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LABORATORY TESTING OF ACROSS THE ROAD
LASER SPEED MEASUREMENT DEVICES

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P David Fisher
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LABORATORY TESTING OF ACROSS THE ROAD LASER SPEED MEASUREMENT DEVICES

By

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ABSTRACT

LABORATORY TESTING OF ACROSS THE ROAD LASER SPEED MEASUREMENT DEVICES

By

Stefano Angelo Mario Lassini

In this dissertation we describe the instrumentation developed and the testing procedure used to test in a laboratory setting Across the Road Laser Speed Measurement Devices [AR-LSMD]. Also, we develop a theoretical model for the various possible error modes for this class of speed measurement devices. Said model is then used to characterize some of the erroneous readings detected in the readings of a specific AR-LSMD that we were allowed to test. As a result of our study we developed the technology and the hardware needed to test AR-LSMDs and we were able to provide to the manufacturer of the device that we tested significant information that could be used to improve the performance of their product.

To My Family

Acknowledgments

I wish to recognize the contributes provided to this project by Dr. P. David Fisher, the director of the MSU Instrumentation Design and Testing Laboratory and my academic advisor during my graduate program. I am also grateful to Jamillah Ervin for the help she provided during the data collection phase of my tests.

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1: Introduction

The MSU Instrumentation Design and Testing Laboratory has been for many years actively involved with the testing of various speed measurement devices available to the law enforcement community and with the development of related standards both at the State and Federal level. The newest technological development in this field is represented by the Laser Speed Measurement Devices, or LSMDs. These devices have been developed to overcome some of the limitations of the more commonly used Doppler radar devices, but their introduction has required the development of a new set of testing and training standards.

This thesis details the development of the hardware and software necessary to test in a laboratory environment a class of these laser devices, the Across the Road LSMD, or Ar-LSMD. Moreover, in this work we developed a model to describe some of the errors that were detected during the testing of a specific AR-LSMD that was loaned to our laboratory for conducting out preliminary tests.

With the simulator that we developed we were able to perform tests on this device that would have been otherwise impractical or impossible to conduct in the field and this led us to discover inaccuracies in the measurements taken by it when the target is travelling at high speeds. Such inaccuracies were not evident in the field testing phase because the limitations of the test vehicle and of the test track did not allow us to test at speeds greater than 70 miles per hour.

The results of the lab testing, together with the theoretical model that we developed to describe them, will now allow the manufacturer to correct the problems that we detected in the design of the device we tested, so as to make this device compliant with the Michigan Speed Measurement Task Force standards. To our knowledge, our simulator is the first device of this kind to be developed and it will serve both the testing and training needs of our lab and the research and development needs of the manufacturers of such devices.

Chapter 2 of this thesis details the theory of operation of an AR-LSMD, including the advantages and disadvantages of such devices. Chapter 3 describes the Simulator that was developed as part of this thesis to allow us to test AR-LSMDs in a laboratory setting. Chapter 4 contains a description of the test performed on an actual AR-LSMD and an analysis of the experimental results of the laboratory test.

Chapter 5, finally, contains an assessment of the simulator's performance and of the performance of the device we tested.

2: Across-the-road laser speed measurement

This chapter presents an overview of the theory of operation of across the road laser speed measurement devices and an analysis of the advantages of AR-LSMDs and of the possible errors that can be introduced in the measurements of such devices by an improper setup and alignment.

2.1: Across-the-road speed measurement:

The principle of across the road laser speed measurement is very simple and seemingly foolproof, relying on the definition of speed itself. A typical device for this kind of measurement consists of two laser emitters placed on the side of the road, as shown in Figure 2.1, and some sort of detection and timing device used to determine how long it takes for a target to travel the known distance D between the two laser beams.

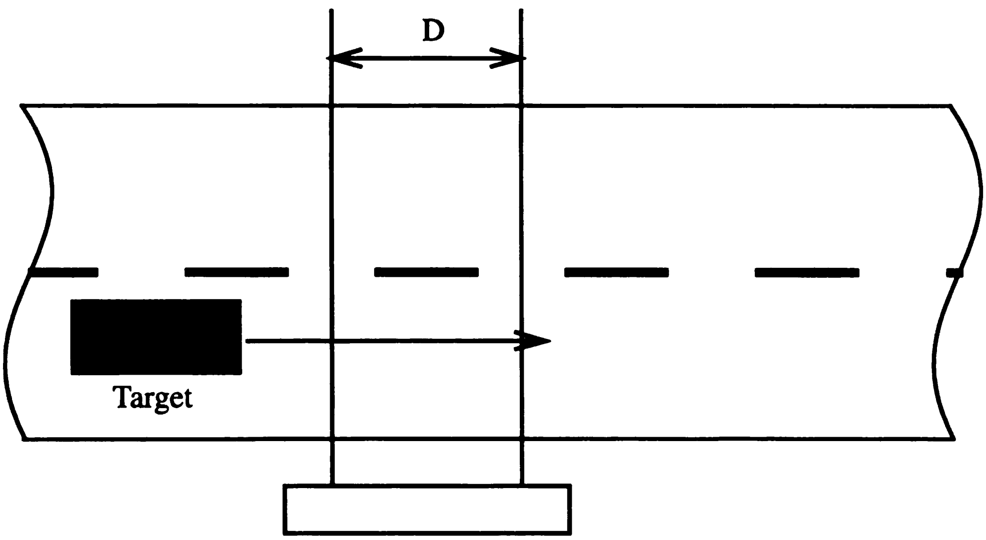

Fig. 2.1: Typical AR-LSMD

If T is the time taken by the target to go from the first to the second beam, the target velocity can be easily computed with the formula:

$$Vmeas = \frac{D}{T}$$

There are several advantages in using AR-LSMDs: among these the first is the almost complete undetectability of the speed measuring device. Unlike radar and, to a far smaller extent, down the road LSMDs, this device does not illuminate the target before the measurement is taken, so conventional detectors like the ones currently available on the market will not be able to signal the presence of an AR-LSMD.

Another advantage of this apparatus is a good target discrimination without the need of physically aiming each individual vehicle. This reduces the fatigue in the operator and, in combination with a computer controlled camera, enables unattended operation, therefore possibly freeing up law enforcement personnel normally devoted to speed enforcement.

There are, however, some questions about the possibility of introducing errors in an across-the-road device by improperly setting up the measuring device or by possible misalignment of the measuring beams that could occur during extensive field usage.

In our analysis we have identified three possible sources of geometrical problems that. alone or in combination, could result in significant errors in the measurements taken.

2.2 Beam misalignment:

The first source of errors is the possible lack of parallelism in the two laser beams. As we can see in Figure 2.2, if the two beams are not parallel the effective range width on the target, D', will be different than the design specification, D.

In this case, the effective range width, D', is:

$$D' = D + (\tan\theta 1 - \tan\theta 2) \times X$$

Where θ1 and θ2 are the angular deviations of the two beams measured counterclockwise from their nominal position and X is the distance between the beam emitter and the target. The resulting error in the determination of the target speed can then be computed as,

$$Verr = Vmeas - Veff$$

where Veff is the effective target speed. By operating the proper substitutions Verr can also be computed as:

$$Verr = \frac{(\tan\theta 1 - \tan\theta 2) \times X}{T}$$

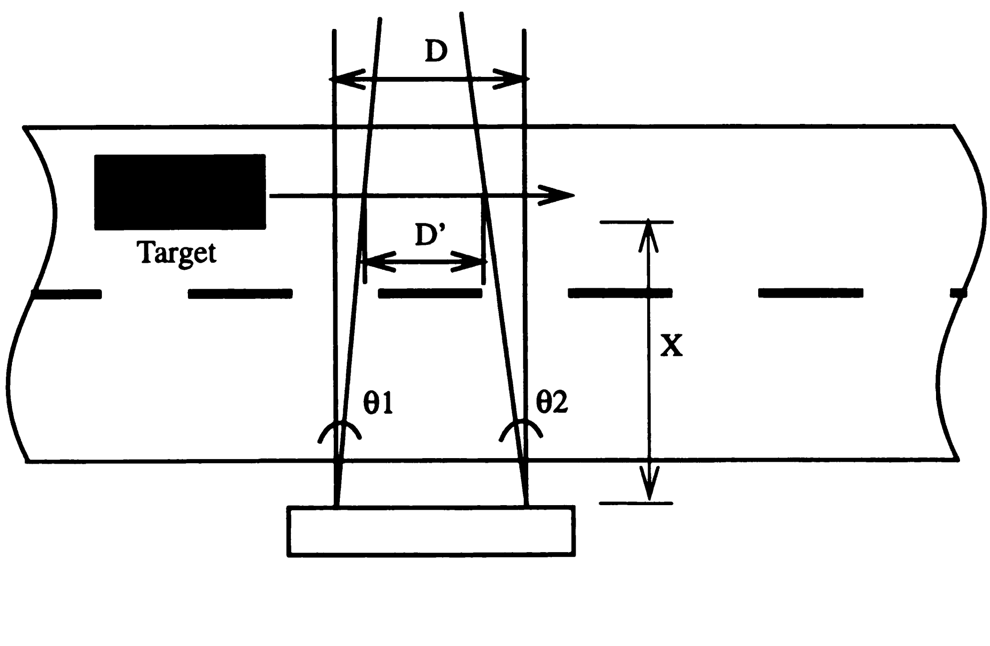

Fig. 2.2: Example of beam misalignment

As an example, let us assume θ1 = -2 degrees, θ2 =2 degrees, X = 4 meters and a speed of 65 m.p.h., to which, assuming an initial beam separation of 400 millimeters and the above beam angles, would correspond a time T = 9.614 milliseconds. With these parameters the error can be computed from the above formulas to be about 12.55 meters per second, or about 28 miles per hour. Because this kind of beam misalignment can occur for a variety of causes during the operational life of an AR-LSMD, and because of the magnitude of the error that can be introduced by it, it is necessary for the operator of each device to have a way to detect this problem before using the device on the road. A simple device like a measuring stick with laser detectors at both ends could be used in the field to verify the parallelism of the two beams before operating the device.

