

THE LIGHTWEIGHT PAVEMENT PROFILE INSTRUMENT

Development and Applications



**MICHIGAN DEPARTMENT OF TRANSPORTATION
M·DOT**

Materials and Technology Division



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**THE LIGHTWEIGHT PAVEMENT PROFILE INSTRUMENT
DEVELOPMENT AND APPLICATIONS**

J. R. Darlington

**Final Report on a Highway Planning & Research
Investigation Conducted in Cooperation with the
U. S. Department of Transportation
Federal Highway Administration**

**Research Laboratory Section
Materials and Technology Division
Research Project 84 G-262
Research Report No. R-1318**

**Michigan Transportation Commission
Barton LaBelle, Chairman;
Charles Yob, Vice-Chairman;
Jack Gingrass, Hannes Meyers, Jr.,
Irving Rubin, Richard White
Patrick Nowak, Director
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This report, authorized by the transportation director, has been prepared to provide technical information and guidance for personnel in the Michigan Department of Transportation, the FHWA, and other reciprocating agencies. The cost of publishing 200 copies of this report at \$3.21 per copy is \$642.20 and it is printed in accordance with Executive Directive 1991-6.



INTRODUCTION

In April 1984, the Materials and Technology Division of the Michigan Department of Transportation submitted a proposal to the Federal Highway Administration under the Highway Planning and Research Program to "...develop a Lightweight Profiling Vehicle (500 lb including driver) which is capable of travelling over recently placed concrete. The vehicle, with its associated equipment, would be capable of obtaining the true pavement profile. From this profile data a complete analysis of ride quality would be obtained."

The project underwent a significant change in focus during its course. This was primarily due to emergence of the California Profilograph (CALPRO) as a contractors' quality assurance tool. The following chronology will provide an historical perspective.

1. Most ride quality measuring devices developed before 1968 were used primarily to rank roads in relative roughness for maintenance scheduling. These early machines could not provide an absolute and universal roughness measure, nor could they be used to compare roughness across states. The machines were not stable mechanically and were not precisely reproducible. In addition, there were no standard data reduction methods.

2. In 1964, General Motors presented the GM Rapid Travel Profilometer (GM RTP) concept (1) which produced an accurate, stable and reproducible road profile.

3. In 1979, the State of Michigan began to use the GM RTP for acceptance testing of new pavement construction. Acceptance was based on a statistic computed from the profile. It is the Ride Quality Index (RQI) and was derived from a subjective ride study performed here in 1972.

4. In 1984, the Lightweight Pavement Profile Instrument, called 'Lightweight,' project was undertaken to address concerns of highway contractors. They felt it was necessary to monitor ride quality during construction. Measurements made by the State of Michigan RTP after project completion did not permit correction of the paving process during construction.

5. In 1989, the State of Michigan permitted use of the California Profilograph for pavement acceptance testing. This was due to increasing availability and use of the CALPRO by other states.

Use of the CALPRO for acceptance testing compelled a redesign of the Lightweight Instrument's software. These changes are described briefly later in the text.

Throughout this report, extensive use is made of a viewpoint adopted in fields dealing with fluctuating signals. This is a viewpoint from which

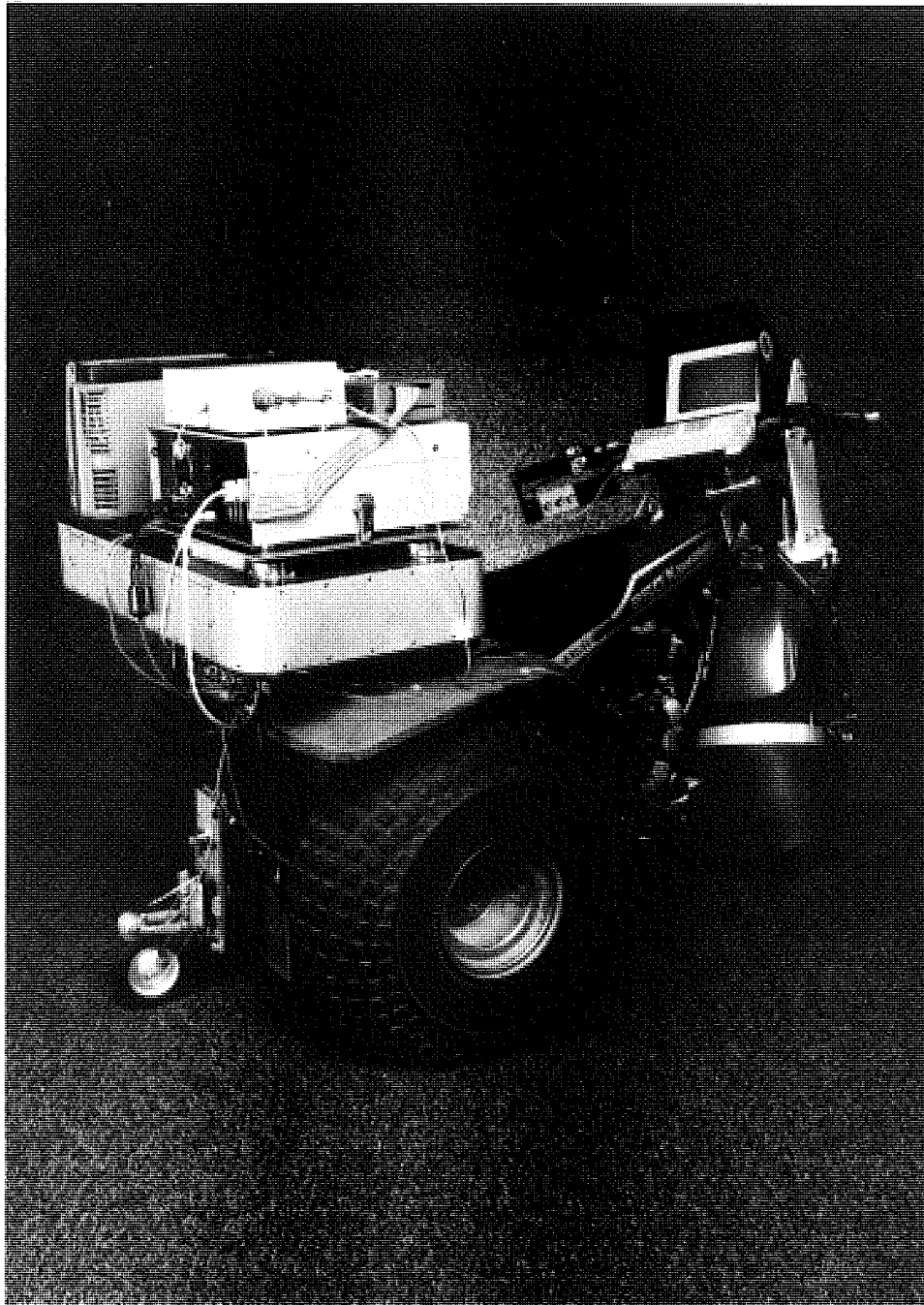


Figure 1. Overall view of Lightweight Profile Instrument.

moving profilometers and vehicles are described by their response to frequencies induced by the profile. Descriptive units are cycles or radians per second. Profiles in this domain are seen as random signals with specific statistical properties. Units are cycles or radians per foot. It will aid the reader to bear in mind the relationship between profile wavelength, vehicle speed and induced frequencies. For example, a 7.5-ft wave traversed at 15 ft/sec will produce a 2 Hz signal. The same wave traversed at 22.5 ft/sec induces a 3 Hz signal.

HARDWARE DEVELOPMENT

Vehicle and Generator

The Lightweight Profile Instrument vehicle had to meet three conditions: It had to exert a low force under the tires (low psi), the gross weight had to be as low as possible, and there had to be accommodations for the sensors, computing equipment, electronic assemblies and a small gasoline generator.

These conditions were met with a Kawasaki Model KLT250-C2, 362-lb all-terrain vehicle, the "Prairie" model (Fig. 1). It has a luggage rack ideally suited for the generator, computer and electronic packages. Pressure under the tires works out to approximately 2 lb/sq in. while fully loaded with equipment and driver. At the present time, three-wheel units of this type cannot be purchased. However, a similar vehicle with four wheels should work even better.

Power requirements are met with a 600-w gasoline generator. This produces 120 v.a.c, 60 Hz for the computer and optical distance sensor. All other electronic power needs are met by using the +5-v supply from the on-board computer. A 5-v to plus and minus 15-v.d.c. converter is located in one of the electronic packages. This supply powers analog circuits, the accelerometer and odometer. All logic is 5 v.

Odometer

All high speed profiling devices suffer the same persistent problem, accurate measurement of test section length. The best odometer units at this time are the front wheel encoders used on many GM-type Rapid Travel Instruments. These units require frequent calibration because the tire diameter changes over time. Wheel encoders are not feasible on all-terrain vehicles because the tire size changes extensively over very short time intervals. A method was sought that would provide accurate distance measurement without any need for periodic calibration. Moreover, a precise 3-in. sample spacing was required to take a major burden off the computer when processing the profile. In addition, an accurate speedometer was needed with an output displayable on the driver's monitor. The device shown in Figure 2 meets these needs.

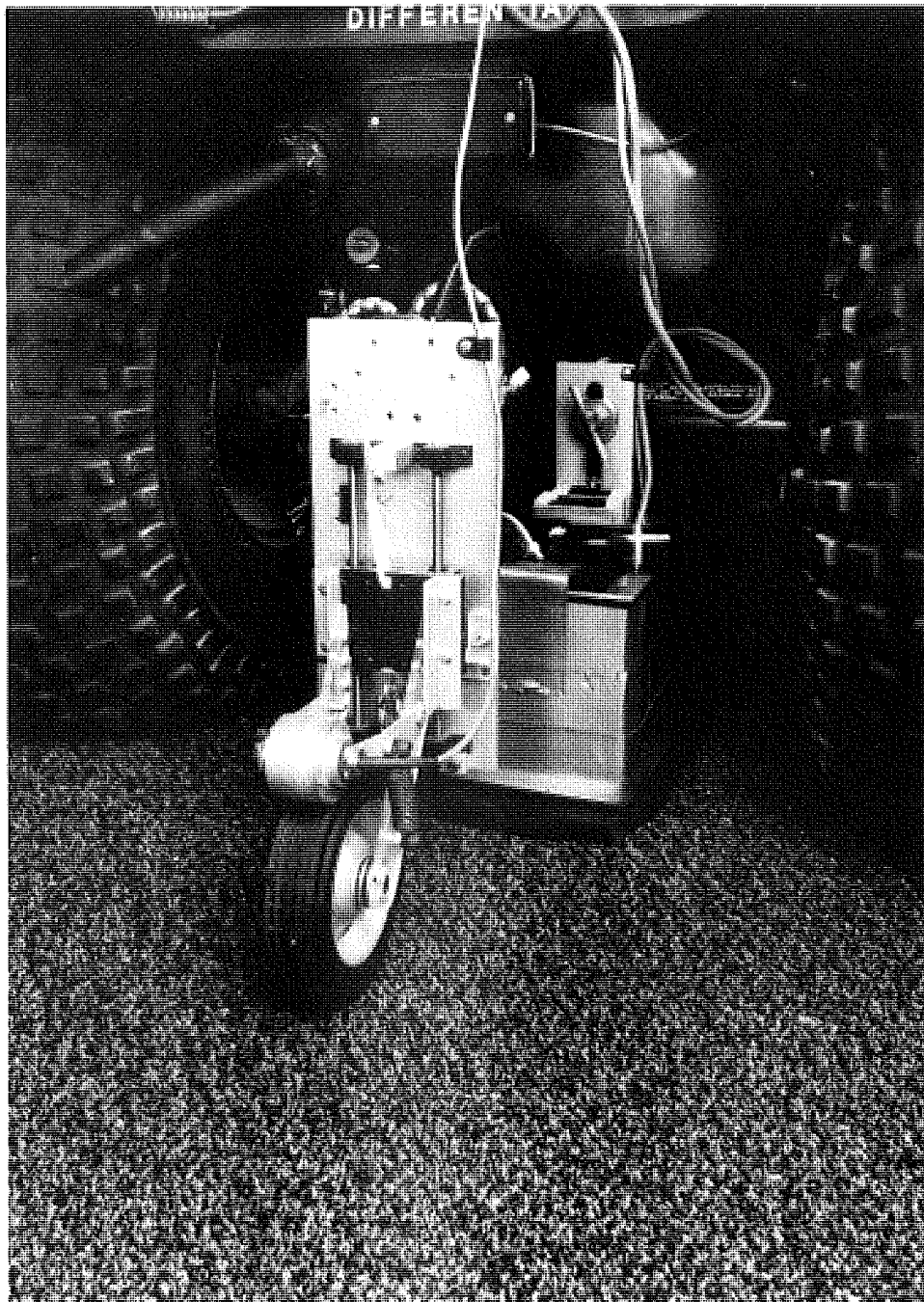


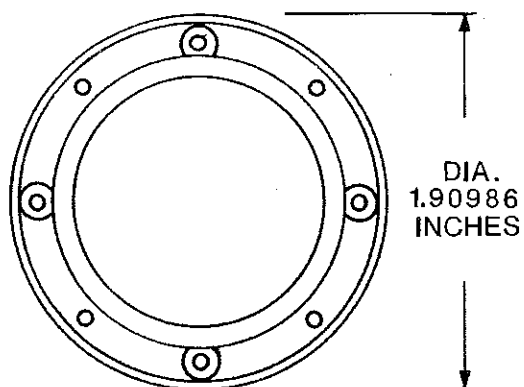
Figure 2. Precision odometer on intermediate wheel.

The odometer consists of an assembly that bolts to the vehicle's drawbar hitch in a fashion that lets it castor from side to side during course changes. The vertical plate carries a linear ball bearing table that is pulled down by shock cord passed over nylon pulleys and then connected behind the plate. The table carries a fork assembly that holds a surface contact wheel and the measuring wheel. The surface contact wheel merely transmits surface motion to the measuring wheel. Thus the roadway contact wheel diameter can change without affecting calibration. The measuring wheel is a precisely machined cylinder turning on ball bearings. It is held against the roadway contact wheel by springs. Its circumference is 6-in. \pm 0.001 in. Inside the rotating cylinder a support shaft carries an optical interrupter cell. An annular ring attached to the cylinder wall provides a hole every 22.5 degrees. The holes pass through the photo-interrupter to produce 16 pulses per revolution. Figure 3 shows the odometer plan. The emerging pulse train is used in two ways. First, it is fed to a frequency-to-voltage converter. The voltage produced is sampled, scaled, and displayed on the operator's screen as vehicle speed in mph. Second, the pulse train is divided by eight to produce two pulses per revolution. This provides a 3-in. sampling pulse to the computer.

