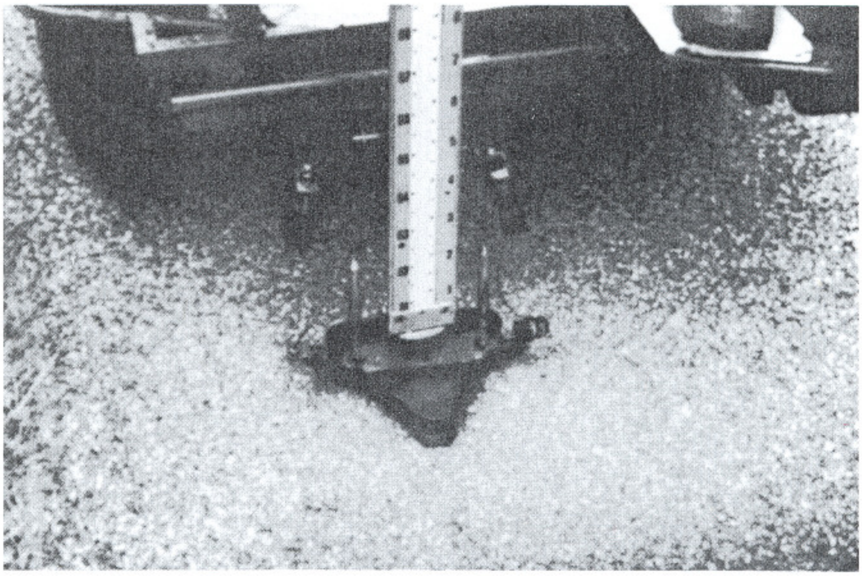

Figure 9.--Turtle sets on the ground. (Note cable connection.)

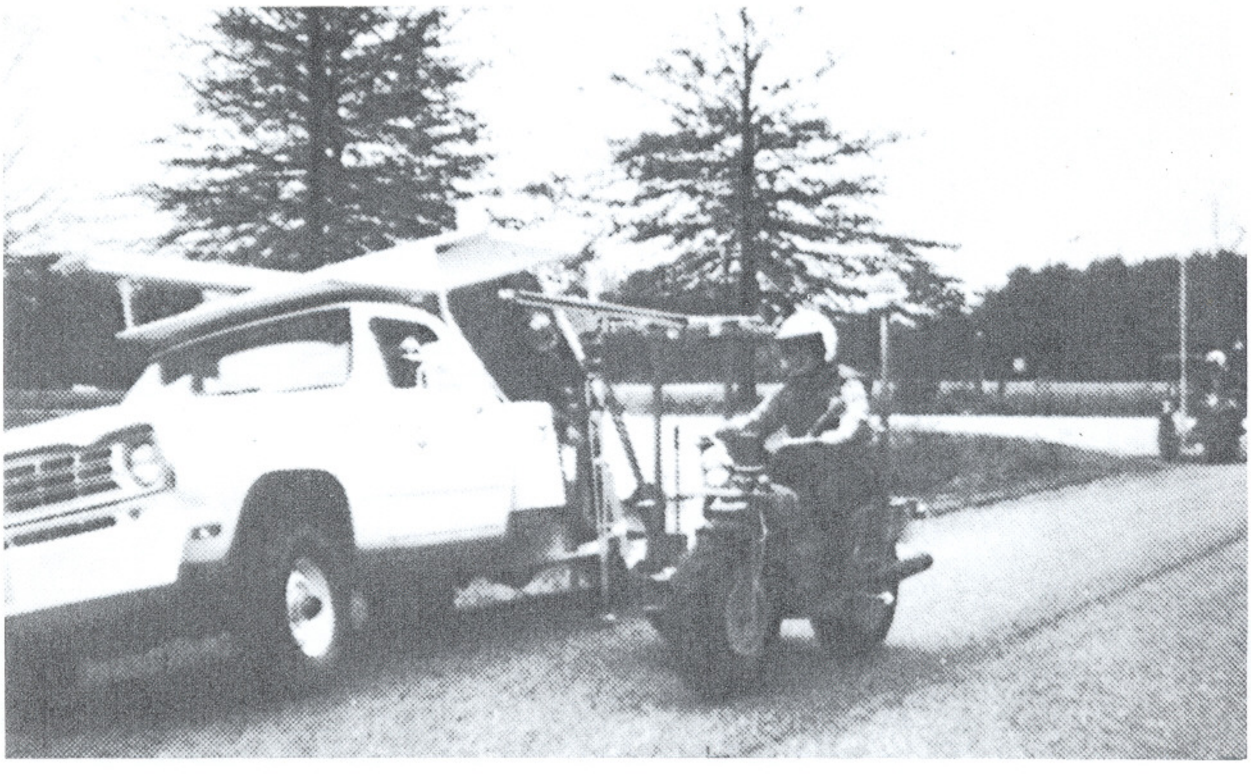

Figure 10.--Rearward rodman moves from former position to new forward turning point while passing the observer vehicle.