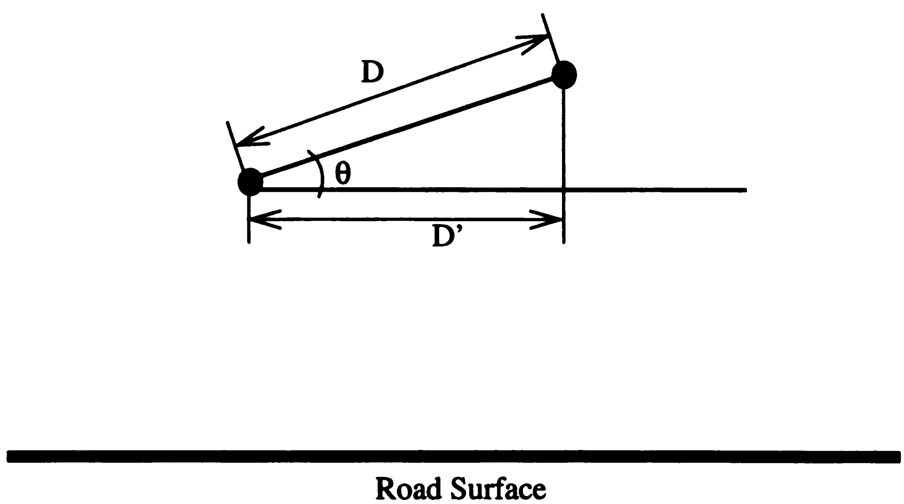

Fig. 2.3: Vertical tilt

2.3 Vertical tilt

The second source of errors is the lack of parallelism between the plane containing the two laser beams and the road surface. In this situation, depicted in figure 2.3, the effective width of the measurement range is reduced proportionally to the cosine of the inclination of the laser emitter. In this situation the measured speed will always be higher than the actual speed of the target as shown by the following:

$$D' = D \times \cos\theta$$

$$Verr = \frac{D}{T} - \frac{D \times \cos\theta}{T}$$

As an example, let us consider an inclination of 10 degrees and a target moving at 65 m.p.h., and an initial beam separation of 400 millimeters. In this case the speed that would be registered by the AR-LSMD would be 66 miles per hour: much less than before but still unacceptable under Michigan guidelines. In a similar scenario, a tilt of 25 degrees would cause a reading of 71.7 miles per hour, or an error of 6.7 m.p.h.

As we see, also this error can be significant and is usually due to incorrect setup of the unit in the field. Current devices do not have any way to automatically detect this problem, even if some provide a bubble level in the mounting base to check the alignment. Without an automatic cutoff on the measuring device it would be possible to challenge the validity of a measurement taken by an AR-LSMD due to the above effect.

2.4 Horizontal tilt

The last kind of geometrical distortion in an AR-LSMD's measurement occurs when the two laser beams are not perpendicular to the direction of travel of the target, as shown in figure 2.4.

In this final scenario the actual distance traveled by the target vehicle, D', will always be greater than the inter-beam spacing of the measuring device. This will always introduce a negative error, so that the speed measured by the AR-LSMD will always be less than the actual speed of the target. The magnitude of such error can be computed easily according to the two following formulas:

$$D' = D \times \sec\theta$$

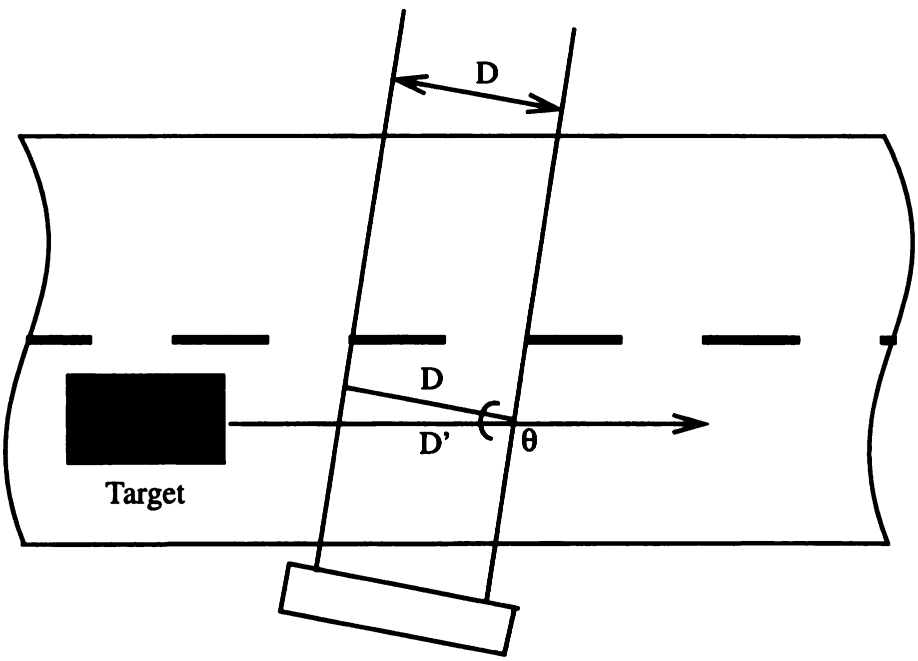

Fig. 2.4: Horizontal tilt

and

$$\text{Verr} = \frac{D - D \times \sec\theta}{T}$$

Again, if we consider a tilt of 25 degrees and a target speed of 65 m.p.h. the measured speed would be 58.9 m.p.h., thus the error would be -6.1 m.p.h.

Because the error introduced by this particular geometric distortion of the measuring range is always in favor of the motorist whose speed is being measured it is not as critical, from the legal standpoint, to have a mean of automatically detecting it.

This notwithstanding, it is important that the operator of an AR-LSMD is aware of the existence of this kind of error when setting up the measurement apparatus in order to achieve the best accuracy from the instrument.

3: Speed simulator for AR-LSMD

This chapter contains a description of the simulator that was designed as part of this thesis to allow our laboratory to perform the tests needed to certify the compliance of a particular AR-LSMD to the standards set forth by the Michigan Speed Measurement Task Force for this kind of device.

Usually such a simulator would be provided by the manufacturer of the device undergoing the certification tests, but in the case of the device that we tested the mechanical simulator that was used for its certification in Europe was neither accurate nor flexible enough to be used for testing under the much more stringent standards in force in Michigan.

3.1: Design rationale

In order to certify the compliance of any LSMD to the standards adopted in Michigan our laboratory needs to be able to test the accuracy and the precision of its readings at any speed between 5 and 195 miles per hour. Moreover these tests need to be conducted at power supply levels ranging from 10.8 Volts to 16.3 Volts and at temperatures from -30 degrees Celsius to + 60 degrees Celsius.

The above requirements are obviously impossible to meet during the field evaluation of a device, therefore it is paramount to have a way to simulate a speeding vehicle in the laboratory environment and in such a way that the simulated vehicle is indistinguishable from an actual vehicle to the device under test.

For across-the-road laser devices the solution originally proposed by the manufacturer was purely mechanical. The simulator that was supplied to us by the manufacturer of the AR-LSMD consisted of a toothed belt mounted on two wooden gears, with a white strip painted on the outside. By controlling the rotational speed of the gears, that were driven by an AC motor, it was possible to control the linear speed of the simulated target, the white section painted on the belt.

While this device worked, it was not accurate nor fast enough to meet our testing needs. It suffered from overheating in the motor's bearings that were limiting the maximum speed achievable to less than 100 miles per hour and only for brief periods of time. In addition, the device required quite a long time to be set up, it was cumbersome to operate and inadequate for the goals of MSU's Instrumentation Design and Testing Laboratory.

It was immediately clear that the solution would have to be an electronic, computer controlled timing system interfaced to some kind of device able to simulate the presence of a target in front of the laser emitter and detector assemblies of the AR-LSMD.

Several possible solutions were investigated, including combinations of mirrors and high speed mechanical shutters, electro-acoustic modulators, Q-switches and other devices normally used as safety interlocks on laser systems. While in principle any of the above devices should have worked, we were not able to find a supplier that could provide a device that could fit our design parameters and the constraints imposed by the device under test, such as minimum aperture size and minimum insertion loss in the case of the electro-acoustic modulators. A manufacturer would have been able to provide us with a custom Q-switch that could meet the minimum requirements, but the cost of two such devices would have been prohibitive (on the order of $30,000 per unit).

3.2: The Electronic Target Simulator

None of the laser switches that we investigated was able to fulfill all of the design requirements of the AR-LSMD simulator. Therefore we had to develop our own custom hardware to interface to the laser beams. The result is what we call an Electronic Target Simulator, or ETS.