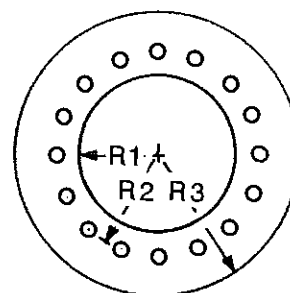
There is an inherent difficulty with any type of wheel assembly that contacts the road. Various discontinuities in the pavement cause a high vertical acceleration even at moderate vehicle speeds. Any acceleration above 1 g will cause the wheel to lose contact and slip. The wheel cannot be held down by increased mass so a spring must be employed. The spring must provide a high enough downward force to produce an acceleration counter to that generated by the road. High spring force requires a stronger assembly thereby increasing the mass. This, in turn, requires stronger springs and so on. Ideally, a follower wheel assembly would have vanishingly small mass, a high downward spring force and a tire providing high damping. Suggestions for dealing with this matter appear in the Problems and Recommendations Section.

Accelerometer

The Michigan Department of Transportation worked with the General Motors Corp. on evaluating and finding applications for the GM Rapid Travel Profilometer (1). Since this is the only system that provides a true profile, it was natural to use the RTP concept for this new application. The GM system requires a high sensitivity servo-null type of accelerometer to measure vehicle bounce and longwave pavement features. Acceleration is double integrated and filtered to obtain vertical displacement that is free of low frequency noise contamination. It is also necessary to measure and filter displacement between the accelerometer and pavement surface. Such a sensor measures vehicle bounce and shortwave features directly. When vertical displacement from the distance sensor is algebraically added to displacement derived from acceleration, vehicle bounce is cancelled and only the road profile is left. The profile band width is selectable by adjusting the included high-pass filter breakpoint.

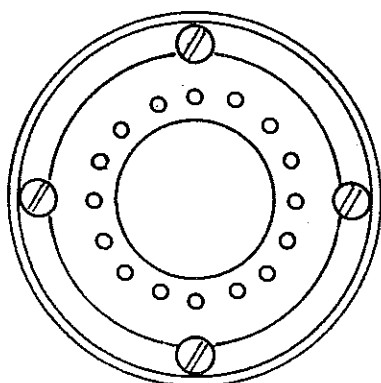


ODOMETER CYLINDER
END VIEW

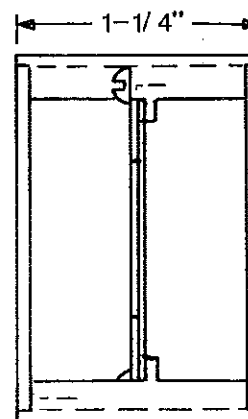


INTERRUPTER
RING

R1 = $27/64$ "
R2 = $34/64$ "
R3 = $47/64$ "

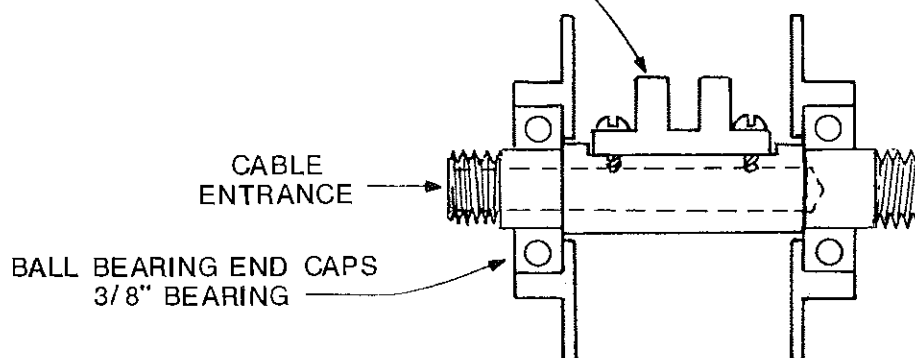


INTERRUPTER RING
IN PLACE



ODOMETER CYLINDER
SIDE VIEW

HARRIS H21A3
PHOTON COUPLED INTERRUPTER



ODOMETER AXLE
SIDE VIEW

Figure 3. Lightweight odometer (actual size).

In theory, the accelerometer could be used alone, mounted by itself, on a long trailing arm pulling a soft, highly damped follower wheel. This would work only on vehicles travelling at low to moderate speeds of no more than 12 mph. Vehicle bounce would not appear if the arm were properly designed. This experimental setup was implemented during initial phases of the study. Unfortunately, accelerometers with the required sensitivity and dynamic range are not presently available. It is difficult to insulate the unit from high acceleration caused by faults and other discontinuities. This is no problem with the standard GM RTP setup because acceleration induced by discontinuities is measured by the distance sensor not by the accelerometer.

Returning to the standard GM RTP setup the accelerometer was mounted on a vertical plate visible in Figure 2. Displacement was measured by a linear potentiometer mounted on the plate with its wiper attached to the moving table. This setup was plagued by two problems. The first was engine vibration, which caused a high frequency, engine speed dependent, displacement whose second derivative exceeded capacity of the accelerometer. This caused the unit to lose its zero bias and produce large low frequency excursions. These translated to large displacement hills and valleys in the profile. The problem was thought to be solved by isolating the accelerometer on a separate plate attached by damping foam. This did eliminate engine vibration but the same large hills and valleys reappeared on new concrete construction that was transversely textured. It was determined that vibration induced through the follower wheel by surface texture was again exceeding the accelerometer capacity. This was verified by mounting the accelerometer on the vehicle frame just over the sensor plate. Although this solved the problem, it was unsatisfactory because the accelerometer was not directly over the follower assembly which is free to castor. Finally, the displacement sensor was replaced with an optical distance sensor. The accelerometer together with this new sensor was mounted on the rear axle housing which is remarkably free of vibration (Fig. 4). It was now possible to mount the accelerometer on an extremely resilient and well damped vibration isolator because the distance sensing unit was attached at the same point. This will allow future units to be constructed with a much simpler odometer system, one not requiring the expensive linear ball bearing table and associated machine shop operations.

Optical Sensor and Isolation Mount

A new vertical distance sensor has appeared in the marketplace. This is a MQ-LA-S3L-AC120V-S09 from the Aromat Corp. It has a working distance of 4.5 in. and a measuring range of ± 2 in. It is a laser-based unit but the laser is low power and relatively safe. It consists of a control box and sensor head. Its cost was approximately \$2400. Placement of the sensor head and accelerometer on the same vibration-protected plate has greatly enhanced the Lightweight Instrument's design. In addition, the costly linear-ball-bearing table and associated machining can be eliminated. The unit does require shielding from ambient light. Figure 4 shows the foam lightshield box surrounding the sensor assembly. A cloth skirt

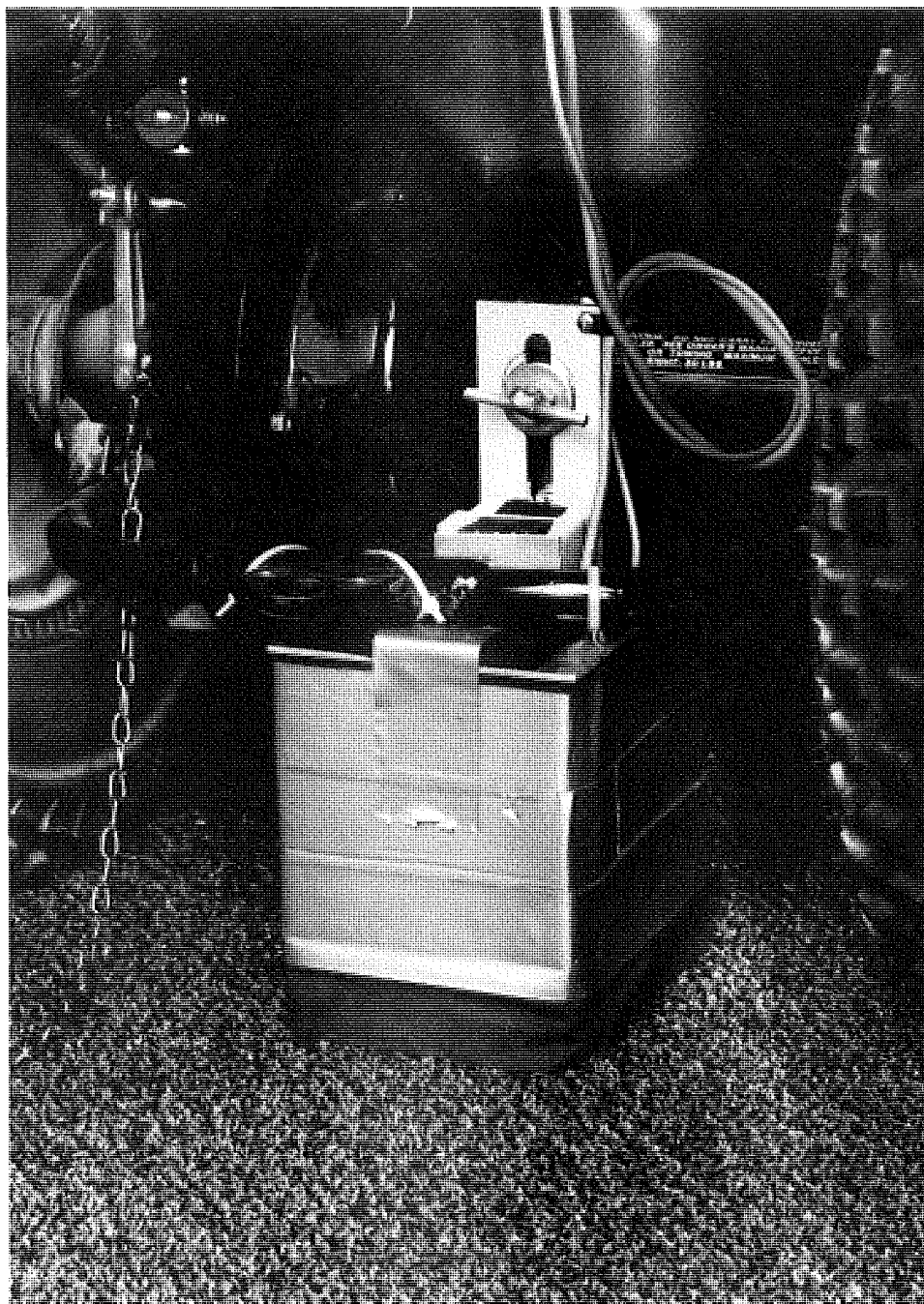


Figure 4. Sensor assembly in place on the rear axle.

lightly touches the ground with a driver in place. In late spring 1992, the Aromat Corp. plans to market a new unit much better suited to highway profile work. It solves several minor problems with the current unit and at less cost, \$1500 per unit.

Figure 5 shows the sensor mount that normally attaches to the rear axle with a U-bolt clamp. The Aromat distance sensor head is mounted under a protective plate just below the Systron Donner Model 4855F-40A servo null accelerometer. The sensor plate is attached to the mounting plate by a cascaded low-pass mechanical filter. This provides four orders of vibration isolation or 24 db of attenuation per frequency octave. The mechanical filter breakpoint was empirically determined to be 17 Hz. This is much lower than any vibrations induced by the engine or road texture. Any frequencies detrimental to accelerometer operation are highly attenuated. In addition to cancellation of vehicle bounce this mounting scheme also cancels any bounce of the mounting plate itself.

Figure 6 shows construction of the vibration isolating mount. An intermediate plate is mounted to the main support plate with two vertical strips and two horizontal blocks of foam rubber. The vertical strips are any good quality, preferably closed cell, foam which provide main support. The horizontal blocks are composed of 1-in. Sorbothane, a high damping coefficient foam. This material tends to sag under constant load so cannot be used for main support. The intermediate plate is 1/8-in. aluminum alloy with approximately 80 g of additional mass in the form of lead blocks attached as shown. This is done so that the intermediate and sensor mounting plates will have similar masses. A sensor mounting plate is attached to the intermediate plate using foam blocks as above. The bonding agent is a good quality five-minute epoxy glue. Glue should be applied only to the metal surfaces. Do not apply heavy pressure to the assembly during cure or glue will soak into the foam.

Computing and Conversion Equipment

The computer, visible in Figure 1, is an IBM PC/AT compatible with a flip-top case. It contains one 3.5-in., 1.2-megabyte floppy and a 20-megabyte hard drive. In addition, it contains a Metrabyte Model DAS16F Analog-to-Digital conversion card. All additional electronic boxes are fastened to the computer's top cover. The computer is shock mounted to a plywood deck that was added to the vehicle. Looking forward in Figure 1, the keyboard and monitor are visible, mounted on the steering assembly. The keyboard and monitor are downsized units available from the Datalux Corp. The monitor is a monochrome VGA unit. There are recommendations about the monitor in the Problems and Recommendations Section. The keyboard has a protective skin cover. All interfacing to the electronic packages is accomplished by the Metrabyte card located in a computer expansion slot. The Metrabyte card requires some auxiliary electronics described in a later section. Additional commentary about the computer appears in the Problems and Recommendations Section.