1. After completion and verification of the observations, the recorder signals the rear rodman to move to the next turning point. The rodman then shifts the rod into the transport position, raises the turtle, and proceeds forward.

2. At the same time, after the observer has lifted the tripod and instrument off the ground, the recorder/observer proceeds with the vehicle to the next setup point.

3. When the recorder arrives at the previous forward rod, the recorder sets the individual distance counter to zero and measures the distance to the next setup point.

4. Meanwhile the previous rear rodman has reached the previous forward rod, stops briefly to reset the individual distance counter, and proceeds to the setup point. Here, the rodman stops briefly to read the counter and proceeds until the counter shows a value twice the amount read at the setup point. An alternative would be to reset the counter after reaching the setup point and then proceed until the same value appears on the counter display. This indicates that the rodman has reached the new forward turning point location before proceeding to set up the rod for the next set of observations.

Because all Twinmasters have two counters, one is used to accumulate the distance of the length of the section. The counters were first calibrated by determining the number of counts for a number of taped distances. The results were then tabulated, and they now accompany the vehicles. It will be necessary to repeat these calibrations from time to time because fluctuations in tire pressure and tire wear affect the number of counts per distance unit.

RESULTS

After the design was modified, the motorized leveling system was given a number of functional tests, which led to several improvements in the components.

In December, 1978, an operational test was conducted along a short line of 8.8-km length in the vicinity of the NGS Instrument and Equipment Branch at Corbin, Va. The test emphasized quality and procedural matters rather than speed. The results obtained during this test period were encouraging. The accuracy level was at ± 0.7 mm for 1-km leveling, while the production increased by about 25 percent. Because the results came from a small sampling of data, their meaningfulness for routine field work had to be accepted with reservation.

At the end of January, 1979, the motorized leveling equipment was employed along the Gainesville-Baldwin level line in Florida under actual field conditions. The following remarks reflect the technical performance of the system:

The system worked well on all types of open road, independent of the density of traffic. On a four-lane highway with wide shoulders and heavy traffic, work would progress at the same rate as on smaller roads with almost no shoulder and very little traffic. In cities and towns major problems were encountered when main traffic arteries were traveled. However, with prior planning and by the avoidance of major lines of traffic, good progress was obtained.

The rod vehicles, Rokon Mototractors, held up relatively well. Considering the lack of suspension and shock-absorbing devices on these vehicles (except for the balloon tractor tires), it was surprising that the vehicles and the rod brackets endured as long as they did. Failures in the rod bracket were caused by continuous vibration and bouncing during travel, which resulted in frequently broken bolts.

The starter-generator system also had a number of failures, mostly in the electrical system. The Rokon engines performed quite well until the last several days when one of the engines stopped. The breakdown may have been caused by overheating the motor and running it at idle most of the day, as a result of problems with the starter-generator system.

The field personnel made a number of recommendations that should be considered in future specifications. If motorbikes with sidecar attachments are used again as rod vehicles, the sidecars should be mounted on the left side of the bikes to provide greater safety for the rod personnel.

The observer vehicle, a Dodge 200 pickup truck, was not well suited because of its size, in particular, the size of the engine. The personnel who developed this system were aware of the problems inherent in the vehicle but budgetary constraints left no other choice. The heat produced by the engine, which escaped to either front side of the vehicle, did or did not interfere with the line of sight depending on the direction of the wind. Therefore, the investigators were aware of the possibility of additional refraction effects. Certainly, this effect was partially reduced by the line of sight consistently elevated to about 1.8 m above ground compared to 1.5-1.6 m in conventional leveling.

Minor mechanical problems did not significantly interfere with the progress or affect the quality of the work. An evaluation of the Florida field data shows an overall increase in productivity of 30 percent, as summarized in table 1.