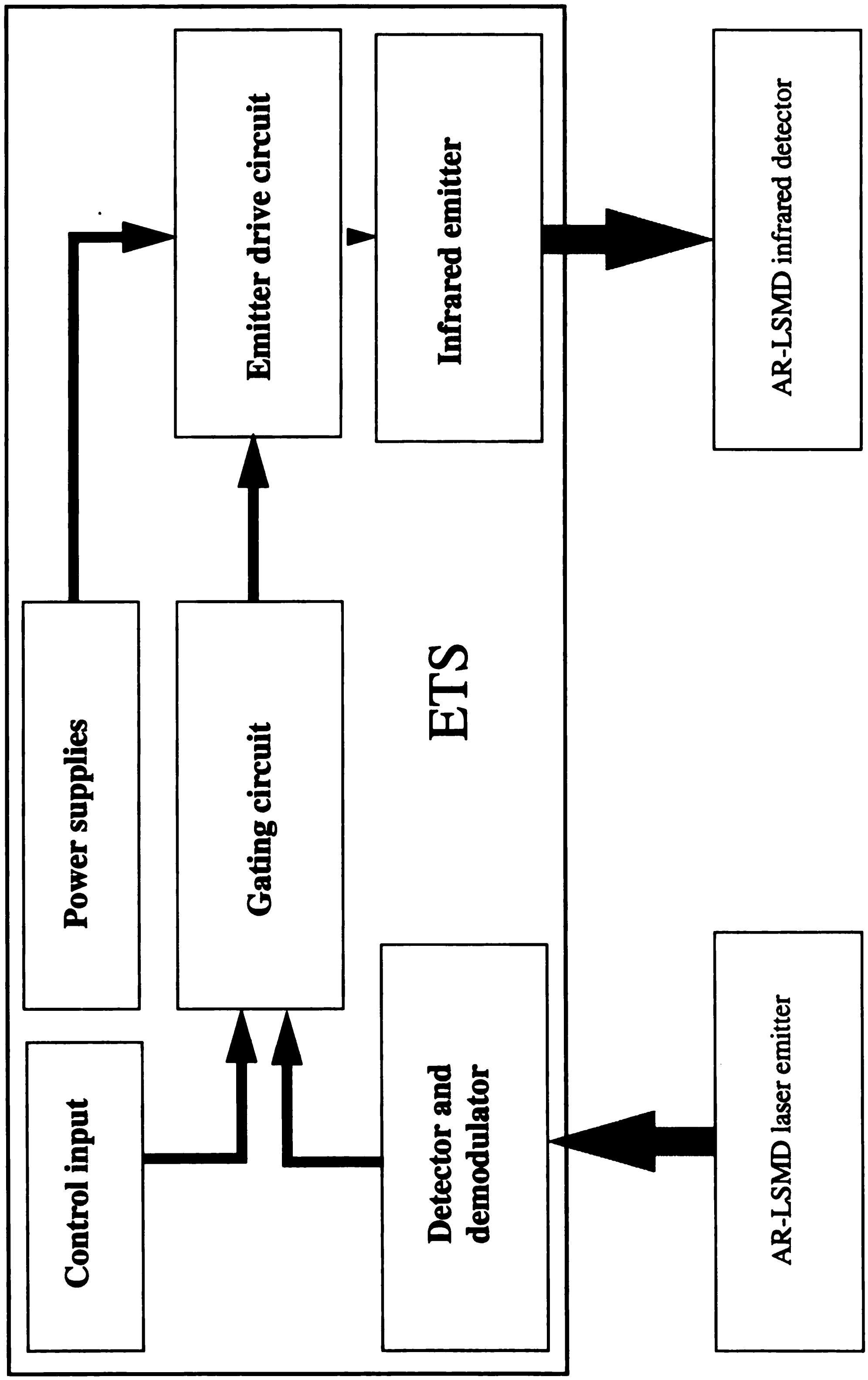

Fig. 3.1: Electronic target simulator - block Diagram

As shown in figure 3.1, the ETS is composed of five functional blocks: the laser detector and demodulator circuit, the gating circuit, the power supplies, the emitter drive circuit and the infrared emitter. The detector and demodulator circuit receives the laser pulses emitted by the AR-LSMD's lasers and transforms them in a logic level pulse train that can be handled by the rest of the circuit. The Device that we tested modulates its laser beams with a CW scheme where the lasers are turned on for 10 microseconds every 142 microseconds. Figure3.2 shows the oscilloscope trace of the Start and Stop beams of the device under test as detected by a Siemens PIN photodiode identical to the ones used in the detectors the AR-LSMD loaned to us, while figure3.3 shows the corresponding demodulated signals as measured with a Fluke 97 digital storage oscilloscope at the input of the gating circuitry.

The gating circuit controls the output of the Electronic Target Simulator. In the quiescent state a '0' logic level is applied to the Gate input of this circuit, thus inhibiting the emitter drive circuits: in this situation the infrared emitter is turned off and the LSMD does not detect any targets. During a simulation the Controller unit will apply a positive going pulse to the Gate input of each of the two ETSs whose duration is equal to the time that a target of a given length will take to travel in front of the AR-LSMD at a given speed. The time skew between the rising and falling edges of the Start and the Stop pulses corresponds to the speed of the simulated vehicle.

The Emitter Drive circuit provides the signals necessary to control the Infrared Emitter. The switching device that generates those signals is an International Rectifiers HEXFET: this particular MOSFET transistor has a very large current handling capability and a very low "on" resistance, thus is able to drive many different kinds of emitters as needed. Although conceptually simple, this circuit required the biggest design effort in the whole ETS. The reason for this is that we were not allowed to conduct any measurement on the