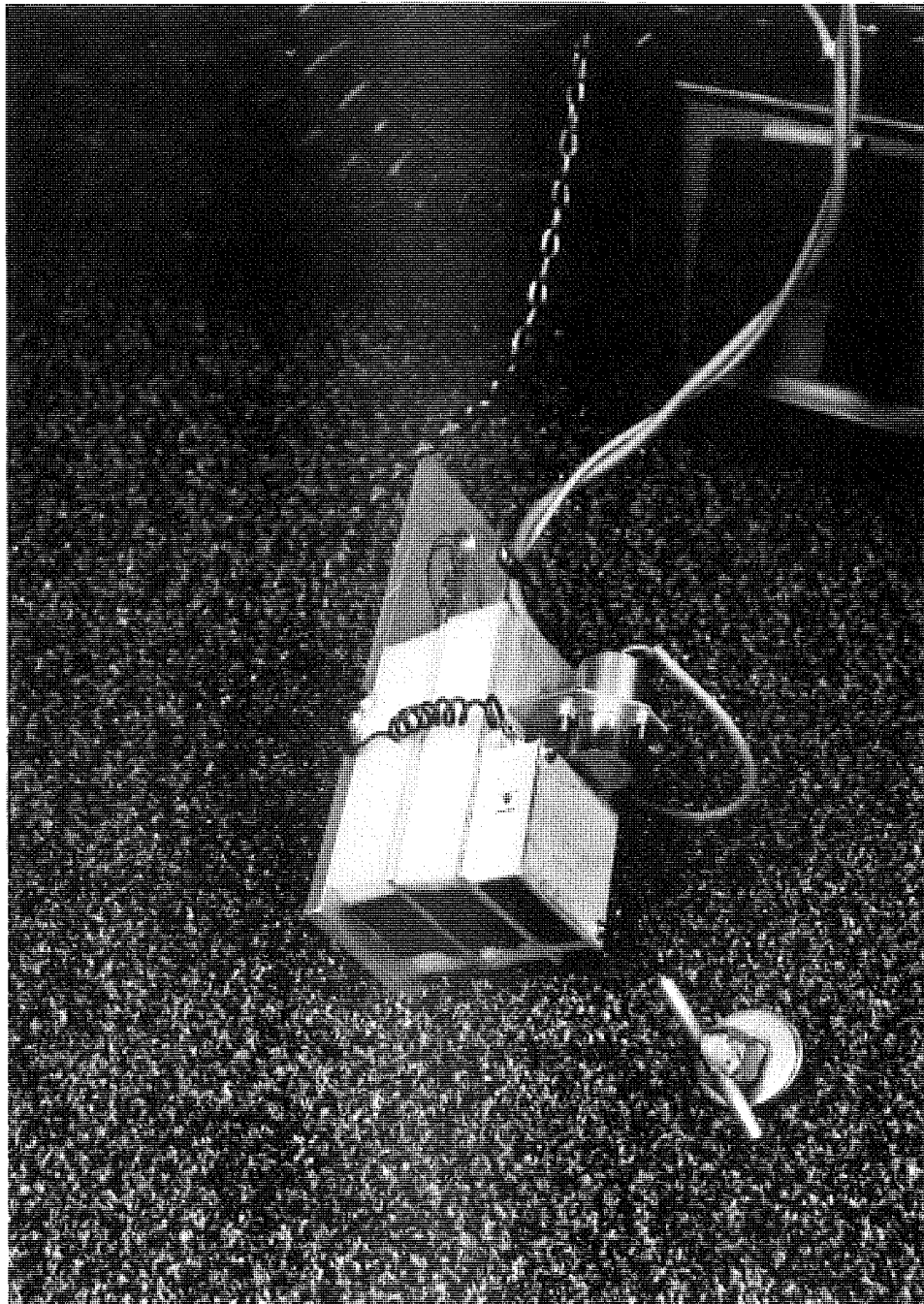


Figure 5. Sensor assembly showing accelerometer and optical distance sensor.

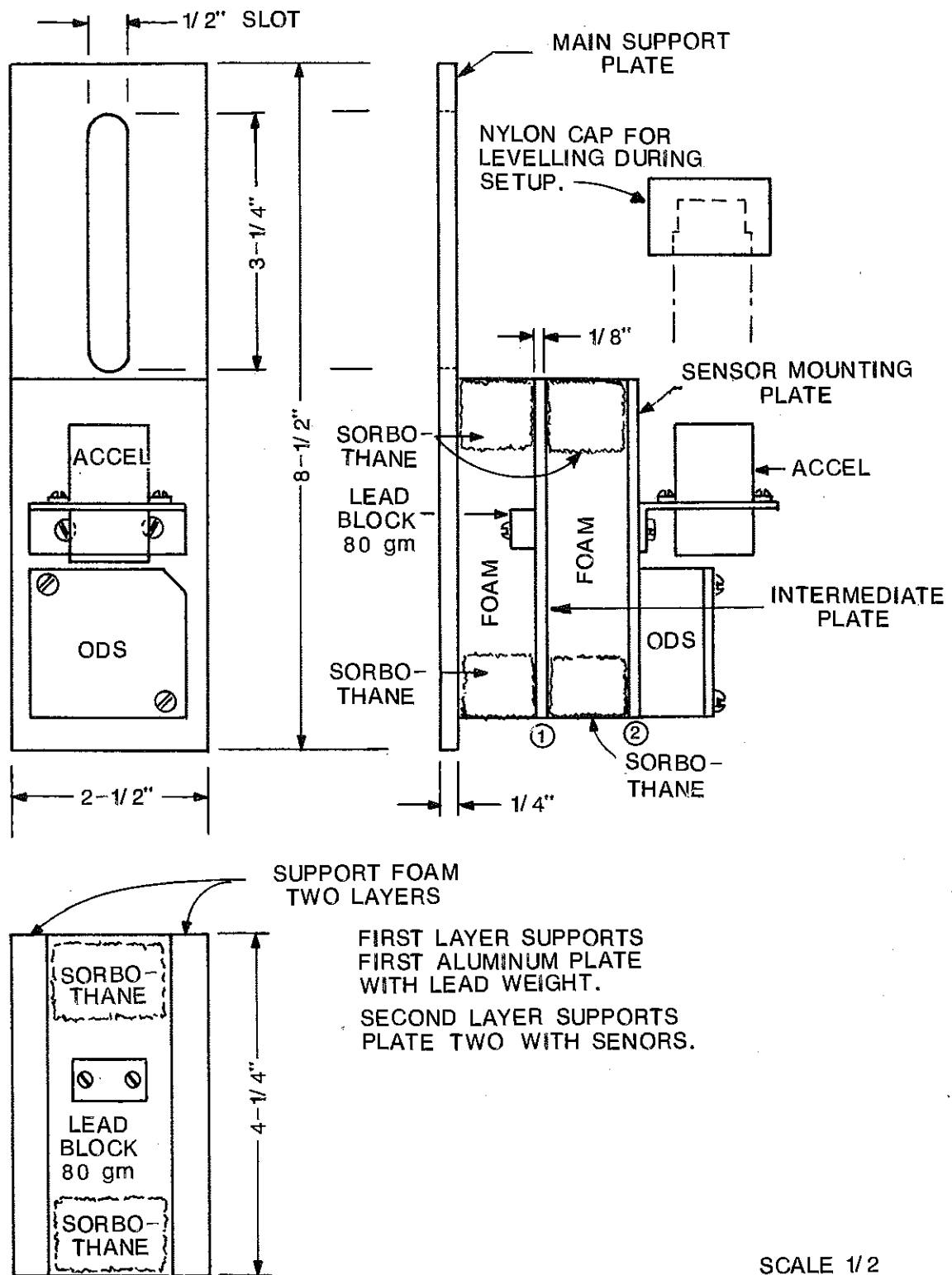


Figure 6. Lightweight Profile Instrument sensor assembly.

Profile Computation Board

The acceleration and displacement signals have to be converted to profile. Early in the development stage the decision was made to compute profile in the digital computer, primarily to achieve vehicle speed independence. Later it became apparent that speed was constrained by other considerations to lie between 8 and 12 mph. Speeds less than 8 mph are not feasible because the accelerometer will not respond to longer wave components of interest. Speeds above 12 mph were not feasible because of odometer design and safety considerations. This opened the possibility of creating a hybrid system in which profile would be computed in the time domain by an analog process board. Further processing would then be performed digitally. A problem seems to arise, however, in letting the vehicle speed range from 8 to 12 mph while collecting data. The analog board is a time domain device with a high-pass filter breakpoint that is set at a given frequency. If vehicle speed varies then the fixed filter frequency cutoff value represents a variable cutoff for the longest spatial wave passed by the filter. For example, suppose the filter breakpoint is set at one radian per second which is equal to 0.16 Hz . At 8 mph a 0.16 Hz high-pass filter would pass a 73.5-ft wave. At 12 mph it would pass a 110.6-ft wave. The problem is resolved as follows. Suppose the emerging profile is sampled in the spatial domain at 3-in. intervals. The data set generated at 8 mph will have the same number of values as that generated at 12 mph. The only difference is that the 12 mph data set will contain wavelengths up to 110.6 ft and the 8 mph set will contain wavelengths only up to 73.5 ft. Next suppose that wavelengths only up to 62 ft are of any interest. If both data sets are digitally high-pass filtered at 62 ft they will be the same. This example is exactly the case for the Lightweight Profile Instrument. An analytical study shows that 25-ft rolling straightedges behave somewhat like a high-pass filter with its breakpoint set at 61.67 ft (1). All data are therefore filtered digitally after acquisition to retain wavelengths only up to 68 ft. Filtration at 68 ft ensures no attenuation of waves at 62 ft.

Variable vehicle speed also presents a difficulty at the high frequency end of the data spectrum. Analog-to-digital converters must be preceded by an analog low-pass filter that removes all frequencies above a value determined by the sampling rate. This is known as the Nyquist rule and it requires that the signal be sampled at least twice for each cycle of the highest frequency present. The Lightweight Instrument sampling rate is determined by vehicle speed since the odometer provides a pulse every 3 in. Thus, at 8 mph the sampling rate is 47 samples per second. This sample rate requires removal of all frequencies above 23 Hz . At 12 mph the sample rate is 70 samples per second. This sample rate requires removal of all frequencies above 35 Hz . Suppose now that the pre-filter, known as an anti-alias filter, is set at 21 Hz . This filter would more than satisfy requirements at any vehicle speed between 8 and 12 mph. It certainly removes all frequencies above 23 and 35 Hz . On the other hand, the 21-Hz filter passes different wavelengths depending on vehicle speed. At 8 mph 21 Hz is generated by 6.7-in. waves while at 12 mph 21 Hz is

developed by 10-in. waves. As in the longwave case the problem is handled by digital filtration during the computation phase. Both the MDOT RQI and CALPRO data reduction methods call for removal of all wavelengths shorter than 2 ft. Thus digital removal of wavelengths shorter than 2 ft results in identical data sets regardless of vehicle speed.

The analog profile computer board is shown in Figure 7. It receives the accelerometer and optical height sensor signals and converts them to profile. This is a circuit developed in 1964 by General Motors as part of their Rapid Travel Profilometer. In this circuit, acceleration is integrated twice to obtain displacement. The result is summed algebraically with the optical displacement signal. The circuit also combines third order, Butterworth high-pass filtration with the process. At this point vehicle bounce is cancelled (2). The layout is more open than usual to permit board level adjustments during setup and calibration. The photo also shows some adjustable potentiometers that appear dotted in the schematic (Appendix C). These are not required if the board is to be set up for one radian per second filter breakpoint frequency. The present board does have actual potentiometers for experimental purposes but it appears that one radian/sec is an optimum choice. If other breakpoints are desired then some circuitry not shown will be needed to facilitate potentiometer setting.

The rotary switch selects setup and calibration signals instead of the normal profile-out signal. This enables a computer guided procedure that displays setup and calibration voltages on the computer screen. The RUN-SCALE switch permits adjustment and calibration of the accelerometer. The 21 H_Z, fourth order Butterworth low-pass filter from Frequency Devices Co. is visible near the rotary switch. This is the anti-alias filter previously discussed. Green LED's verify presence of ± 15 v.

Auxiliary Board and Handlebar Pod

Figure 8 shows a view into the auxiliary card box which also contains the 5-v to ± 15 -v supply. The block diagram, Figure 9, shows the four major functions of the board. These are:

- 1) Produce a voltage proportional to vehicle speed. This is digitized and displayed during a run.
- 2) Generate a sampling pulse train with an exact 3-in. spacing.
- 3) Develop and present three voltage levels corresponding to operation of the handlebar pod.
- 4) Supply a precision 480 H_Z crystal controlled pulse train to simulate the odometer pulses. This is used for test and calibration purposes.

A schematic for the auxiliary board is shown in Appendix C. From top to bottom the circuits are described as follows:

- 1) The precision oscillator starts with a 2.4576-MH_Z crystal clock. Its output is divided by 5120 to produce a 480-H_Z pulse train. This is exactly what the odometer should produce at the standard profiling speed

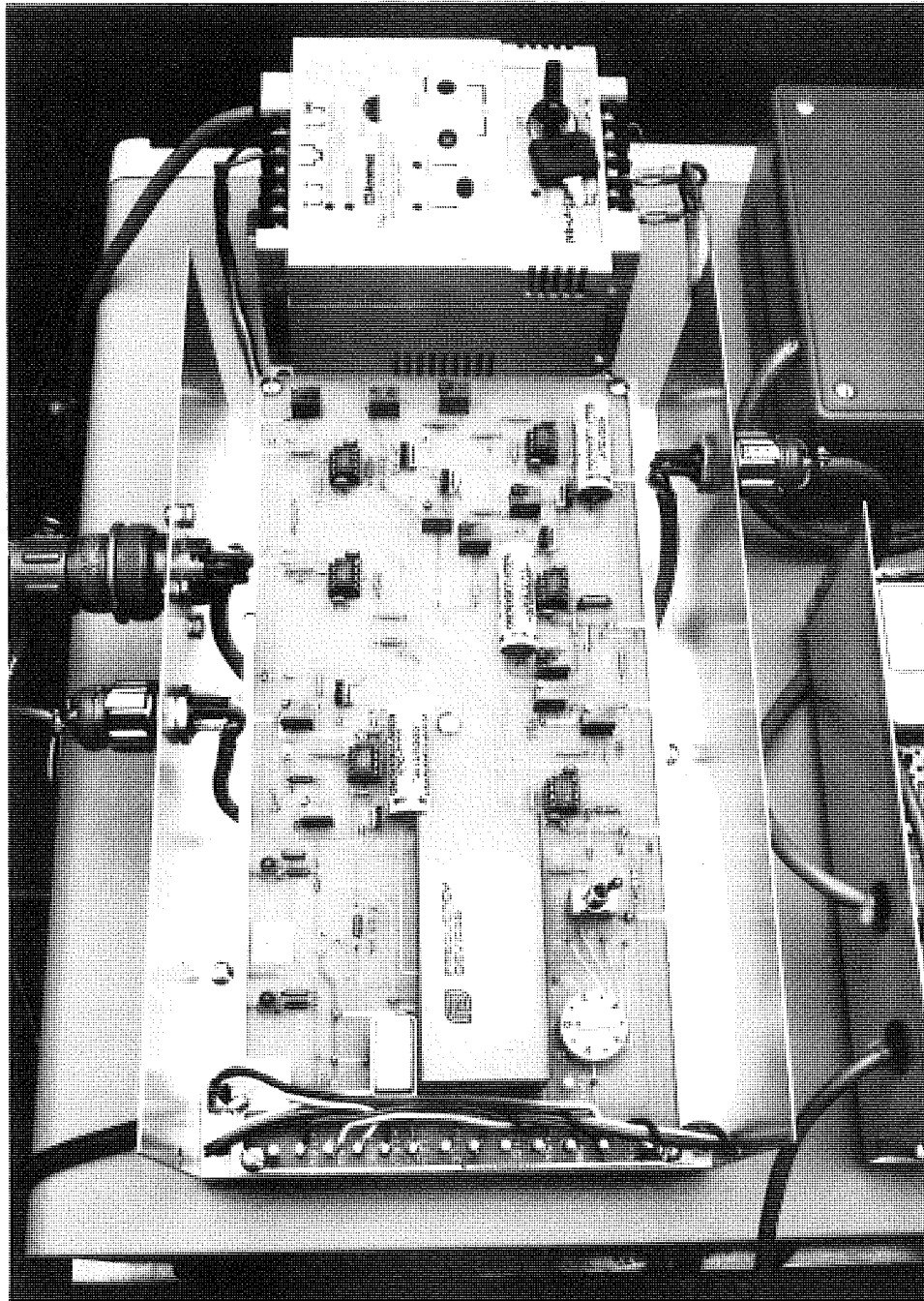


Figure 7. Analog profile computer board.