It is evident that the cycle time per setup alone is not necessarily indicative of the overall progress. The difference in setup length also plays a significant role. The average setup distance in the motorized mode is 20 percent longer than in the conventional mode as a result of the higher position of the line of sight. The progress per hour is probably the most objective indicator. Another remarkable achievement is the reduction in the percentage of reruns. From these facts, the test again showed that motorized leveling is a method which increases productivity by at least 30 percent.

Table 1.--Improvement of leveling operations

	Conventional leveling	Motorized leveling	Improvement (percent)
Total number of setups	1412	2274	-
Total single run distance (km)	114.331	222.331	-
Survey hours	97.9	144.1	-
Survey days	21	32	-
Setups per hour	14.4	15.8	10
Setups per day	67.2	71.1	6
Time min./setup	4.2	3.8	10
Setups per km	12.4	10.2	18[1]
km/hour	1.17	1.54	32
km/survey day	5.44	6.95	29[2]
Percent of one way leveling reruns	9.7	6.7	31

[1]Fewer setups were required in motorized leveling as a result of a higher position of the line of sight.
[2]Adjusted for difference in hours/day worked.

In Europe, users of the motorized leveling mode have claimed an increase in production between 50 and 100 percent compared to conventional leveling. These percentages appear to be much higher than the 30-percent increase effected by the NGS system. However, two points must be kept in mind. First, the increase in production reported by European users was obtained during extensive levelings, while the production increase by NGS was obtained when the system was still in an experimental stage, and only from one line of about 100 km in length. Second, until the introduction of the motorized mode, European agencies used conventional leveling exclusively without the support of a motor vehicle, as is customary with NGS. The use of a support vehicle by NGS to perform conventional leveling already results in a higher production rate than that of European agencies.

The United States' daily rate is somewhat misleading when compared to European results because 2 to 3 hours of the workday are lost in travel time between the party headquarters and the work area, a problem not encountered to such an extent in Europe.

Production is not the only decisive factor. The quality of the product must also be considered. Here again, motorized leveling gave good results. Figure 11 shows the elevation differences for bench marks common to both the new (1979) and the old (1954) levelings. They have been plotted against the bench mark positions along the Gainesville-Baldwin line.

Elevation differences were obtained by subtracting the old (1954) adjusted bench mark elevations, which were assumed to be free of error, from the new (1979) benchmark elevations. Three sets of differences were formed:

1. 1979 conventional, single-run leveling minus 1954 conventional, double-run.

2. 1979 motorized, double-run leveling minus 1954 conventional, double-run.

3. 1979 combined minus 1954 conventional leveling, double-run. "Combined" means that the motorized double-run and conventional single-run observations were used together to compute new bench mark elevations.

The differences between the motorized and the new conventional elevations were computed and plotted.

By visual inspection of the graph (fig. 11), both 1979 runnings with respect to the 1954 running appear as nonrandom. This was also proved by subjecting the data to a statistical randomness test, although the data sets were relatively small. However, the apparent nonrandomness may be caused by the presence of autocorrelation in the accumulated heights obtained from even uncorrelated height differences. Table 2 shows the characteristic trends of the differences between runnings.

Table 2.--Trend characteristics

	$C_N - C_O$	$M - C_O$	$M - C_N$
T_S	X	-	X
T_{NS}	X	X	-

C_N = 1979 conventional leveling, new (single-run).

C_O = 1954 conventional leveling, old (double-run).

M = 1979 motorized leveling, new (double-run).

T_S = Secular trend.

T_{NS} = Nonsecular trend.