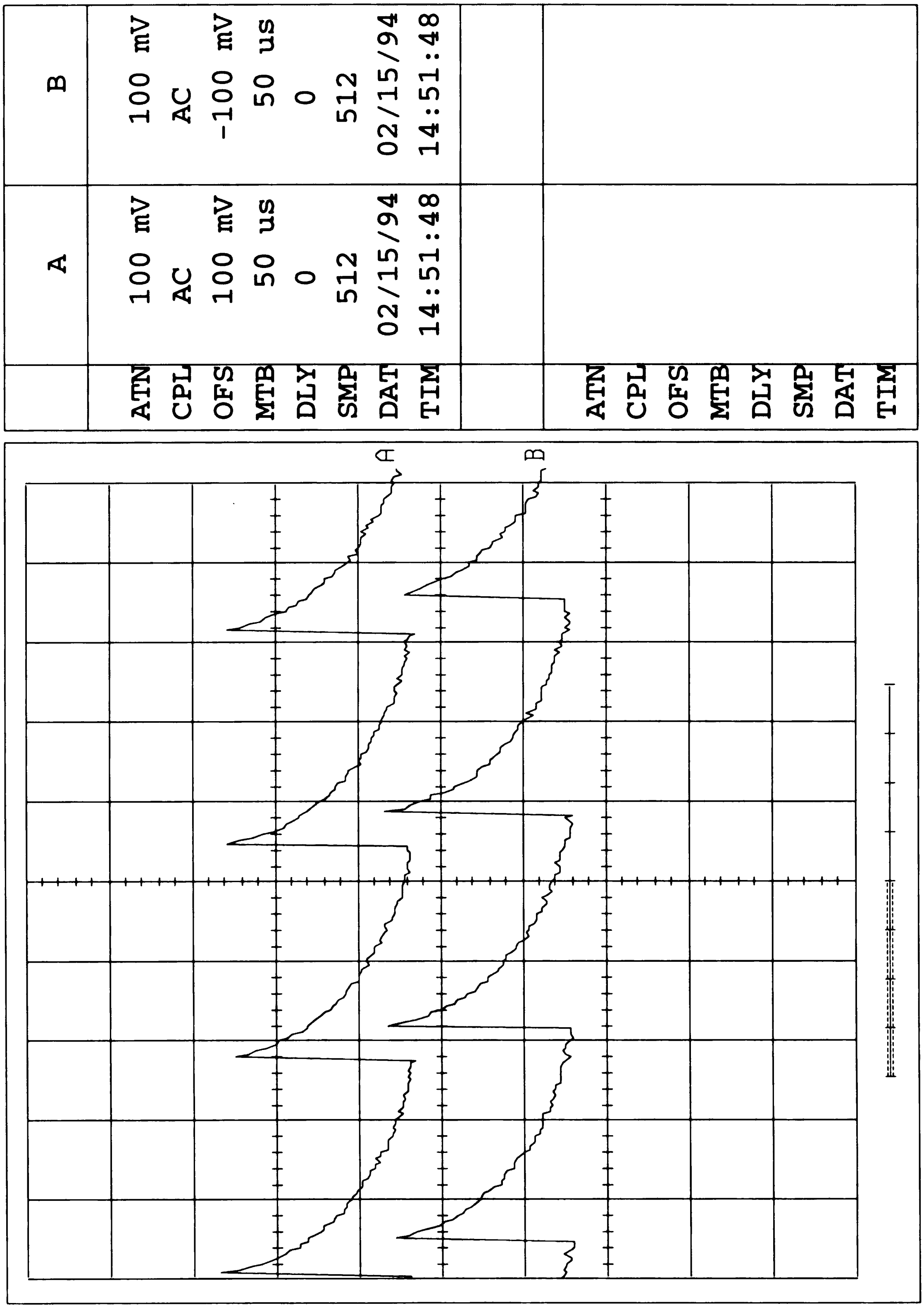

Fig. 3.2: Laser pulses from the AR-LSMD under test

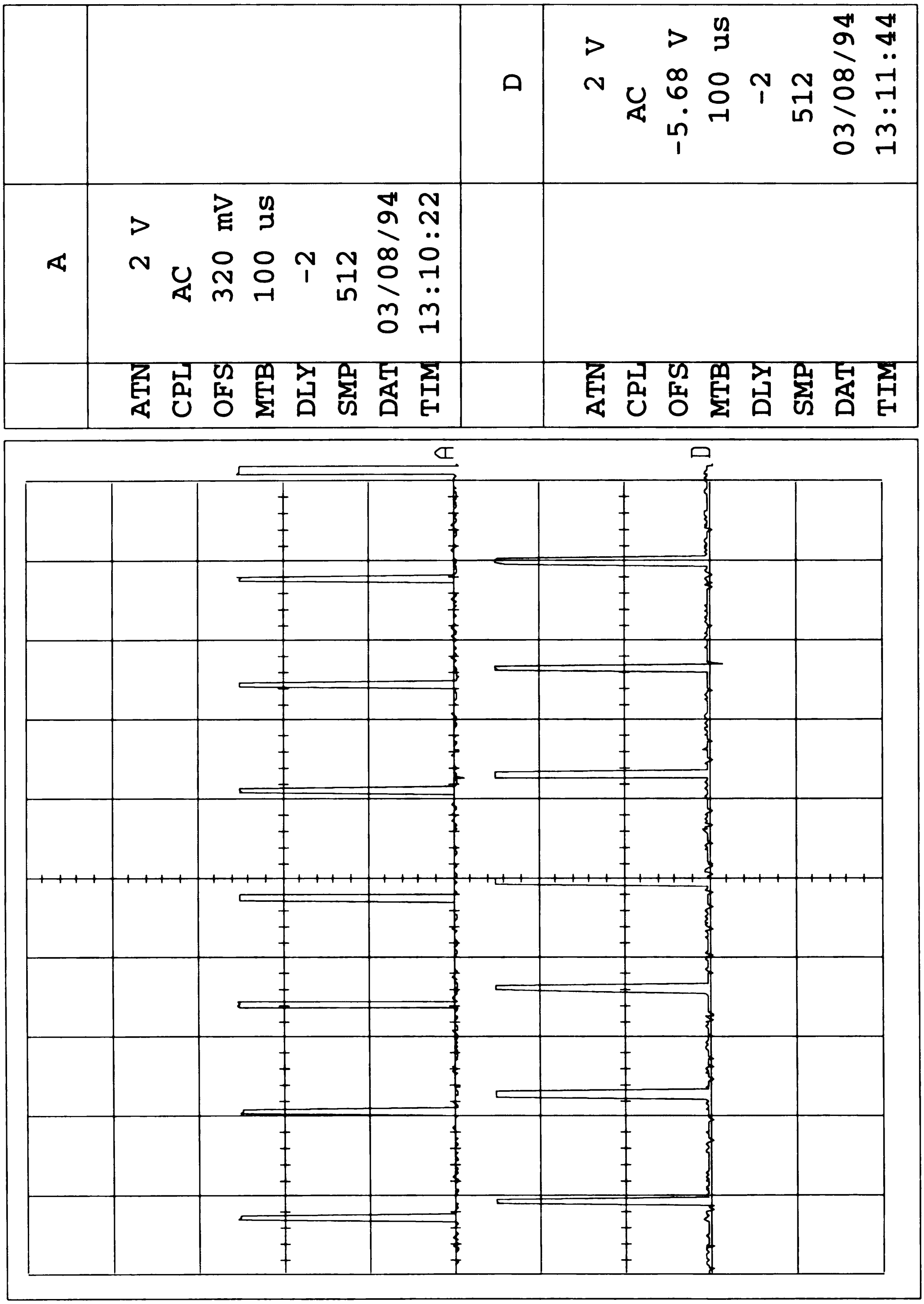

Fig. 3.3: Demodulated laser pulses at the input of the gating circuit

AR-LSMD detector circuits and we were not provided by the manufacturer of the device under test with specifications on the acceptable optical power levels to present to the receivers. This, combined with the fact that the LSMD under test appears to dynamically adjust the gain on its detectors to compensate for background radiation, required a large amount of trial and error experimentation to find a combination of optical power levels on the output of the ETS that could reliably drive the detectors without causing them to saturate and consequently introduce errors in the speed measurements.

Finally, the infrared emitter transforms the pulses coming from the drive circuit back into infrared energy at the same wavelength of the lasers emitted by the test device. Figure3.4 shows the pulse trains corresponding to a target travelling at 65 miles per hour, while figure3.5 shows the output infrared signal from the ETS, detected using the same PIN diode used in figure 3.2. As we can see by comparing these two figures the signal emitted from the device we tested is indistinguishable from the one generated by our ETS.

In our initial design we used a gallium arsenide infrared laser diode with a center emission wavelength of 900 nanometers that was supplied to us by the manufacturer of the device that we were testing. After a few experiments with unreliable outcomes we decided to switch to an infrared LED that has its emission peak at the same wavelength of the lasers that we were previously using but that has the advantage of a better control to obtain the desired optical power levels. The lasers, even at the minimum drive current necessary for initiating the lasing effect, proved to be too powerful and to invariably saturate the receivers of the AR-LSMD.

The complete Electronic Target Simulator is encased in a custom made steel enclosure. On one side of this enclosure is an aluminum flange that mates to the front of the AR-LSMD emitters and that has the necessary ports and shields to transfer the infrared signals to and from the ETS without having them interfere with each other. Figure 3.6 shows a picture of