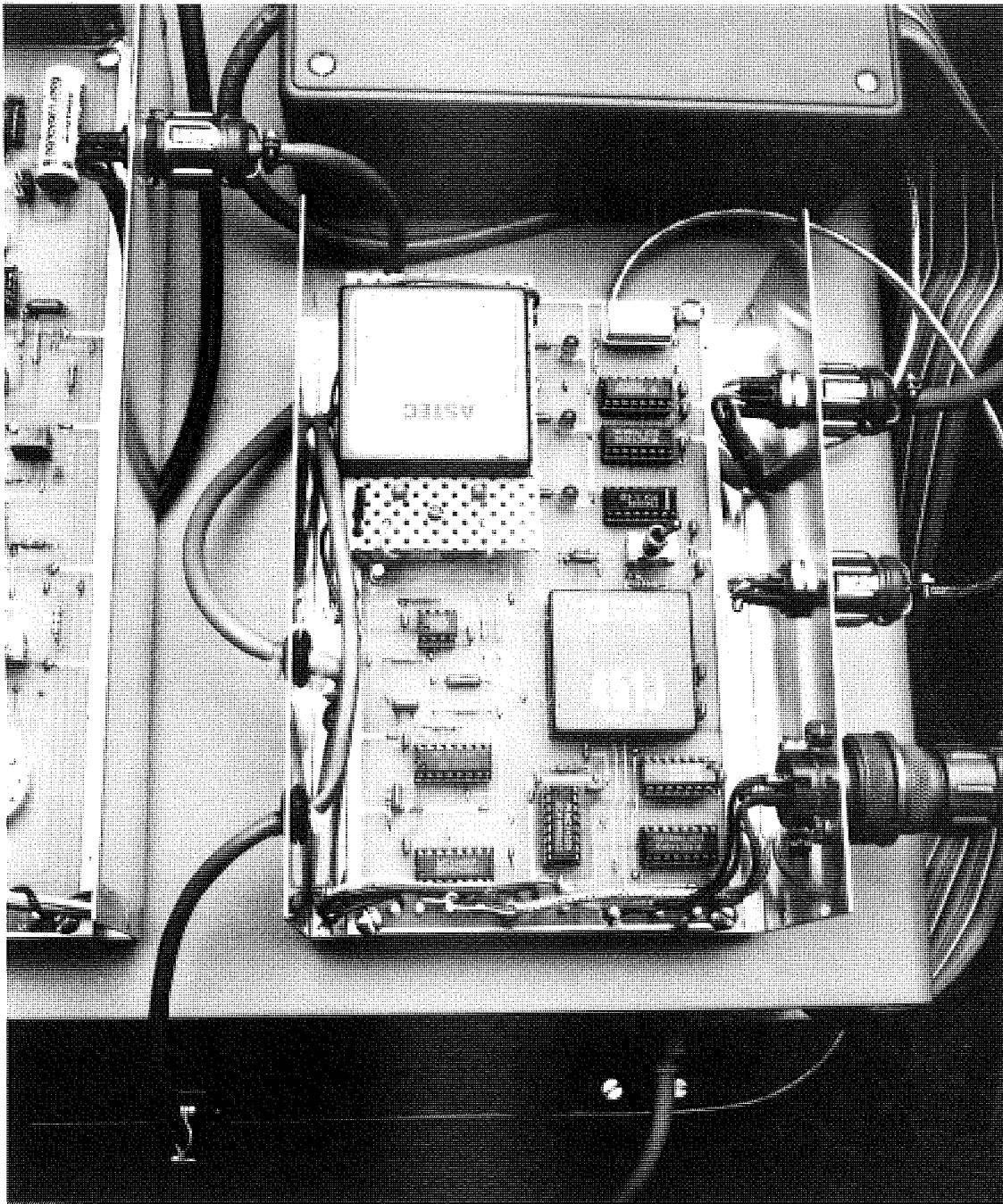


Figure 8. Auxiliary board showing 5-v to ± 15 -v.

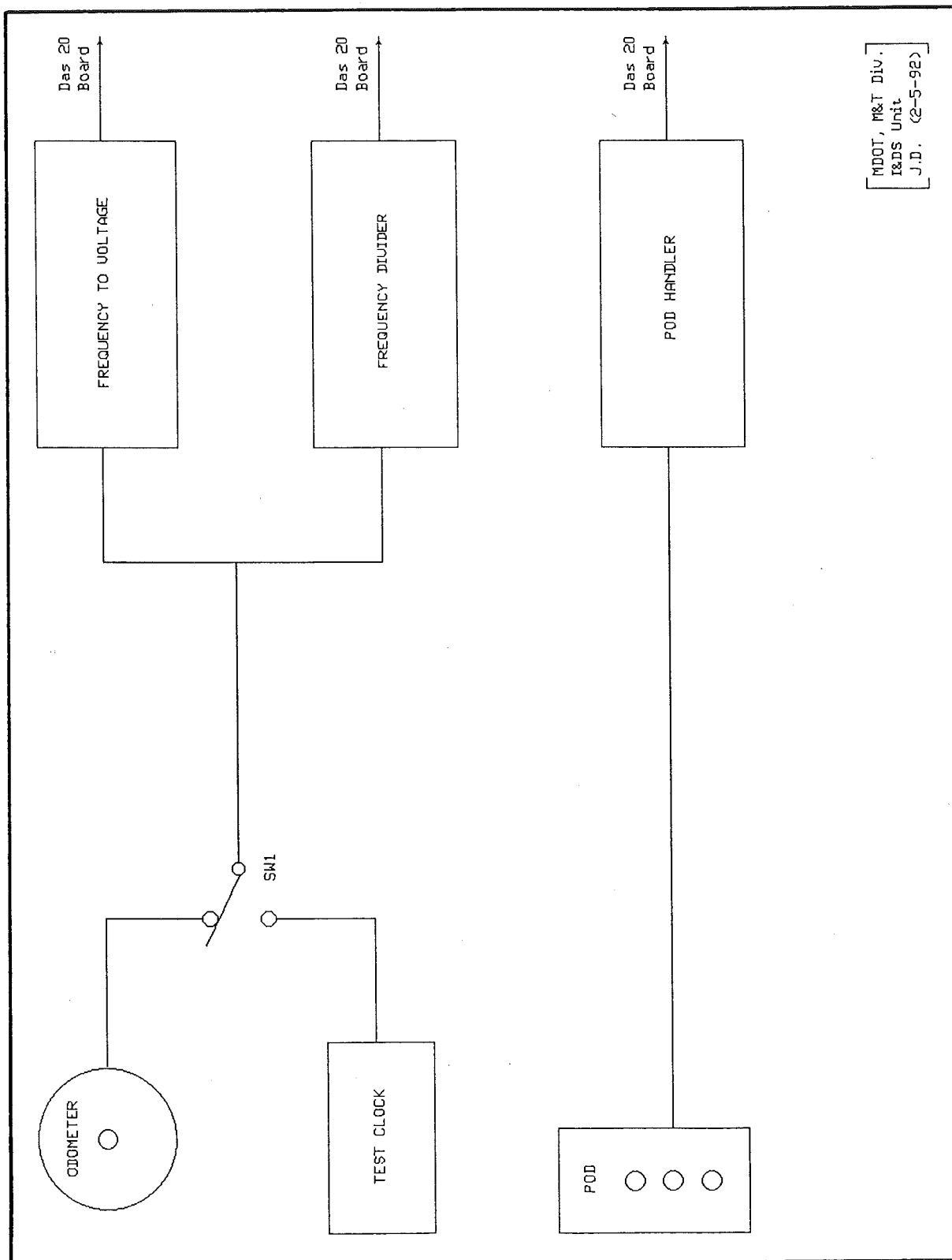


Figure 9. Block diagram of Lightweight Profile Instrument auxiliary board.

of 15 ft/sec. This is 10.2 mph. During tests or calibration the TEST-RUN switch selects this pulse train for input to the frequency-to-voltage converter and the divide by 8 circuit.

2) The odometer photocell excitation and readout circuit is next. It operates a Harris H21A3 photon-coupled interrupter. The TEST-RUN switch normally selects this signal for input to the system.

3) The frequency-to-voltage converter is an Analog Devices Unit of Type 451.

4) A sampling pulse train is derived from the odometer or test clock by first converting to a 5-v logic level. Division by 8 is next, followed by conversion to a 3 microsecond pulse for the sampling trigger.

5) The last circuit handles the handlebar pod which establishes long pulses at two levels and polarities. These levels are digitized and used to provide various operator inputs during the run. START and MARK is a quarter-second 5-v pulse. EXCLUSION is a 2.5-v level held for duration of the excluded portion. STOP is a 0.4 second negative 5-v pulse.

Green LED's verify operation of the power supplies at a glance. The handlebar pod, visible in Figure 1 under the left grip, is simply a box of momentary pushbuttons wired as shown in Appendix C. The box needs to be readily accessible near the operator's left hand without requiring release of the handlebar grip. Any contact bounce from the pod switches is eliminated by a 4490 de-bounce chip on the auxiliary board.

Burst Generator Board

It is possible to use two different digitizing boards for this application. One is the Metrabyte DAS20 or equivalent which costs \$1575. The other is the CIO AD16F from Computer Boards Inc. which costs \$859. The cheaper board will not do what is called a Block Scan in Mode 6 which is required for the Lightweight Instrument. The simple board shown in Figure 10 was developed here to achieve a Block Scan in Mode 6 using the cheaper card. It is powered by the computer and can be located in the terminal box as shown. Appendix C shows a schematic for the device. The rotary switch must be set to the number of channels to scan; three for the Lightweight Instrument. The schematic shows that a single pulse going in, triggers a burst of pulses out that correspond in number to the switch setting. These are spaced in time by a crystal clock that allows sufficient time for the digitizing card to perform a conversion and store the results in memory. The card uses Direct Memory Access.

SOFTWARE DEVELOPMENT

An important goal of computer programming for this project was creation of "user friendly" software. To this end extensive use was made of a windowed environment for all running operations. The setup and

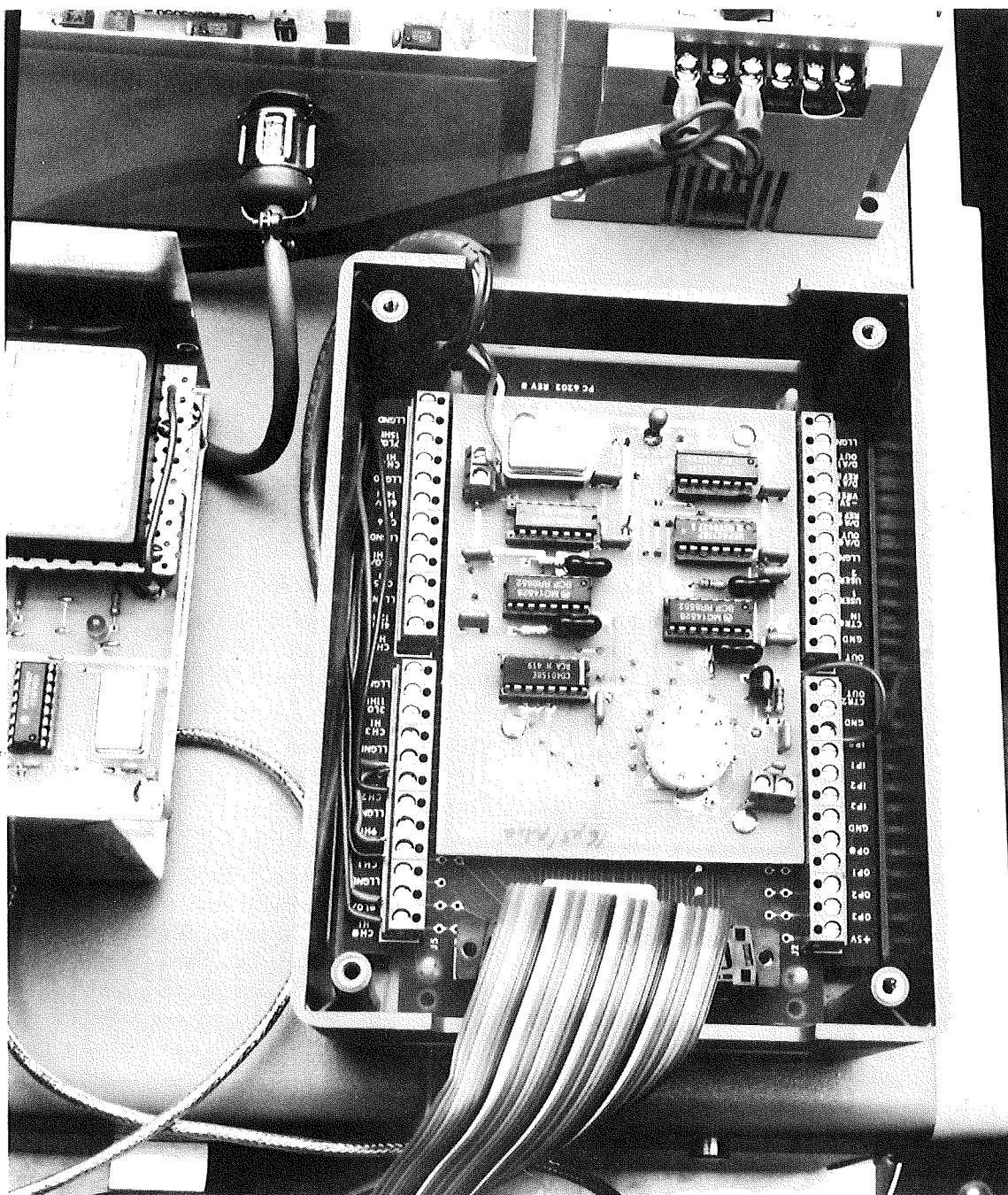


Figure 10. Burst generator board mounted in the A/D terminal box.