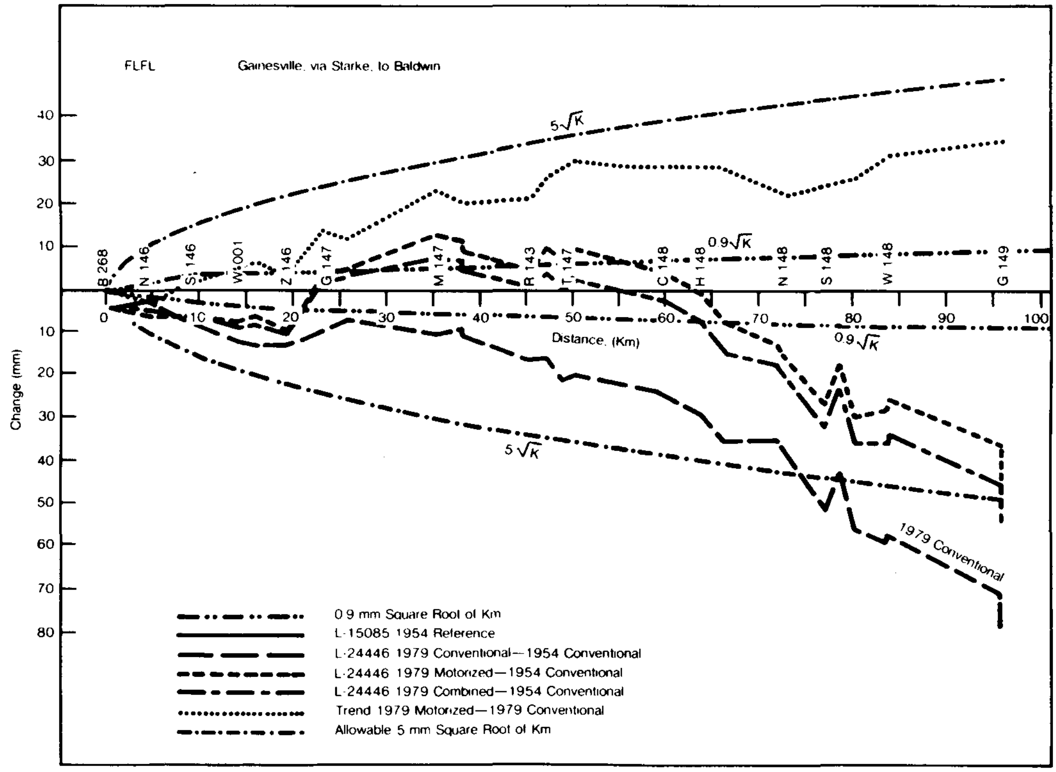

Figure 11. Comparison of repeated levelings, Gainesville, Fla., via Starke to Baldwin.

In particular, the almost linear difference of $M - C_N$ suggests a constant and accumulative systematic error rather than a quasi-systematic error resulting from autocorrelation.

Statistical analysis of the data produced a standard error s = 0.9 mm for 1 km of double-run leveling, which compares well to the average value s = 0.7 mm obtained from all lines in the NGS network. When evaluating this information, the reader should keep in mind that: first, the project was still in an experimental stage and, second, the refraction caused by the heat of the engine in the observing vehicle certainly influenced the observations even though a trend could not be found at a significant level. Correlation between $|\rho|$ and R, i.e., the absolute values of the section differences F + B and the section length, was also investigated. A correlation factor, r = 0.4, was found to be significant at the 95-percent and 99-percent levels. However, the importance of the value r = 0.4 can be argued because certain schools of thought believe that correlation factors of <0.8 are not significant. In this case too much meaning should not be placed on these values because the amount of data is relatively small. On the other hand, the results may well be an indication of the performance of motorized leveling in general.

Finally, the test also indicates that the elevated line of sight and the use of heavier rod supports, and tamping them before setting the rods, help to reduce systematic errors below those of conventional single-run leveling and provide a greater reliability of the results. The differences between the motorized double-run leveling and 1954 conventional double-run leveling lie not only well within the limits of the allowable error, $5\sqrt{K}$ mm, i.e., tolerance for a first-order, class II, level line, but also satisfy the tolerance $4\sqrt{K}$ mm for first-order, class I.

The behavior of the differences between the 1979 conventional single-run leveling and the 1954 results indicates the presence of systematic errors from the very beginning, which obviously could not be reduced by operational procedures. At the end of the line, the deviation from the old results is almost twice that obtained in motorized leveling and falls well outside the limits of the requirement of first-order, class II leveling while each single-run of the motorized leveling falls within these limits.

Florida is an area subject to crustal movement. Various investigators have shown that subsidences of 1 mm/year are quite common. Uplifts have also been found. Taking into consideration the accidental error derived from the observations, i.e., in this case $0.9\sqrt{K}$ mm as obtained from the line adjustment, the results of the test apparently indicate appreciable subsidence towards Baldwin of about 30 mm/25 years. The spike near the 80-km mark seems to result from a bench mark movement and is of identical nature in both the double-run and the single-run leveling.

REMARKS

Motorized leveling is a modern surveying mode, one which must be applied with reason and logic. There will be locations where only the rod vehicles can be used (e.g. in mountainous areas and some urban locations). Yet increased production is achievable in general because relocating the leveling rods takes less time than using the conventional mode.

The use of sophisticated equipment in motorized leveling requires more planning and organization than conventional leveling. The greater organizational effort, however, shows an increase in production and a reduction in cost.

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