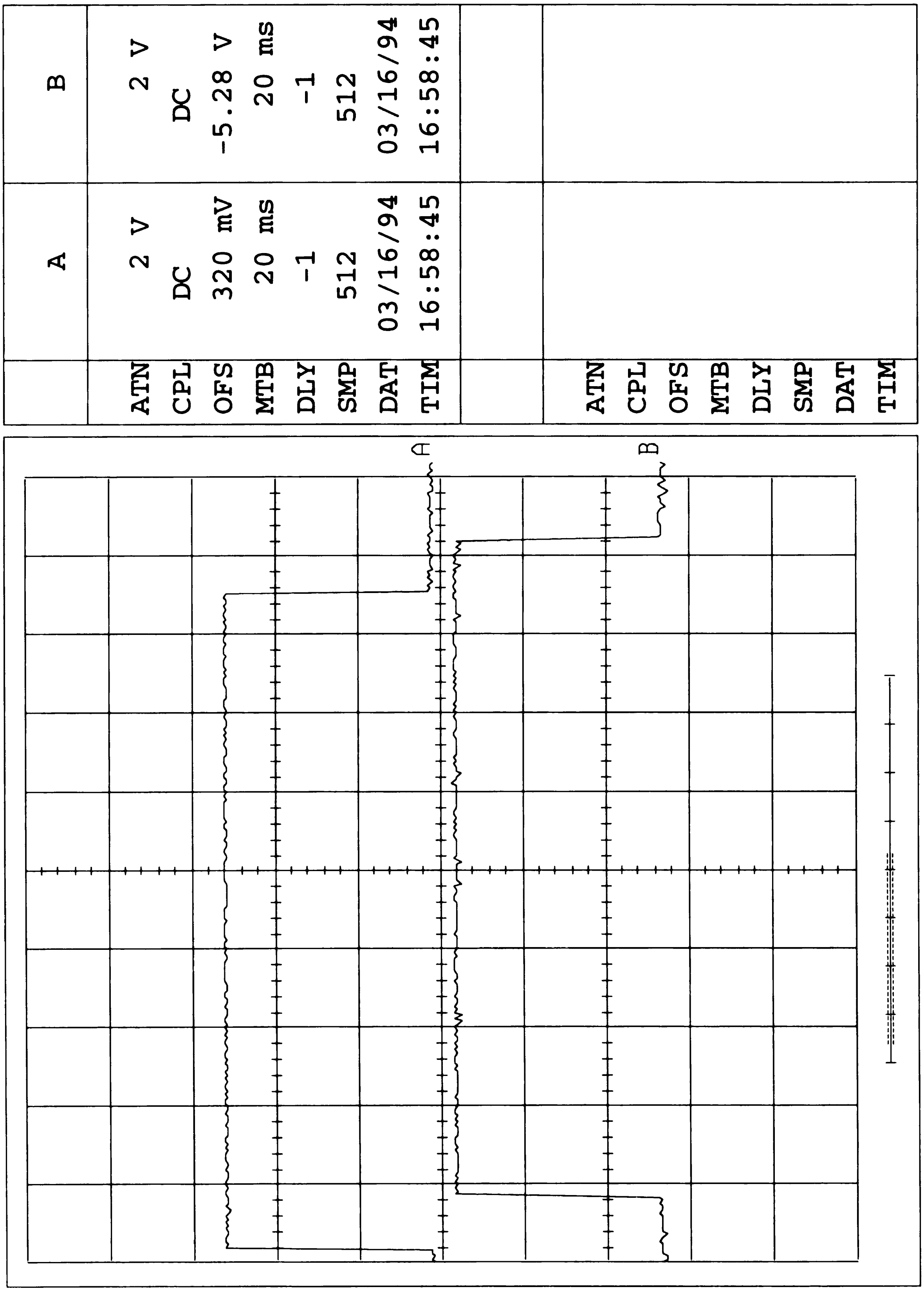

Fig. 3.4: Pulse train for a simulated 65 m.p.h. target

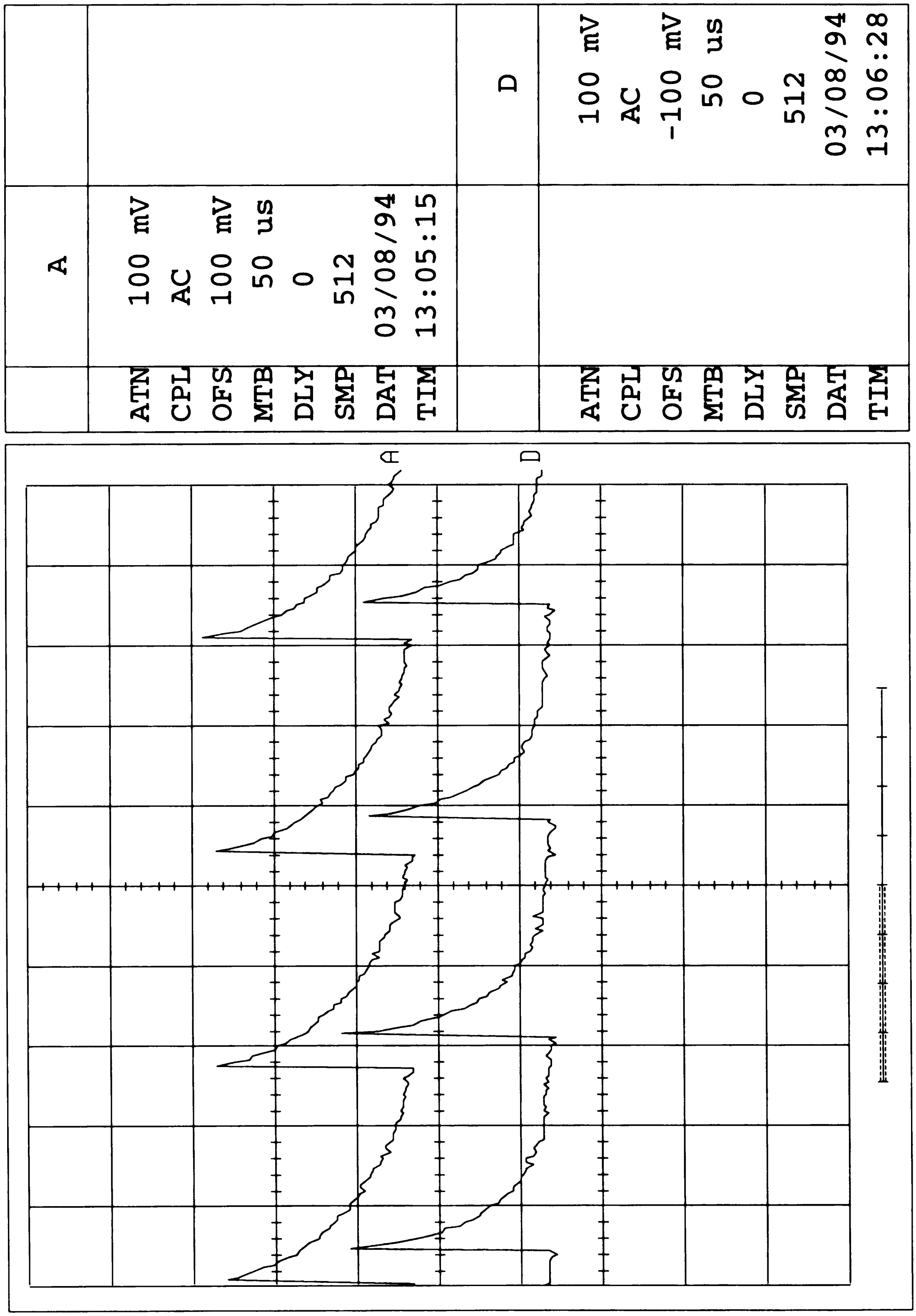

Fig 3.5: Infrared emissions from the ETS

two completed Electronic Target Simulator boxes with the mounting flange and the external connectors in evidence. The four pin connector carries the power, ground and logic signals from the Control unit, while the BNC connector can be used to interface to an independent oscilloscope or other timing device to independently verify the quality of the signals produced by the AR-LSMD Simulator.

3.3: the Control Unit

The two ETS boxes need precisely timed control pulses to simulate a moving target: in our AR-LSMD Simulator these pulses are generated under microprocessor control by a Control Unit built around a Motorola MC68HC711E9 microcontroller.

To simplify the development process we decided to use a Motorola 68HC11 EVBU evaluation board as the platform for our custom hardware: this board provides a socket for a 68HC11 microcontroller chip and the support circuitry necessary to connect it to a PC or any other host provided with an RS-232 port. This evaluation board also comes with a simple but effective debugger that allowed us to develop the time critical part of the Simulator's code in a fairly efficient way.

The 68HC11 EVBU does not have an external memory interface on board, but it provides some limited breadboarding space where the needed circuitry can be assembled. Moreover the clock circuit provided on board is based on a ceramic resonator that we felt not accurate enough for our purpose, so we substituted it with a precision, temperature compensated oscillator.

Figure 3.6 on the next page shows a block diagram of the Control Unit of our simulator, with five functional units on it.

3.3.1: The 68HC11 Microcontroller

The heart of the control logic for the AR-LSMD Simulator is contained in the microcontroller. The 68HC11 is a very versatile 8-bit microcontroller that was selected for this application for several reasons, the most important of which is the highly sophisticated timer chain integrated on the chip itself as one of the peripherals. This timer subsystem allowed us to generate very precise and very repeatable timing pulses under software con-

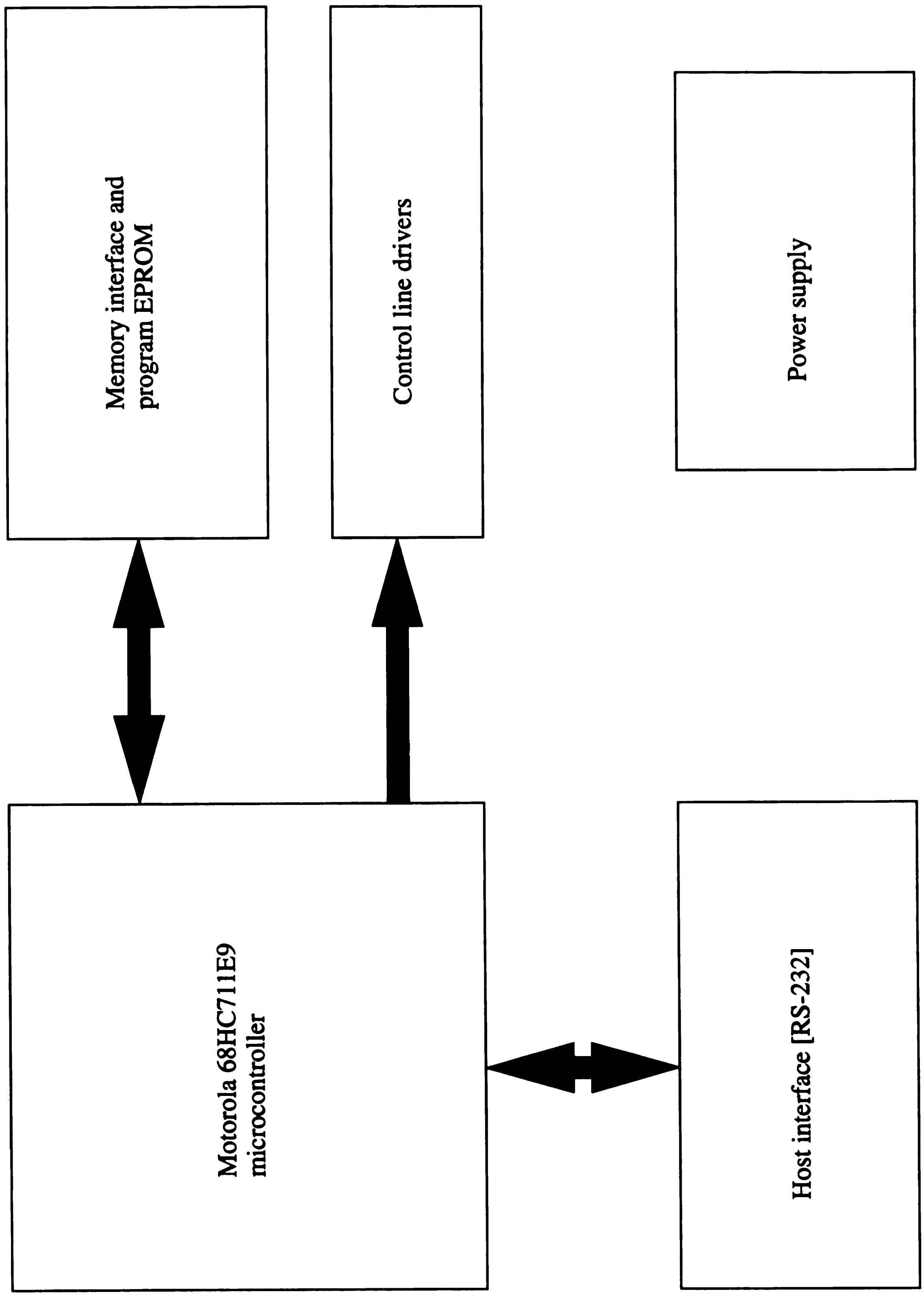

Fig. 3.6: Block diagram of the control unit

trol without the worry of the uncertainty that is always present when timing delays are generated in software in an environment where several interrupts could be active at the same time.

The 68HC11 timer system has up to 5 output channels that can be independently controlled or that can be linked together to act synchronously to each other. [ref 1]

In our design we used two of these channels to control the Start and the Stop ETS, so that up to 3 more channels can be added in the future to support AR-LSMDs that use more than two laser beams to achieve better target discrimination.

Each channel is controlled by scheduling a transition [SET, RESET, TOGGLE or TRI-STATE] to happen when a free running 16-bit counter reaches the count specified in the control register for the specific channel. Once the control registers are properly set the scheduled transitions will happen without further software intervention and independently from the execution state of the Central Processing Unit. Once a transition has occurred a flag will be raised for the corresponding channel so that the software knows when to schedule the next event.

The free-running counter that provides the master time reference for all the timer chain is driven directly by the E-clock of the microprocessor, optionally divided by a prescaler, with an 8-MHz master clock, like on our board. One timer tick can then be either 500 ns, 2 μs, 4 μs or 8 μs, and it can be selected by software only in the first 64 clock cycles after a reset, to protect the time critical operation of the timer chain from faulty software.

Another reason for our microprocessor choice is the flexibility of the memory interface of this chip. By properly setting two jumpers on the evaluation board the 68HC11 can be rebooted in either single chip or extended memory mode, and for debug purposes it can even be rebooted from the serial communication port rather than from the code resident in ROM.

3.3.2: Memory decoding and bus drivers

Due to the size of the code needed for the user interface of the simulator we decided to operate the 68HC11 in its expanded memory configuration, where ports B and C are used as a multiplexed address and data bus. By using an 8-bit wide latch and a few logic gates we interfaced to this bus a 27C256 EPROM that can hold up to 32 kilobytes of code, thus leaving space for future upgrades to the user interface or for the addition of extra functionality in the control software.

Particular attention was also placed on the lines that carry the control signals to the ETS boxes. In order to minimize problems with noise margins on these lines we used high current bus drivers on the Control Unit for these signals. The Start and Stop signals are connected to the ETS via shielded twisted-pair cables that also carry the necessary power and ground signals for the target simulators. To minimize reflections of the control signals on the transmission lines from the Control Unit to the ETS boxes each end of the transmission line is terminated into a matched load.

3.3.3: Power supply

The whole simulator is powered by a 12 Volt, 750 milliampere DC supply with a maximum tolerance of plus or minus 10%. On the Control Unit, a linear regulator is used to provide a 5 Volts power supply for the microprocessor and the rest of the logic circuits of the Control Unit and of the ETSs. To minimize the interference of switching noise with the detectors present in the ETS, the logic power supply is capacitively decoupled in several critical places on the various circuit boards. Moreover each ETS has 2000 μF of tank capacitance on the 12 Volts supply to absorb the transients created when switching on and off the infrared emitters.