calibration procedures are computer-assisted so technical maintenance can be performed by field personnel. When the computer is turned on, an initializing batch file is automatically invoked by the boot up procedure. It first presents a State of Michigan logo followed by a window that allows editing of the date and time if necessary. Any edits cause an operating system and hardware clock update. The batch file then calls a program to display a menu of operational choices. Two of the six choices are implemented at this time. These are, 1. Run a Project and 6, Setup and Calibration. The remaining four choices are presented even though the programs are not written. These additional choices illustrate potential versatility of the Lightweight Profile Instrument. The two main programs are described separately below. All software was developed in Microsoft Professional Basic 7.1. Three additional support packages were also used and are discussed later.

Operational Software

Users selecting menu choice one, "Run a Project," are selecting the main operational software. This program is called Litesys.Exe. Litesys requires presence of two files in the Root Directory of C drive. These are Fmt.Bat and Fmt.Ins. They are small files used by the main program if a floppy disk needs formatting. Litesys.Exe consists of a small resident program that orchestrates operation of three large overlayed programs. These are the User, Running and Calculating modules.

The User Module was developed in the Basic Language but makes extensive use of two support packages. These are Quick Windows Advanced and Designer Quick Windows. The module presents a series of windows to the user to get his run time choices and test section description. Perhaps the best way to describe this operation is to present the actual screens seen by the operator. These appear in Appendix A and are self-explanatory except for some notes to the reader. Exit from this routine takes place when the operator accepts the final screen as "OK." Just before exit, if the operator so chooses, a job description is written to the hard or floppy disk. The job name becomes a filename with the extension "HDR." A sample HDR file is shown in Appendix B. The routine then returns job-name and an action code to the resident program. The action code can be 1, 2 or 3 corresponding to three actions to be taken by the resident program. They are; 1) Run with all data saved, display results, 2) Run with no save, display results, and 3) Quit.

The resident program next invokes the Running Module. This is brought in as the second of three overlays, possibly displacing some or all of the User Module. This routine, though not large, is quite complex because it is the real-time program that interacts with the digitizing card, odometer and handlebar pod. Most programs of this type are based on an interrupt service routine that would be invoked by the hardware each time a sampling pulse is received. Interrupt routines are usually fairly complex programs written in machine language. They may conflict with the system clock when high data rates are required. A unique feature of the digitizer board

is exploited here to avoid an interrupt routine. This card can deposit digitized values directly into a specified region of memory via Direct Memory Access. This is called a DMA transfer and is done entirely by the hardware. The Running Module simply clears locations into which the card will deposit digitized values. Then a simple test of the proper memory location will indicate presence of a new data group. Thus a simple polling environment is established in the Running Module. No service latency arises because the digitizer board itself is operating in an interrupt environment.

In operation, the Running Module first changes the screen to inverse video in CGA. This provides large black characters on a bright white background. The program then sets up and synchronizes the digitizing board to the incoming sample pulses. Next it displays the vehicle speed and waits for the operator to press START/MARK on the handlebar pod. As soon as START/MARK is detected the screen also displays distance travelled in feet. During a run, profile data are stored in memory along with status of the handlebar pod switches. Pod status is stored in the high order nybble of each profile value. This is possible because the digitizer card produces 12 bit values leaving 4 bits unused in the two byte stored numbers. This enables a single pass of up to six miles for a computer equipped with 512k of memory. This is based on a sample stored every 3 in. When Running Module detects STOP from the handlebar pod it stops the digitizing board, puts the screen back to normal and returns to the resident calling program. A long integer is also returned indicating size of the stored profile data set. The resident program then stores all profile data on the hard or floppy disk if requested by the operator. Data are stored in a file with the user specified job name. It has the extension "DAT." Each run is preceded by a screen showing miles of storage available on the disk selected. The operator is informed that storage is taking place. The Running Module uses a routine from the Hammerly Pro Bas Basic support product for rapid screen updates.

The resident program next invokes the Calculating Module. This is the third of three overlays. It is by far the largest module and immediately sets about processing the profile after notifying the operator that calculations are underway. The Calculating Module (Calc) is sent two items, a job name and an action code. It returns two quantities, the overall Michigan Ride Quality Index (RQI) and California inches-per-mile. These are for screen display. If action code is 1 the operator has elected to save results to a file named "job-name" with the extension "ANS." If the action code is 2 then final results are displayed as usual but not saved. Calc performs a number of operations on the data. It contains a routine that simulates passage of a standard California Profilograph over the profile. Data from this operation are then analyzed by a routine that simulates behavior of a human trace reducer according to the California specification. It also calculates the Michigan Ride Quality Index which is an unpublished specification based on variance (power) of the profile after it has been bandpass filtered into three bands. These are 50 to 25, 25 to 5 and 5 to 2-ft wavelength bands. The natural log of variance from

each band is then weighted according to a statistically derived linear scale. These are summed to produce a number which is highly correlated with subjective opinion of roadway quality.

These quantities are calculated for each one-tenth mile and for each test section. Results for partial sections may appear for each side of an excluded section or near a test section boundary. The complete analysis is presented in an output file, a sample of which is shown in Appendix B.

Analysis requires about 90 seconds of computer time for each mile of test section. When analysis is complete the User Interface screens reappear. When the job description screen is reached it presents all the previous inputs. These can be edited or accepted as required. Two portions of the Calc module require elaboration. These are the California Profilograph and Trace Reducer models.

California Profilograph Model

This is a straightforward model that replicates behavior of a 25-ft rolling straightedge going over the profile. Model bogey wheels are arranged longitudinally as those on the CALPRO but do not ride in the same wheel-path. Instead, the model bogey wheels ride in the same wheelpath as the measuring wheel. Moreover, only the averaging bogeys are used, not those providing truss support on the opposite side. To the extent that differences exist between measuring and bogey wheelpaths the Lightweight Instrument could fail to replicate the CALPRO. This effect has not been found significant in validation tests run to date.

A second anomaly is apparent when actual CALPRO traces are compared with output of the Lightweight CALPRO model. The CALPRO device uses a reference that is determined by average elevation of the front and rear bogey wheels as it rolls along. The Lightweight Instrument uses an inertial reference that extends for approximately 100 ft. This slowly tilting straight reference takes an arbitrary position above the roadway so may be tipped at any angle (1). This sometimes produces an apparent discrepancy between actual CALPRO traces and those generated by passing the CALPRO computer model over profile obtained by the Lightweight. Nevertheless, if a CALPRO blanking bar is applied to each trace the same scallops appear but not necessarily in identical locations above and below the central opacity. This happens because the same profile is present in both cases but one may appear locally different. It was simply measured with respect to a different reference point. This effect has not significantly affected test results to date.

Trace Reducer Model

It was a significant task to model the behavior of a person trained in CALPRO trace reduction. This process is carefully described in the CALPRO specification but requires a fair amount of subjective human judgement. This occurs when placing a blanking bar on the trace to minimize profile extensions outside the central opacity. It also occurs when

deciding the number of straight segments into which a long curved section should be divided. The first task, that of placing the tenth-mile equivalent blanking bar is handled by linear regression. In this operation a best fit regression line is calculated for each 528-ft contiguous section. The blanking band of plus and minus 0.1 in. is then established normal to this line. Profile above and below the band is then ready for further analysis.

The second task, that of dividing up the curved sections is easy to do but intricate to explain. The CALPRO is found to be a high-pass filter with its breakpoint set at 62 ft (1). Beyond 62 ft the profile is attenuated but at a slow rate. Thus wavelengths substantially longer than 62 ft can show up if their original amplitude is high. These waves are not wanted in the CALPRO trace reduction protocol. They are removed by breaking up the profile into short straight segments covered by a section of the blanking bar. The same effect could be realized by more powerful high-pass filtration of the recorded profile. A third order, high-pass, Butterworth filter is employed in the Calc Module to greatly attenuate all waves longer than 68 ft. The 68-ft breakpoint ensures that profile will not be attenuated at 62 ft. The filter does, in a consistent way, what the CALPRO trace reducer must do by hand. That is, it flattens the trace.

A final operation on the profile cleans up "chatter" seen on actual CALPRO traces. These shortwave features are to be ignored by the trace reducer. They are less than 0.006 in. in horizontal extent corresponding to actual features less than 2 ft in length. They are removed by third order, low-pass, Butterworth filtration set at 2 ft. Next, the data are reduced by the CALPRO protocol without further manipulation. This calls for addition of peak amplitudes for each scallop extending outside the "opacity." They must extend more than 0.03 in. and reach at least 2 ft along the horizontal axis. The sum is expressed as inches per mile.

Setup, Calibration and Testing

The program, Litecal.Exe is invoked from the initial menu. All screens are presented in CGA with inverse video to increase legibility. It is the second of two packages complete at this time. It opens with a short menu asking if the operator wants to do a SYSTEM CHECK, CALIBRATION, or EXIT. SYSTEM CHECK asks the operator to remove the small electronics box cover and check for power by noting three green LEDs. The operator is asked to switch over to internal clock using the RUN-TEST switch. Next a key push tests the internal clock, speed chip and analog-to-digital card in the computer. Any failures are listed on the screen. The operator is then asked to push the handlebar pod switches START/MARK, EXCLUSION and STOP when requested. Any failures here are reported. Finally the operator is asked to perform a Bounce Test. This test checks the accelerometer, optical distance sensor and most of the analog computing and auxiliary board functions. All these devices must be working and properly calibrated so that vehicle bounce will be cancelled. An RQI is calculated after 30 seconds of bouncing the rear ledge of the vehicle. If this value is not zero an appropriate failure message appears. If all tests pass, the operator is asked to return to standard

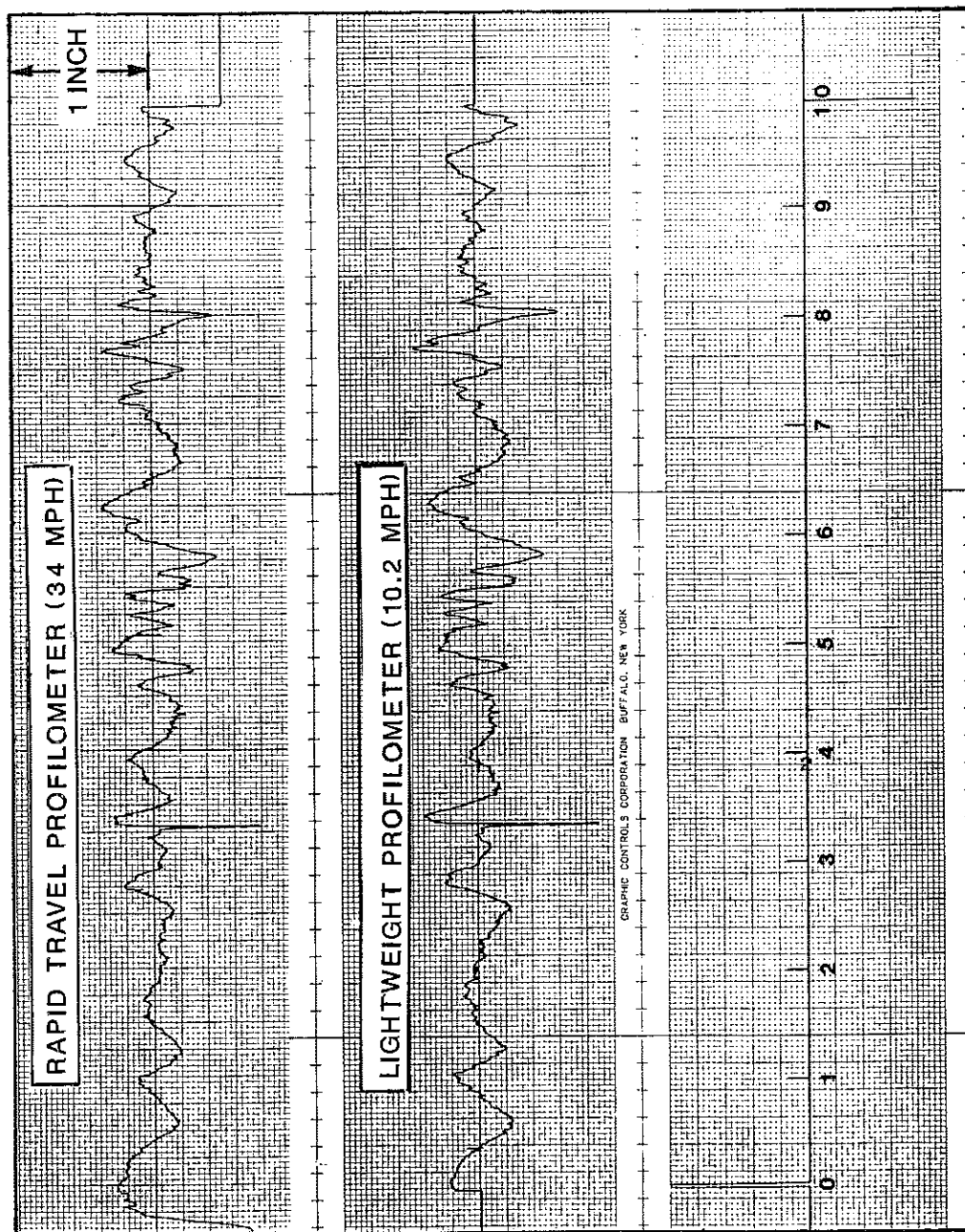
conditions. All screens presented for System Check are shown in Appendix D with additional commentary.