3.4: The control software

The across-the-road LSMD simulator relies heavily on the control software for its operation. We can distinguish two main entities in the code that controls the device, the user interface code and the ETS firing routines. These two sections of the code were developed separately using different techniques in order to produce efficient code that could be easily debugged and whose operation is fully predictable in the time critical sections, like the ETS firing control.

3.4.1: Writing low level code on a microcontroller

The ETS firing control routines are the core of the whole speed simulator and as such they need to be completely certifiable to ensure that the speed being generated really corresponds to the speed selected by the operator and that there cannot be undetected anomalous situations that could generate false outputs.

In order to fulfill these criteria we decided to write this part of the code in assembly language and to be careful as to unroll all loops and minimize the amount of branching in the time critical sections, so that there would be only one execution path possible at any given time. As a result of this approach we wrote three version of the firing routines, each one slightly different and each specialized for a specific kind of simulation: single target simulation, two separate target simulation and two overlapping target simulation.

The cost paid in terms of increased code space was minimal, especially when compared to the size of the user interface code, and we feel that the capability of predicting exactly the sequence of events during a time critical simulation far outweights it.

Each version of the firing routine takes as input the speed and the length of the target in terms of timer ticks as computed by the user interface code. After synchronizing with a roll-over of the free running counter this routine schedules the necessary edge transitions on the two control channel that drive the ETS boxes. After scheduling each set of transitions the code will wait in a busy loop for the event to occur before scheduling the next set. Control returns to the calling routine only after the full target simulation has been accomplished.

The firing routines were the first part of the code to be developed and they have been tested extensively since the very early revisions of the hardware, to the point that we are now confident that they are highly reliable.

3.4.2: The user interface

The other part of the control software is the user interface and the various housekeeping routines that are needed for the proper operation of the simulator. The design constraints on this part of the code are very different than the ones posed on the ETS firing routines, therefore the design choices that were made are quite different in this section of the program.

One of the original design requirements of the AR-LSMD simulator was ease of operation, so that it could be used without the need of extensive training. This required a simple, menu based user interface that could hide the details of the operation of the simulator from the user as well as the capability to operate in conjunction with standard hardware and software, like IBM compatible personal computers and their operating systems.

Another constrain on the development of this section of the code was the fact that it was not possible to develop and debug it directly on the target microcontroller due to the limited size of the Random Access Memory available on chip, only 512 bytes.

These requirements prompted us to develop the user interface in ANSI C, so that it could be modified quickly to adjust to the changes in the evolving hardware. Having the interface written in C also allowed us to debug the algorithms used by compiling it on a Sun workstation with a very quick and efficient compile and debug cycle, without having to burn an EPROM for each new version of the code. The advantages of this approach were numerous in terms of development time and complexity of the final product: the time needed to correct minor mistakes went from hours to minutes, and the C compiler automatically provided support for all the floating point calculations needed to compute the firing times for the ETSs from the targets speed and length and from the dimensional parameters of the AR-LSMD being tested.

Notwithstanding the advantages of a high level programming language, writing C code for a microcontroller like the 68HC11 could sometimes introduce some subtle problems, mainly due to the limited amount of memory available and the fact that it is shared by both variables, system stack and user stack. Circumventing these problems required modifying some of the library functions and the startup code that is automatically linked in the final binary image to be burned into the EPROM. Moreover, we decided to adopt some unorthodox programming practices, like keeping all of the program variables globally visible and returning values from the various subroutines by directly modifying global variables. These practices are against the accepted style rules for writing in C and often are taken as examples of bad programming on bigger machines, but on a microcontroller they have the advantage of minimizing the usage of the stack and therefore become highly desirable.

The finished code is designed to communicate with the user via an RS-232 serial asynchronous interface at 9600 baud, so that any personal computer can be used as a terminal. To provide maximum flexibility several menus guide the user through the steps necessary to input the various simulation parameters and to select the desired kind of simulation.

The code is written to be easily extendable to handle future AR-LSMDs with different inter-beam spacing and, possibly, with more than two laser beams, even if such support will also require the addition of other ETS boxes and the relative control logic on the Control Unit

3.5: Software state machine

The core of the ETS firing routines implements a simple state machine. Any device that can implement a similar state machine can be used to control the ETS boxes, so that several different configurations of the simulator are possible to respond to different testing needs.

This state machine, illustrated in the diagram of Figure 3.7, is composed of four main states.

The initial state is the Idle state, where the simulator is waiting for the command to produce a speed. All of the user interaction is currently done in the Idle state, so that once the ETS firing sequence is started there will be no interruptions that could false a measurement.

The first stage of the generation of a target is the Synch state, where the code waits to synchronize with a rollover of the 68HC11 free-running counter. This is done so that all timing parameters for the target pulses are always measured relative to a known reference. The Synch state is entered upon a specific user directive.

The next stage of the state machine is the Entry state. This state is entered when the hardware flags a successfull synchronization of the two timing channels used with the reference counter. In this state the code schedules the transitions corresponding to the leading edges of the Start and Stop pulses that control the ETS. The transition between this state and the next is again controlled by the timing hardware: once the last leading edge has occurred the Exit state is entered.

The Exit state schedules the two falling edges of the ETS control signals. Once the last edge transition has occurred there are two possibilities. If the current target was the last of a given simulation the state machine returns to the Idle state. If there are more targets to be simulated, the next state will again be the Synch state. The controller will remain in the Synch state until the inter-target time has expired, after which it will proceed to generate a new target.

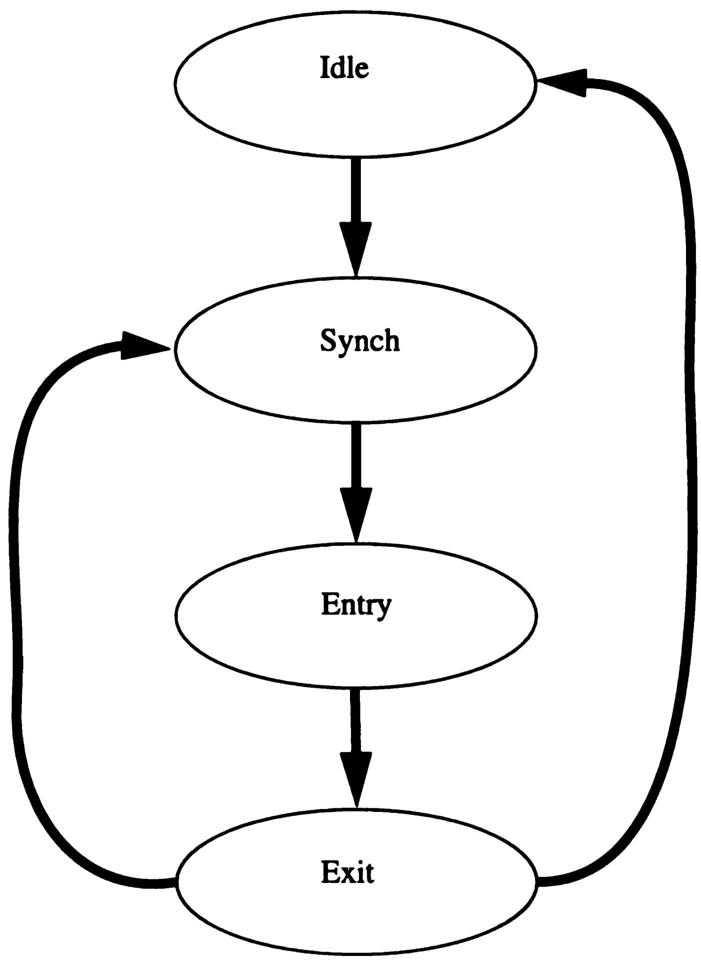

Fig. 3.7: Control state machine.

3.6: Implementation details

To validate the ETS concept and to perform the tests that we needed we built a working prototype of our speed simulator. At the moment, many of the details of the hardware and software that compose the MSU Across the Road Laser Speed Simulator are proprietary design of the Michigan State University Instrumentation Design and Testing Laboratory, and they can be found in the unpublished technical report: 'AR Laser Speed Simulator Design' [ref. 2]

4: Testing of an across-the-road LSMD

The device that was loaned to us from an European manufacturer is the first across-the-road LSMD that has been submitted for testing to the Instrumentation Design and Test Laboratory at MSU.

Since the Fall semester of 1992 we have had several opportunities to characterize this device both in the field and in the laboratory, first by using the mechanical simulator provided by its manufacturer, and, since October 1993, by using the simulator that we developed independently.

The focus of this chapter will be mainly on the laboratory tests that we conducted and that allowed us to gain considerable insight into the operation of this device.

4.1: The device under test

The AR-LSMD that we tested is a two beam device. It is composed of a laser emitter assembly and a control unit. The laser emitter assembly is normally mounted on a tripod and placed on the side of the road where measurements are to be taken. The tripod head is provided with bubble levels so that the operator can verify that the laser emitter assembly is properly positioned and that there are no geometrical distortions to the measurement range like the ones we discussed in chapter two of this document. The device itself has no automatic cutoff to prevent from taking readings when not properly set up.

The control unit connects to the laser emitter assembly with a multipolar cable that carries both power and data signals between the two units. The device functionality is fully controlled from this unit, that can be hand held or installed inside a patrol vehicle. The various options available are chosen from an alphanumeric keypad on the front panel of the control unit, and the speed readout appears on a LCD display and can optionally be sent to a small printer to obtain a record of each measurement, including a time stamp and information on the location where the measurement was taken.

Several optional devices can be connected to this Ar-LSMD, including a 35 millimeters SLR camera equipped with a custom data back panel that can be used to automatically record on film each speed violation.

In our tests we concentrated on the study of the main units, and while we had a chance to test some of the optional accessories during informal field trials none of the conclusions of our tests apply to any optional accessory or are in any way influenced by them.

4.2: Testing procedures

In designing the series of tests to be performed on the actual Ar-LSMD we followed the guidelines established by the Michigan Speed Measurement Task Force in the Interim Standard and Specifications for the procurement of Laser Speed Measurement Devices. The goal of our tests was to ascertain the compliance of this AR-LSMD to the standards adopted by the Michigan Speed Measurement Task Force so that it could be inserted in the Michigan Qualified Products List upon passing our examination.