If the operator selects CALIBRATION from the menu the operator invokes the setup and calibration procedure. This program works in conjunction with a rotary switch mounted on the profile computation board in the large electronics box. The schematic (Fig. 8) shows all six positions of this switch with a short description of each function. The program uses this switch and the analog-to-digital board to create a voltmeter on the computer screen. Voltages from various points in the circuit are then displayed during setup and calibration. The operator is first asked to remove the large electronic box cover and verify power by checking two green LEDs. The operator is next asked to remove the sensor assembly and level it using an accessory cap and round bubble level. The operator is then asked to move the rotary switch to position 1 and verify a voltage given on the computer screen. Changing to switch position 2 the operator is asked to adjust a labelled screw, VR1, until the screen shows zero volts. With the switch in position 3 and the RUN-SCALE switch to SCALE the operator adjusts VR2 until the screen voltmeter shows 7.72 v. The accelerometer is now scaled and calibrated. The operator is asked to return the RUN-SCALE switch to RUN. Moving to switch position 4 the operator moves the sensor assembly toward or away from a neutral gray surface until the optical distance sensor shows zero volts on the screen. With the rotary switch in position 5 the operator places a precise 1-in. block in the optical path. Adjustment of VR9 to show -0.20 v calibrates the optical distance sensor and completes the process. The operator is next asked to put the rotary switch back to position zero and close up the box. At this point the operator could select SYSTEM CHECK from the menu. The bounce test portion would verify that all settings are correct. Selection of EXIT leaves Litecal.Exe and returns to the main menu. All of the calibration screens described are shown in Appendix E with additional commentary.

VALIDATION TESTS

Validation of the Lightweight Profile Instrument consisted of three distinct phases. They were:

1. Verify that profile traces and Ride Quality Indices from the Lightweight Instrument match those from the Department's GM Rapid Travel Profilometer. A successful match is always expected between profilometers based on the GM concept. Indeed, agreement of profiles between GM type units is a profound advantage of this concept. Failure to match indicates that sensors or calculations are faulty. Validation of the MDOT RTP is traceable to the original unit tested in 1970 (1).
2. Verify that profile traces from the CALPRO computer model are essentially the same as those from an actual CALPRO. These could fail to match for two reasons. First, the CALPRO computer model cannot be exact. This is because the Lightweight Instrument



DISTANCE (100 FT / TICK)

Figure 11. RTP and Lightweight profiles compared.

gets profile in only one wheelpath while the CALPRO measuring and bogey wheels are offset. Second, the Lightweight measures profile with respect to an arbitrary inertial reference instead of that produced by a CALPRO interacting with the roadway. For these reasons, a match in this case means that hand reduction of an actual CALPRO trace and hand reduction of the Lightweight CALPRO model trace yields the same result.

3. Verify that in./mile computed by the Lightweight matches that from hand reduction of the actual CALPRO trace. This would indicate success or failure of the human trace reducer computer model.

Lightweight and RTP Compared

Figure 11 shows a segment of profile trace from the Department's Rapid Travel Profilometer and from the Lightweight Instrument. Although the traces are quite similar they may appear locally different. This is caused by unavoidable differences in the instantaneous reference generated by the inertial process in each vehicle. This can lead to the seeming paradox that traces which look different can contain the same information (1). A closer match could be obtained by a process called tipping (2). This was deemed unnecessary since, as seen below, the match of RQI values was so close.

Ride Quality Indices from the Lightweight Instrument and the RTP truck are given in Table 1. Set A is from a fairly rough flexible pavement while Set B is from a very smooth concrete expressway. Set A includes the mean and standard deviation for each vehicle. Difference in the means is 0.8 RQI units which amounts to a negligible 1.0 percent difference. A statistical measure known as the students "t" test performed on Set A resulted in a "t" value of 2.5 for an N of 8. This indicates no significant difference between the RTP and Lightweight RQI values. Standard deviation for the Lightweight is half that of the RTP but both are acceptably small.

Set B shows that agreement was different by 0.67 RQI units which amounts to 2.7 percent for the very smooth concrete section. This can occur on very smooth roads when the RTP and Lightweight don't travel in identical wheelpaths. On such smooth roads the RQI is somewhat sensitive to slight differences in profile. These findings indicate a successful outcome for part one of the validation tests.

Hand Reduced CALPRO Model Trace

In addition to regular profile the Lightweight also produces a second trace that results when the CALPRO computer model traverses a stored profile. The CALPRO model trace can be plotted from the stored data and reduced by hand as if it came from an actual CALPRO unit. Results from the model should agree with those from an actual CALPRO trace

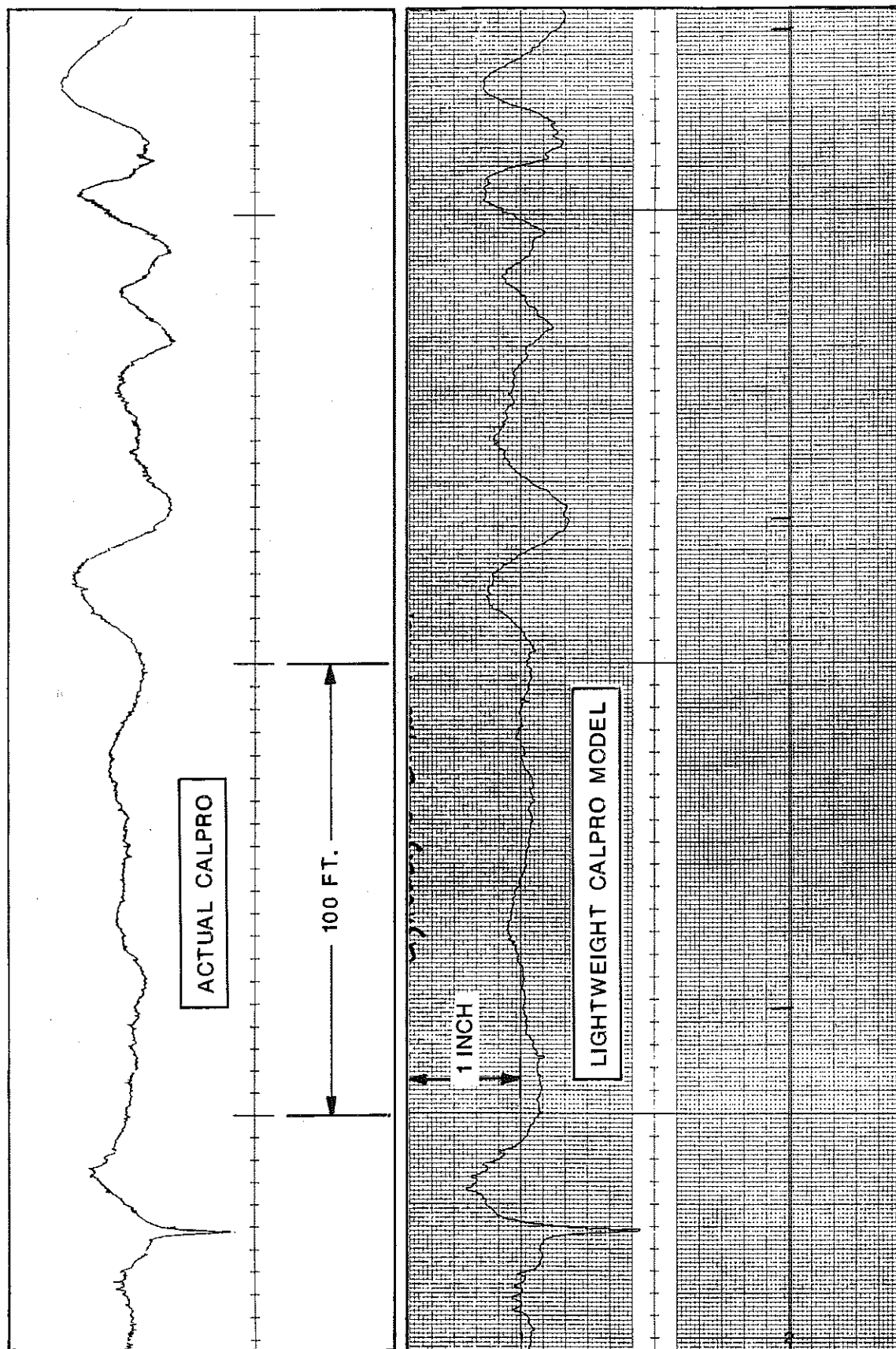


Figure 12. Actual Calpro and Lightweight Calpro model compared.

TABLE 1
PROFILE MEASURES FROM THE RTP
TRUCK AND LIGHTWEIGHT INSTRUMENT

		RTP Truck		Lightweight Instrument	
		Run	RQI	RQI	Inches per mile
Set A Canal Road	1		66.5	66.47	28.67
	2		66.8	66.80	30.21
	3		67.2	66.41	27.60
	4		67.7	66.55	27.76
	5		68.1	65.96	27.41
	Mean		67.26	66.44	28.33
	Std. Dev.		0.58	0.27	1.03
Set B I 69	1		24.6	25.29	0.11
	2		24.4	25.06	0.12
	Mean		24.5	25.2	0.11

if both contain essentially the same information. Figure 12 shows a portion of two profiles from the flexible test section. These are from the Lightweight Instrument and from an actual CALPRO unit that made a test run a year before this analysis was performed. Each trace was reduced by an untrained reducer following the California trace reduction protocol. Results were 28.7 in./mile for the Lightweight trace and 31.2 for the actual CALPRO trace. Evidently the two traces contain essentially the same information. A definitive analysis of this type should be based on a variety of reducers and test sections. Instead, remaining time for the project was focused on the final stage of testing described below.

Computer Reduced CALPRO Model Trace

At this point, the Lightweight Instrument is shown to measure profile accurately by the criteria of its design, the GM RTP concept. Also, the computer model of a CALPRO device is shown to produce traces from the profile that match those from an actual CALPRO. Finally it must be ascertained if the computer model of a human trace reducer is representative of an actual human trace reducer. One problem here is that behavior of the average trace reducer is not known at this time. Almost any computer model will be more consistent than a human reducer. Whether it properly emulates typical human subjective decisions is not as clear. It is possible, however, to prepare a "perfect" model in the sense that it exactly embodies the California trace reducer protocol. In that case, it is difficult to decide which method of reduction should be the standard. One could argue that human trace reducers should strive to replicate

computer results not the other way around. For the Lightweight Instrument, however, the human result will be considered standard even though there are no data from which to derive a statistical evaluation of human trace reducers.

As mentioned above, a human trace reducer got 31.2 in./mile for the flexible test section. Five passes of the Lightweight yielded an average of 28.33 in./mile with a standard deviation of 1.03 units. In addition to these data, a test run was made with a Cox California Profilograph equipped with on-board computing. This is a CALPRO device that uses a computer model of human trace reduction but which incorporated a filter that slightly over-attenuated some features. This filter has since been upgraded on Cox machines. Its result was 28.0 in./mile. Only slightly lower than the Lightweight's 28.33. For the 4000-ft very smooth concrete test section hand reduction resulted in 0.15 in./mile while the Lightweight instrument returned 0.11 and 0.12 for two passes.

Although extensive validation tests were not performed for this study, the GM RTP concept alone ensures that careful construction will result in correct profile. The GM concept itself has been thoroughly tested. Further tests of validity for the CALPRO model and human trace reducer model await development of a large database of comparative results.

PROBLEMS AND RECOMMENDATIONS

All Terrain Vehicles

The vehicle for this study was purchased in 1984. At that time three-wheeled vehicles were legal but are not so now. The obvious replacement would be a four-wheeled unit so long as the same low pressure is maintained under the tires. Most four-wheeled units have better instrument racks than three-wheeled units. Another possibility would be an electric vehicle such as a golf cart. These have several advantages providing the gross weight is not too high. These include low vibration, on-board electrical power through an inverter, no fuel handling danger and good speed control.

Vibration

A major problem was discovered with the servo null type, high sensitivity accelerometer. It was assumed that engine and roadway-induced vibrations sensed by the accelerometer would simply attenuate away during double integration. Unfortunately, some of this vibration was found to exceed the product of frequency and amplitude permitted for these units. The result was a transient loss of zero bias in the accelerometer. This signal double integrated to high amplitude longwave errors in the profile. The problem was first encountered when the accelerometer was in its original position on the vertical castor plate which now contains only the odometer assembly. It was thought a simple vibration isolator would solve the problem. This mount worked for engine vibration but not for that induced by highly textured pavement. The odometer follower wheel transmitted enough signal from the textured surface to overcome the accelerometer vibration isolator. Finally, the two-stage isolator was developed and the mounting moved away from the odometer plate to the

rear axle. This limits the amplitude-frequency product to levels which result in total attenuation during double integration.

Static Charge and Ignition Noise

All terrain vehicles generate a high static electrical charge especially when running on pavement. This is due to charge separation induced by tire flexing and scrubbing. The charges will eventually build up and discharge from wheel hubs to frame causing noise on data lines connected to the computer. This is particularly critical on odometer and handlebar pod inputs. The problem persisted even after these lines were fitted with noise suppression capacitors. The problem was eliminated by dragging a small chain connected to the vehicle frame. As a further precaution, the front wheel hub was also grounded. This was accomplished by a simple slip ring assembly.

Ignition systems on these vehicles produce considerable electrical noise. It was found necessary to shield the spark plug and ignition wires. This was accomplished by covering the high tension wires and plug with grounded metal braid. In some cases it might be necessary to shield the coil as well.

Odometer Problems

The odometer presents a persistent problem for all profiling devices. If the unit is based on a rolling wheel then changes in circumference require constant recalibration. An attempt was made to eliminate this difficulty by providing a device that holds its calibrated value for long periods. In addition, it was important to provide a pulse at exact 3-in. intervals to greatly reduce the computing burden. Both requirements were met by the odometer designed for this project. Because it runs on the treaded surface of an intermediate wheel, changes in the intermediate wheel circumference have no effect. The measuring wheel would wear very slowly because it is all metal and does not touch the road. Moreover, the metal measuring wheel was machined to have a precise 6-in. circumference accurate to 0.001 in. With 16 pulses per turn, every 8 pulses indicates exactly 3 in. of travel. Unfortunately, due primarily to vibration, it has proved difficult to prevent slippage of the measuring wheel on the intermediate wheel. The error is currently 0.3 percent which is within specification but could stand improvement. It is felt that further research into this matter is warranted. Two new odometer schemes developed here will be tested in the near future.

Temperature Control

The computer for this project is an inexpensive PC/AT type unit that is not industrially packaged. This unit, as well as more rugged versions, will need internal warming for cold weather applications. Heat could be provided by a temperature sensing circuit and a resistive element. Typical 600-w generators as used in this study will provide adequate heater power. The heater could be mounted in a protective shell covering the computer and electronic boxes. Incoming air should be filtered. An additional feature might consist of low and high-temperature warning lights.

No attempt was made to assess reliability of the computer's hard disk assembly. The unit used here is an older style Seagate model 225. It has not failed during field testing operations. Nevertheless, it may be preferable to use a solid state hard disk on future units.

Monitor Problems

Two methods were employed to increase visibility of the driver's monitor. The first was a sheet metal shadow box visible in Figure 1. The second was a programming feature that sets up the screen to operate in high intensity, reverse video with CGA size characters. These are larger than normal VGA characters. Even with these techniques diffuse daylight washes out visibility while direct sunlight almost completely obscures the view. A liquid crystal display solves the problem. At present there are few manufacturers who provide a VGA monitor in LCD with backlighting. One such is the Datalux Corp. They sell a flat panel VGA monitor that is highly visible in direct sunlight. It has backlighting for viewing when ambient light is low. If this display is used, a temperature sensor and heater must be added for use when temperatures drop below 40 F. At this time, LCD monitors cost about \$950 but the cost is expected to be significantly less within two years.

Software Dissemination

Software for this project consists of two large programs written in Microsoft Professional Basic 7.1. These are the Main Operating System and Testing with Setup and Calibrate. Three basic add-on packages were also used for special functions. The first two are the "Hammerly Pro Bas" and "Programmers Toolkit" from the Tera Tech Co. The third is "Quick Windows" from the Software Interphase Co. In addition two auxiliary programs are utilized. These are the Metrabyte Das16F analog-to-digital card driver from the Metrabyte Corp. and "Automemu" from Magee Enterprises. All this software interacts in a complex way with specific hardware on the Lightweight. Because of this complexity, a listing of the code would serve little purpose. It could not be compiled without the necessary libraries and changes for different hardware configurations. For these reasons interested readers are encouraged to contact the Michigan Department of Transportation, Materials and Technology Division. The Department could then supply technical support and error-free copies of the software on diskette for subsequent customizing.

CONCLUSIONS

The Lightweight Pavement Profile Instrument permits pavement quality analysis within hours after paving. It measures profile by the proven GM RTP concept at a far lower cost than truck-based units. Cost of the unit without the vehicle should be less than \$6000. This includes the computer system with digitizing card, optical distance sensor, accelerometer, odometer, generator and electronic and mechanical assemblies. Analysis of the profile is by no means limited to CALPRO numbers. In fact, any

actual CALPRO or computer model CALPRO seriously distort the profile. Because its profile is accurate, the Lightweight permits calculation of any other measure. These could include, but are not limited to, such measures as RQI, IRI or the new PI number developed by Janoff (3). For this reason the Lightweight has far more potential than simply as a high speed replacement for the California Profilograph. In all cases, users of the unit are assured that they can obtain any measure required by a particular contracting authority. Once an accurate profile is generated and stored, any analysis of that data is possible. As the main menu screen in Appendix A illustrates, there is an immediate opportunity for additional analysis programs to be written. Only selections 1 and 6 are currently implemented.

A moderate amount of field use has shown the Lightweight unit to be robust and reliable. There have been no computer program crashes or hard disk failures despite lack of an overall cover, air filtration or temperature control. As with any precision measuring instrument, reasonable care must be exercised. A small protective trailer was fabricated for this unit and is highly recommended. Operation in rain, snow or on wet pavement is not supported.

Readers interested in technical advice are encouraged to contact the Michigan Department of Transportation, Materials and Technology Division.

REFERENCES

1. Darlington, J. R., "Evaluation and Application Study of the General Motors Corporation Rapid Travel Profilometer," Michigan Department of Transportation Research Report No. R-731, 1970.
2. Spangler and Kelly, "GMR Road Profilometer," Research Publication GMR-452, 1964.
3. Janoff, Michael S., "Pavement Roughness and Rideability Field Evaluation," NCHRP Report 308, Transportation Research Board, 1988.

APPENDIX A
OPERATIONAL COMPUTER SCREENS

MICHIGAN DEPARTMENT OF TRANSPORTATION

MATERIALS AND TECHNOLOGY LABORATORY

LIGHTWEIGHT PROFILOMETER SYSTEM

Startup logo. "Exploding" window.

DATE AND TIME CHECK
EDIT ANY WRONG VALUES
THEN
TAB TO NEXT ITEM

DATE: 11/14/91

TIME: 18:39:36

PRESS RETURN WHEN DONE
THIS REPEATS IF INVALID

< OK >

Startup, date-time system update screen.

LIGHTWEIGHT PROFILOMETER MENU

- > 1 - RUN A PROJECT
- 2 - FILE OPERATIONS
- 3 - VIEW JOB RESULTS
- 4 - VIEW A PROFILE
- 5 - PLOT A PROFILE TO CHART RECORDER
- 6 - SETUP AND CALIBRATION
- 7 - EXIT TO NC

Profilometer operational program

February 13, 1992 8:29:07 am

Memory: 371 K

Press H for Help

Main Menu

TYPE S TO SAVE RESULTS AND DO 10TH MILE ANALYSIS
TYPE D TO DISPLAY OVERALL RQI AND IN/MI (NO SAVE)
TYPE T TO TERMINATE PROGRAM

TYPE S, D OR T

Screen 1 of job sequence

DO YOU WANT DATA AND RESULTS
STORED ON HARD OR FLOPPY DISK?

TYPE H OR F

Screen 2.

THERE ARE 433.6 MILES OF STORAGE
AVAILABLE ON THE HARD DRIVE.
DO YOU WISH TO CONTINUE OR EXIT TO
DELETE SOME OLD JOBS?
CONTINUE? (Y/N)

Screen 2a. Invoked if H is selected for screen 2.

PLEASE INSERT FLOPPY IN DRIVE
TYPE ANY KEY WHEN READY

Screen 2b. Invoked if F is selected for screen 2 and there is no floppy in drive.

```
C:\JOBS>format a:<c:\fmt.ins  
Insert new diskette for drive A:  
and strike ENTER when ready
```

```
Head:    0 Cylinder:    0
```

FLOPPY IS NOT FORMATTED (OR BAD)
STAND BY FOR FORMATTING

Screen 2c. Invoked if F is selected for screen 2 and the floppy is not formatted.

THERE ARE 34.2 MILES OF STORAGE
AVAILABLE ON THE FLOPPY DRIVE.
DO YOU WISH TO CONTINUE OR EXIT TO
DELETE SOME OLD JOBS?
CONTINUE? (Y/N)

Screen 2d. Invoked if F is selected for screen 2.

PLEASE ENTER A JOB NAME
EIGHT CHARACTERS OR LESS

JOB NAME:

Screen 3.

FILE ALREADY EXISTS. OVERWRITE?

TYPE Y OR N

Screen 3a. Invoked if the jobname given for screen 3 already exists.

JOB REPORT HEADER INFORMATION

EDIT AND RET FOR EACH FIELD.
RET ON OK (OR TAB TO cancel OR DISTRICT)

DISTRICT: ROUTE: _____

PVT TYPE: _____ PASS NO.: ____

BEGIN STA: _____ LANE: ____

ok

cancel

Screen 4.

SPEED (MPH)

TEST SECTION

DISTANCE (FT)

10.2

73

TEST IN PROGRESS

PRESS STOP BUTTON TO END TEST

Screen 5. Displayed during a run.

APPENDIX B
SAMPLE OUTPUT FILES
(Does not include data file)

```

JOB FILENAME  A:I69NB1.HDR

11/14/91      14:02:31

DISTRICT: 8      ROUTE: I69nbt1

PVT TYPE: conc      PASS NO.: 1

BEGIN STA: 1558+00      LANE: 1

```

Typical project header file.

```

A:I69NB1.ANS

10th MI SEG      RQI      CAL IN/MI

      1      31.64      0.40
      2      24.10      0.00
      3      23.05      0.00
      4      28.38      0.00
      5      22.14      0.00
      6      27.47      0.51
      7      18.11      0.00
END TST SEC      1 @      3941.00 FT. RQI= 20.95, IN/MI= 0.00
TST SEC RQI IS 25.29, CALPRO IN/MI IS 0.11

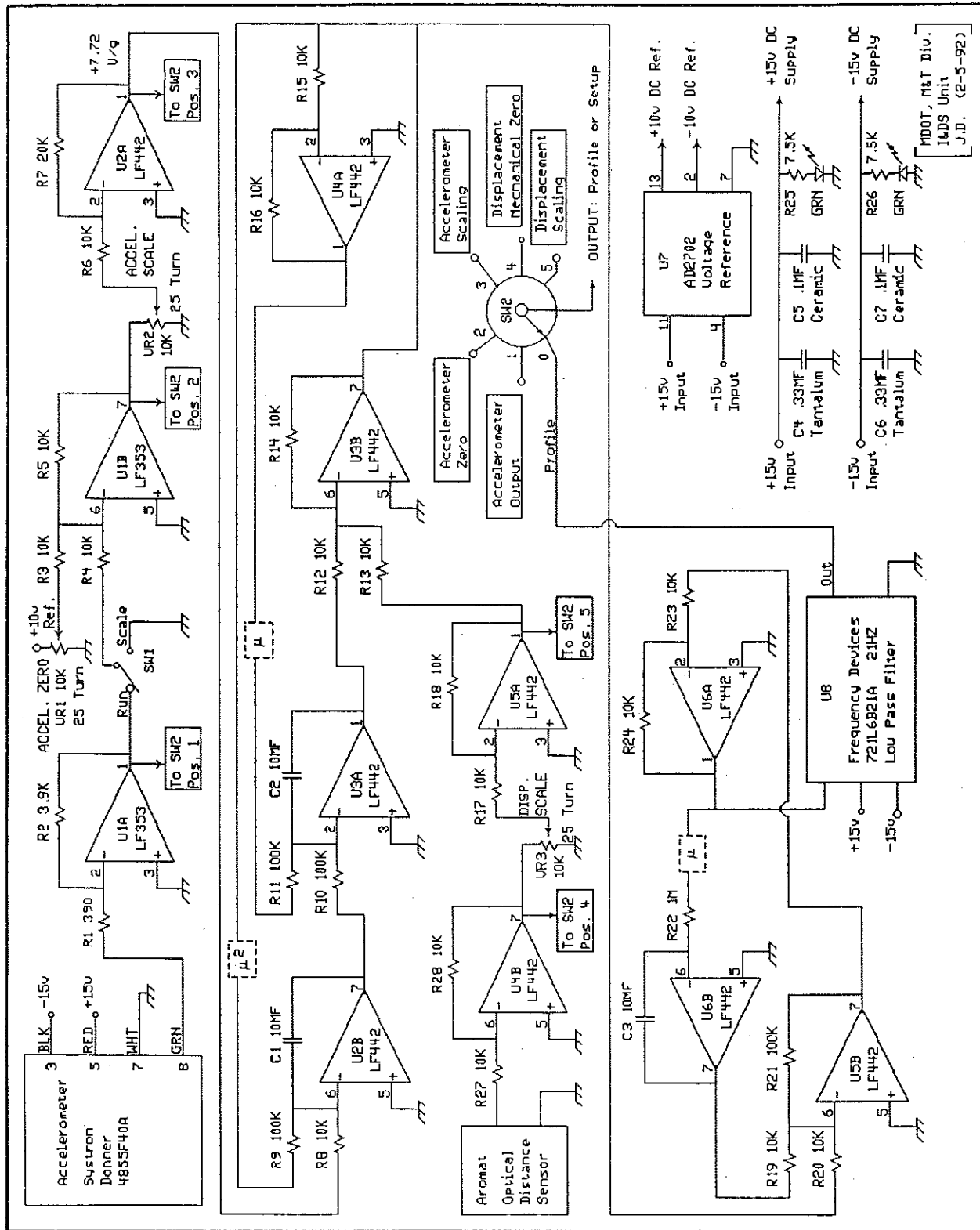
RQI FOR TOTAL RUN = 25.29 CALPRO IN/MI FOR TOTAL RUN = 0.11

END OF RUN

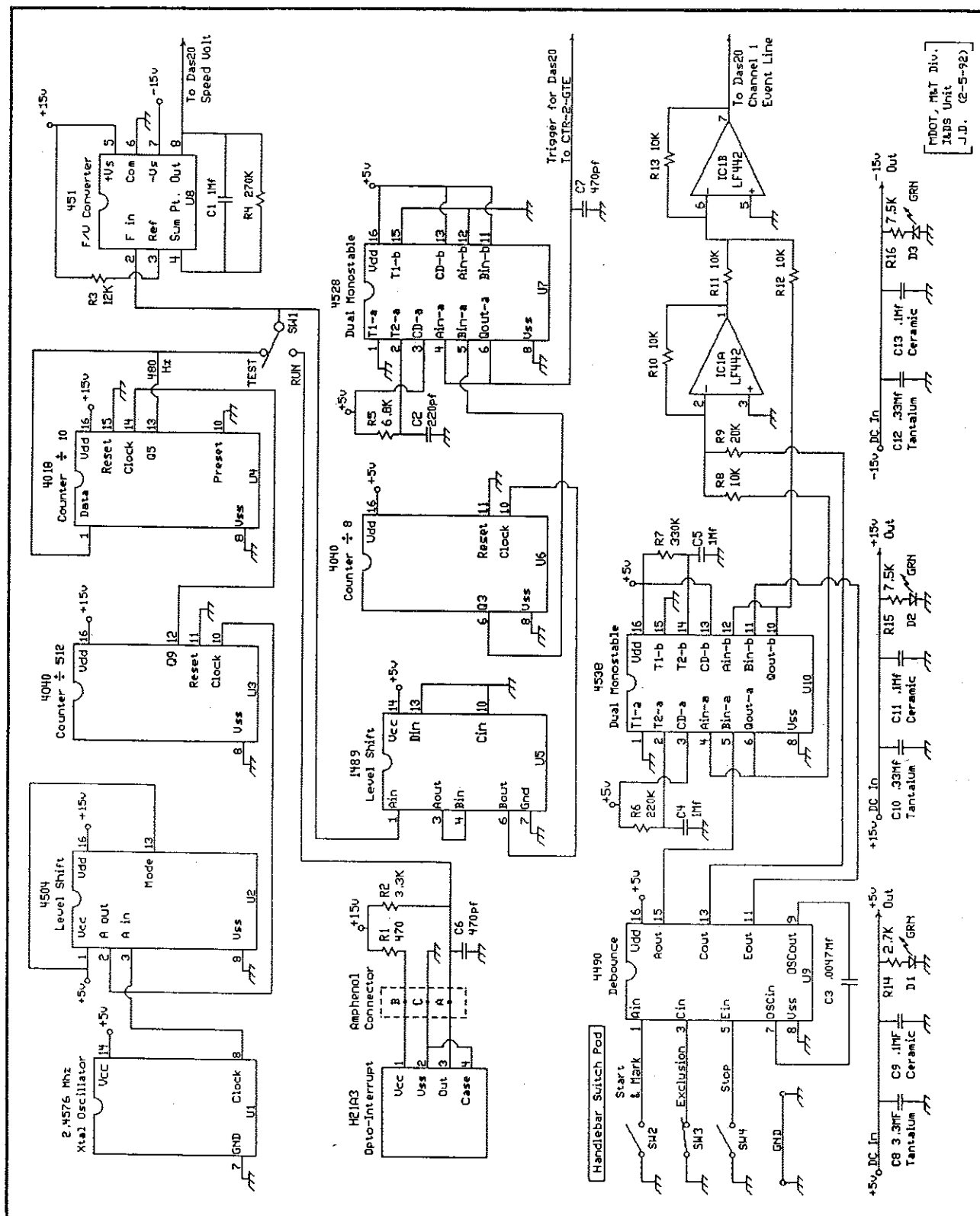
```