According to these guidelines, each LSMD that will be used in Michigan has to satisfy or exceed, among others, the following criteria: [ref. 3]

1) The LSMD should be able to measure the speed of any target traveling at any speed ranging from 5 m.p.h. to 195 m.p.h. with a resolution of 1 m.p.h.

2) For each reading the maximum allowable error is plus or minus one mile per hour, and the cumulative average of the readings corresponding to the same target speed should be between minus one to plus zero miles per hour from the actual speed. This requirement indicates that if any bias exists in the measuring device it should be in favor of the speeding violator.

3) The LSMD should be able to fulfill the two above requirements while being operated at temperatures ranging from 30 degrees Celsius below zero to 60 degrees Celsius above zero and at power supply levels ranging from 10.8 Volts to 16.3 Volts.

4) The LSMD should not be affected by various kind of electromagnetic interference such as the ones that could be generated by the electrical devices mounted in a police patrol car.

In order to test for compliance to the above criteria we decided to collect one hundred readings at each of the following simulated speeds: 5 m.p.h., 25 m.p.h., 45 m.p.h., 65 m.p.h., 85 m.p.h., 105 m.p.h., 125 m.p.h., 145 m.p.h., 165 m.p.h., 180 m.p.h. and 195 m.p.h. The log of these experiments is enclosed in the first part of Appendix A.

Successful completion of these tests, that were conducted at room temperature and at nominal power supply levels, would have allowed us to proceed to a second testing phase where we would have stressed the environmental limits of the device under test.

4.3: Room temperature test findings

The device under test did not successfully pass the first phase of our tests. While it showed excellent consistency of results and accuracy at simulated speeds between 5 and 65 miles per hour, high speed tests show a large percentage of erroneous readings, and the deviation from the actual speed appears to increase as a function of the speed being simulated. While at low speed the indications of the measurement apparatus matched very closely the simulator output, with cumulative errors from zero miles per hour to small negative fractions of one mile per hour, at speeds of 85 miles per hour or above up to 50% of the readings presented an unacceptable positive error. Figure 4.1 shows the margins of error detected in the device under test as a function of simulated speed. The abscissa in this fig-

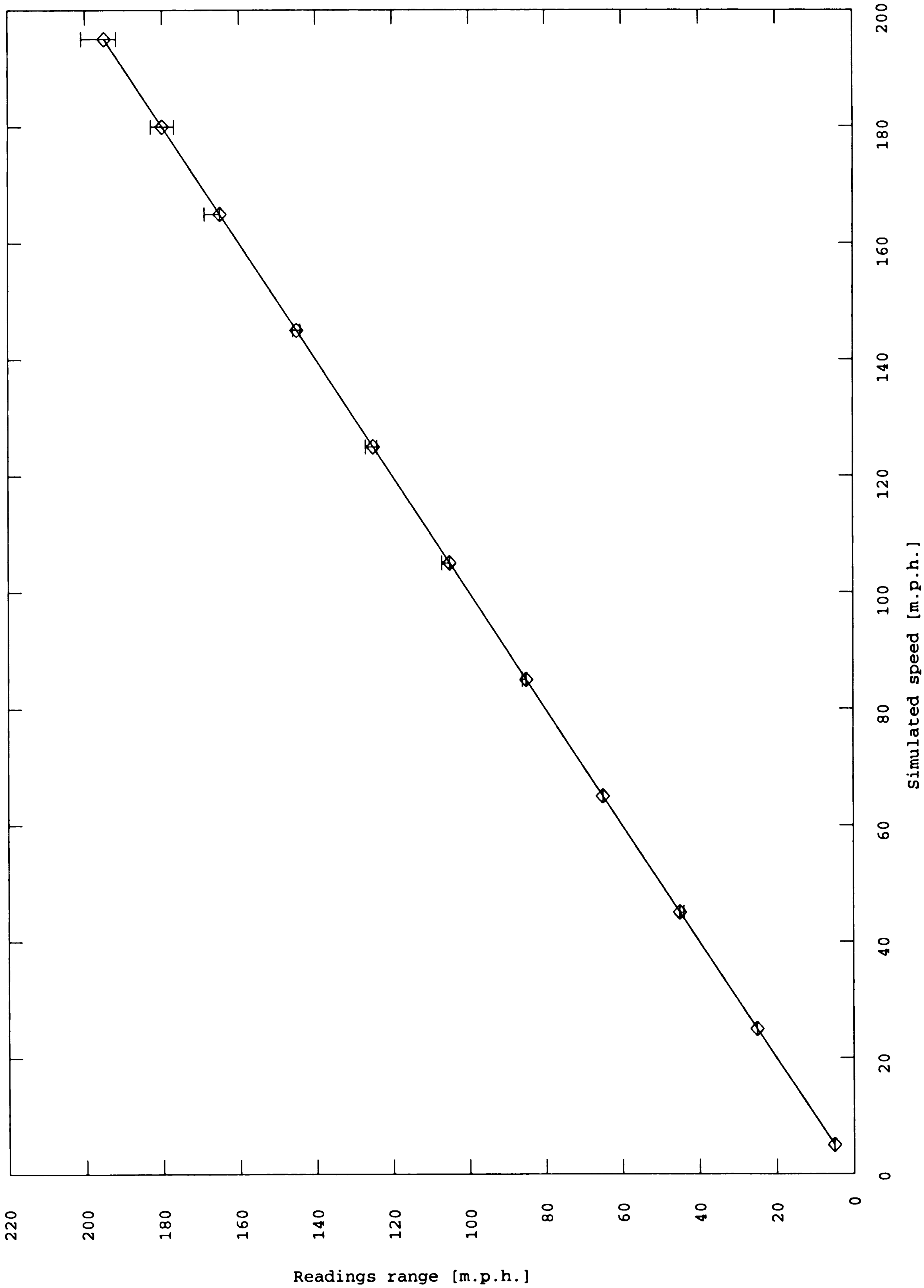

Fig. 4.1: Observed errors in the measurements of the device under test

ure is the simulated speed in miles per hour, and for each measurement point an error bar indicates the variability of the measured speed.

To explain these errors we had to take a close look at the details of the operation of the Ar-LSMD with which he were working, and especially at the modulation scheme employed by the laser emission of this apparatus.

As we can see from figures 3.2 and 3.3, as well as from the detail shown in figure 4.2, the two laser beams in this AR-LSMD are modulated in a pulse train with a period of 142 microseconds; each beam is on for approximately 10 microseconds and off for approximately 132 microseconds. Moreover only one beam is on at any given time: this is done so that the detection circuits can discriminate the reflections coming from the Start beam from those of the Stop beam. The time between a Start pulse and the corresponding Stop pulse is approximately 22 μs.

This modulation scheme holds the key to the explanation of the errors in the readings of this AR-LSMD. There are two sources of error in this scheme: one is the possibility of skipping a Start pulse if a target enters the laser range in the 22 microseconds between the firing of the Start laser and the firing of the Stop laser. The other is the coarse quantization of the time measurements taken by the AR-LSMD under test, due to the large interval between successive laser pulse in the same beam.

The errors that we observed during our experimentation result from a combination of the two above error sources and without setting up tests specifically designed to isolate one from the other it is difficult to tell for any given speed what percentage of the error is due to which error mode.

The probability of skipping a pulse in the measurement of the speed of a target is independent from the speed of the target itself. Assuming, as reasonable, that the arrival time of a target into the measurement range is uniformly distributed and there is no relationship

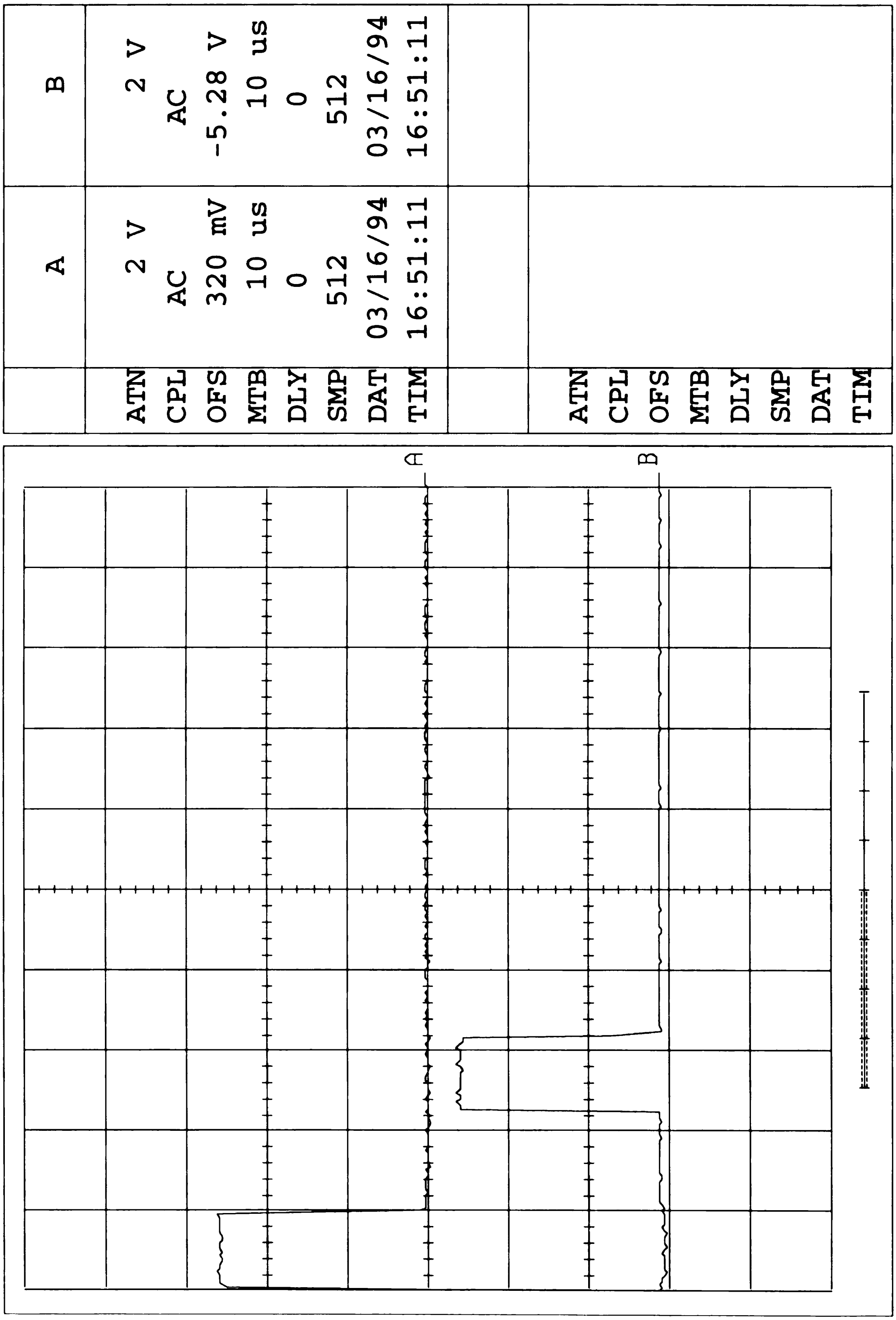

Fig. 4.2: detail of the laser modulation of the AR-LSMD under test

between this arrival time and the modulation of the laser beams the probability that a target will enter the range in the dead time between can be easily computed as