Typical project result file.

APPENDIX C
SYSTEM SCHEMATICS

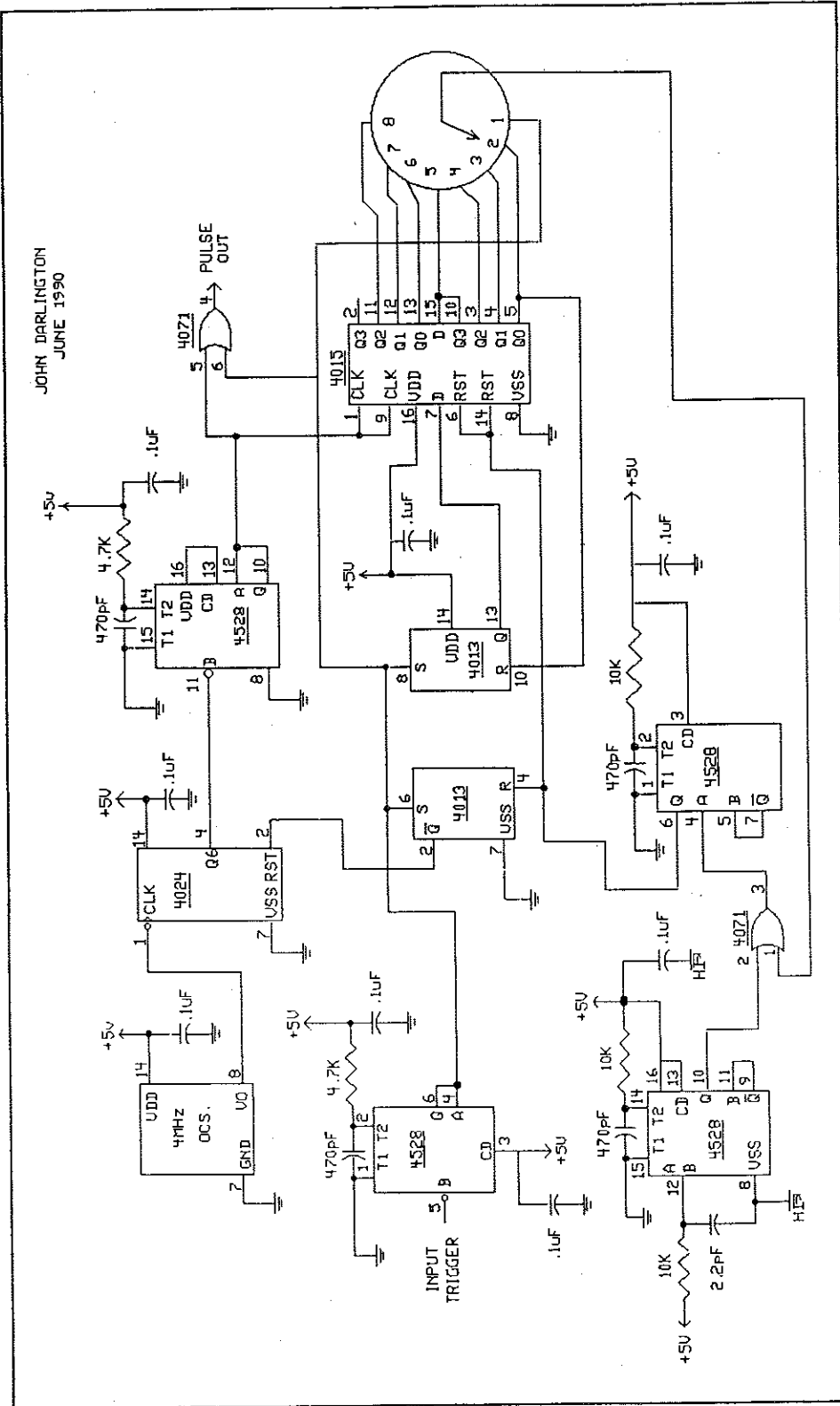


Analog profile computation circuit - Lightweight Profilometer.



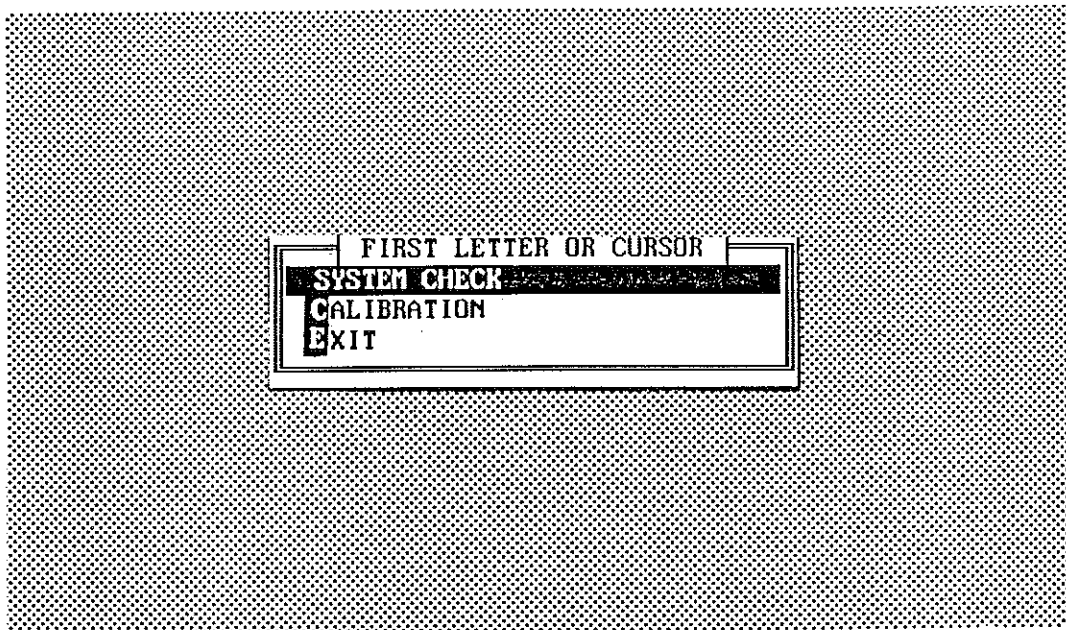
Utility card circuit - Lightweight Profilometer.

JOHN DARLINGTON
JUNE 1990



Single trigger to burst generator for DAS16F - 1 to 8 channels.

APPENDIX D
SYSTEM CHECK COMPUTER SCREENS



Menu for check and calibration routines.

INTERNAL CHECK

1. Step to rear of bike.
2. Open cover on small card box.
3. Check for 3 green LED's.
4. Push toggle from RUN to TEST.

PRESS ANY KEY WHEN READY

RUNNING, PLEASE WAIT

- If no change after 10 sec.
- A. Is RUN-TEST switch on TEST?
 - B. Repair test clock in small box or:
 - C. Repair A to D card in computer.

Screen 1.

PRELIMINARY SYSTEM CHECK IS OK.

PRESS ANY KEY TO CONTINUE.

Screen 1a. Invoked if preliminary check is ok.

FAILURE IN ONE OR MORE OF ITEMS BELOW

1. Internal test clock.
2. Speed chip (# 451) on small card.
3. A to D converter card in computer.

STOP in module LITECAL at address 1925:
00C7

Hit any key to return to system

Screen 1b. Invoked if preliminary system check fails.

HANDLEBAR POD TEST.

Press STRT/MARK button. You have 10 sec
STRT/MRK is ok.

Press EXCLUSN button. You have 10 sec
EXCLUSN is ok.

Press STOP button. You have 10 sec
STOP is ok.

End of pod test.

Press any key for next test.

Screen 2.

HANDLEBAR POD TEST.

Press STRT/MARK button. You have 10 sec
STRT/MRK was not pressed or is bad

Press EXCLUSN button. You have 10 sec

Screen 2a. Invoked if pod switch is bad.

BOUNCE TEST

**Bounce vehicle straight
up and down by pressing on
the rear equipment platform.**

Begin when START appears.

End when STOP appears.

START BOUNCE

Screen 3.

BOUNCE TEST

**Bounce vehicle straight
up and down by pressing on
the rear equipment platform.**

Begin when START appears.

End when STOP appears.

START BOUNCE

STOP BOUNCE

BOUNCE TEST IS OK.

**End of system check.
Push switch on small card
back to RUN and close cover.**

PRESS ANY KEY TO CONTINUE.

Screen 3a. Invoked if bounce test passes.

BOUNCE TEST

**Bounce vehicle straight
up and down by pressing on
the rear equipment platform.**

Begin when START appears.

End when STOP appears.

START BOUNCE

STOP BOUNCE

BOUNCE TEST FAILED

**SEEK REPAIR OR TRY CALIBRATION.
PRESS ANY KEY TO CONTINUE.**

Screen 3b. Invoked if bounce test fails.

APPENDIX E
CALIBRATION COMPUTER SCREENS

CALIBRATION

1. Step to rear of bike and remove cover from the large card box.
2. Verify that 2 green LED's are on.
3. Release Sensor Assembly and carefully lift from light shield
DO NOT LOOK DIRECTLY INTO LASER PORT!
4. Clamp Sensor to vertical fixture so laser port is about 4.5' from base.
5. Carefully install nylon cap on accelerometer. Place round level in cap. Tilt fixture to center bubble.

TEST SWITCH is rotary dial on card.

PRESS ANY KEY WHEN READY.

```

=====
*               *
*               *
*               *
=====

```

Screen 1.

Move the TEST SWITCH to position 1.
The window should show about -4.0 volts
The exact value is not critical but
should be within 1 volt.

PRESS ANY KEY TO CONTINUE.

```

=====
*               *
*      0.005    *
*               *
=====

```

Screen 2.

Move the TEST SWITCH to position 2.
Adjust UR1 until you get zero volts.
PRESS ANY KEY WHEN DONE.

```
=====
*           *
*   0.005   *
*           *
*           *
=====
```

Screen 3.

Move the TEST SWITCH to position 3.
Move the RUN-SCALE switch to SCALE.
Adjust UR2 for 7.72 volts.
Return the RUN-SCALE switch to RUN.
PRESS ANY KEY WHEN DONE.

```
=====
*           *
*   0.005   *
*           *
*           *
=====
```

Screen 4.

Now you can remove & store
the bubble level & nylon cap.
PRESS ANY KEY WHEN READY.

```
=====
*           *
*   0.005   *
*           *
*           *
=====
```

Screen 5.

Move the TEST SWITCH to position 4.
Carefully re-clamp the Sensor or
otherwise adjust height so you
get zero volts in the window.
PRESS ANY KEY WHEN DONE.

```
=====
*           *
*   0.005   *
*           *
*           *
=====
```

Screen 6.

Move the TEST SWITCH to position 5.
You should see close to zero volts.
Now slide a 1 inch cal block
under the Laser Sensor.

Adjust VR9 for -0.20 volts.

PRESS ANY KEY WHEN DONE.

```
=====
*           *
*    0.005  *
*           *
*           *
*           *
*           *
=====
```

Screen 7.

Calibration is now complete.

Store the calibration block.
Replace Sensor. Observe height
and vertical set marks.
Move the TEST SWITCH back to 0.
If the small card box is open verify
that the toggle switch is toward RUN.
Replace card box cover(s).

The BOUNCE TEST portion of SYSTEM
CHECK should now pass.

PRESS ANY KEY FOR RETURN TO MENU.

Screen 8.