$$\text{Perr1} = \frac{22}{142} \times 100$$

or approximately 15%.

This error does not appear in the measurement taken at the lower speeds because of the fact that the AR-LSMD is designed to round its measurement to the lower integer mile per hour, so that as long as 142 μs corresponds to less than one mile per hour the device will automatically correct the reading.

As shown in figure 4.3, the incremental speed error corresponding to the time quantization chosen by designers of this device grows more than linearly with speed; it becomes greater than one mile per hour when the target speed is greater than approximately 80 m.p.h. and at the higher end of our measurement range, 195 m.p.h., it reaches the totally unacceptable level of 6.23 m.p.h. It is interesting to notice that errors of the same nature were observed in a previous generation of speed measurement devices, known as VASCAR-plus and based on the same time-distance model used in an Ar-LSMD. [ref. 4]

When the target speed increases to the point at which a difference of 142 μs over a distance of 400 millimeters corresponds to a variation in speed of more than one mile per hour, it becomes impossible for the device to accurately resolve the target's speed within the desired accuracy.

At this point the error introduced by the possibility of skipping a pulse is also compounded to the degradation of the measurement resolution, and the sum of those two errors is what we observed in our measurements.

To confirm the fact that the quantization error becomes dominant at high speed we col-

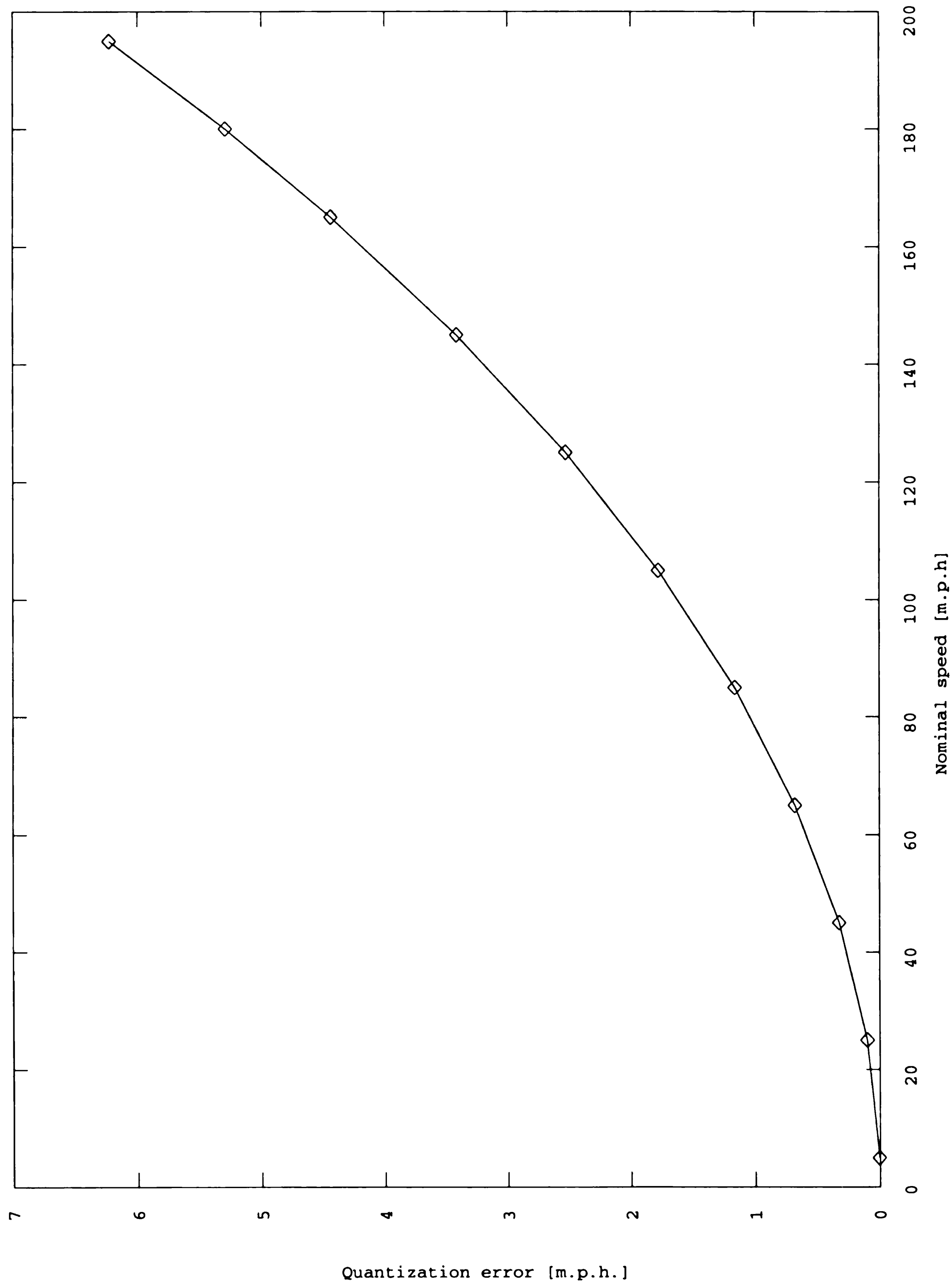

Fig. 4.3: Quantization error versus target speed in the device under test

lected an additional series of measurements where we intentionally biased the output of the simulator up by 0.5 miles per hour from our previous nominal speeds. This second set of tests, included in the second part of appendix A, gave results very similar to the first batch, thus confirming that the device that we tested does round its measurement to the lower integer value when it is able to discern the speed of the target within a mile per hour. At high speed this second batch of measurements proved that the quantization errors overpower the bias that we introduced. As expected the bias increased the number of positive errors at the speed of 85 miles per hour, where the quantization error, while significant, is still of the same magnitude as the bias that we applied.

There a few subtle aspects of the operation of this AR-LSMD that we could not ascertain from the tests we conducted. In particular, we need more information to determine how good the error discrimination of this device is in the case in which the reading taken on a target entering the laser range differs from the reading taken when the same target leaves the range. It is interesting in this regard to notice that even when errors in the measurements were introduced by the two effects described above, the AR-LSMD never identified a reading as invalid.

5: Project review

This chapter reviews the performance of the Simulator that was developed as part of this thesis and outline what future improvements could be done to the simulator itself.
Also, we review the performance of the AR-LSMD that we were allowed to test as part of this project and we suggest some changes in the design of this device that could help improve its performance to the level requested by the Michigan Speed Measurement Task Force guidelines.

5.1: Contributions

We feel that the major contribution of this research to the field of measurement and testing devices is the concept on which the ETS is based. Previous attempts to build a target simulator for AR-LSMDs were based on reflecting back, through mechanical or optoelectronic means, the signal generated by the device under test.
By recreating an optical signal that is indistinguishable from the laser emission of the device under test the ETS eliminates the alignment problems that made all previous attempts only partly successful. Also, the ETS concept allows to control the return signals very effectively, and it allows to simulate anomalous targets or combination of targets like the ones that could be encountered during field use. This capability, not present in the mechanical simulators, allows the testing laboratory to characterize the behavior of an AR-LSMD in any possible hypothetical situation. This last capability is very important when the results of certification tests are used to answer legal challenges that could be brought to the operation of a particular device.

5.2: AR-LSMD simulator performance

With this project, we were able to validate the concept that is at the base of the Electronic Target Simulator and we were able to show that such a concept can be successfully applied to test across the road laser speed measurement devices.

The current ETS was designed to interface to the particular AR-LSMD that we had to work with and, while every reasonable attempt was made to keep the design of the ETS independent from a specific model and vendor of AR-LSMDs, it might lack the flexibility to be able to interface with any arbitrary AR-LSMD that could be introduced into the market, especially because the wavelength of the return signals is currently fixed and future devices could employ different kinds of infrared lasers.

In such a situation the only modification that should be required to the current ETS is the replacement of the infrared emitter and detectors. The ETS was designed so that it would be very easy to change the infrared emitters; the current circuit can be employed with either LED or laser emitters by simply replacing a limiting resistor. The current detector should be usable with a large spectrum of infrared lasers by simply realigning the current circuit. If a new detector was to be used the demodulator circuit might have to be slightly redesigned.The current ETS is designed to be completely independent from the control logic. This will allow future simulators to be built around different control platforms other than the Motorola 68HC11 microcontroller, as long as the device chosen to control the ETS is able to provide timing signal at standard TTL or CMOS logic levels.

While we believe that the current performance of the simulator is more than acceptable, this quantization error could be significantly reduced, if needed, by redesigning the software that operates the Control Unit and by substituting the current microcontroller with a device rated for a higher clock rate.

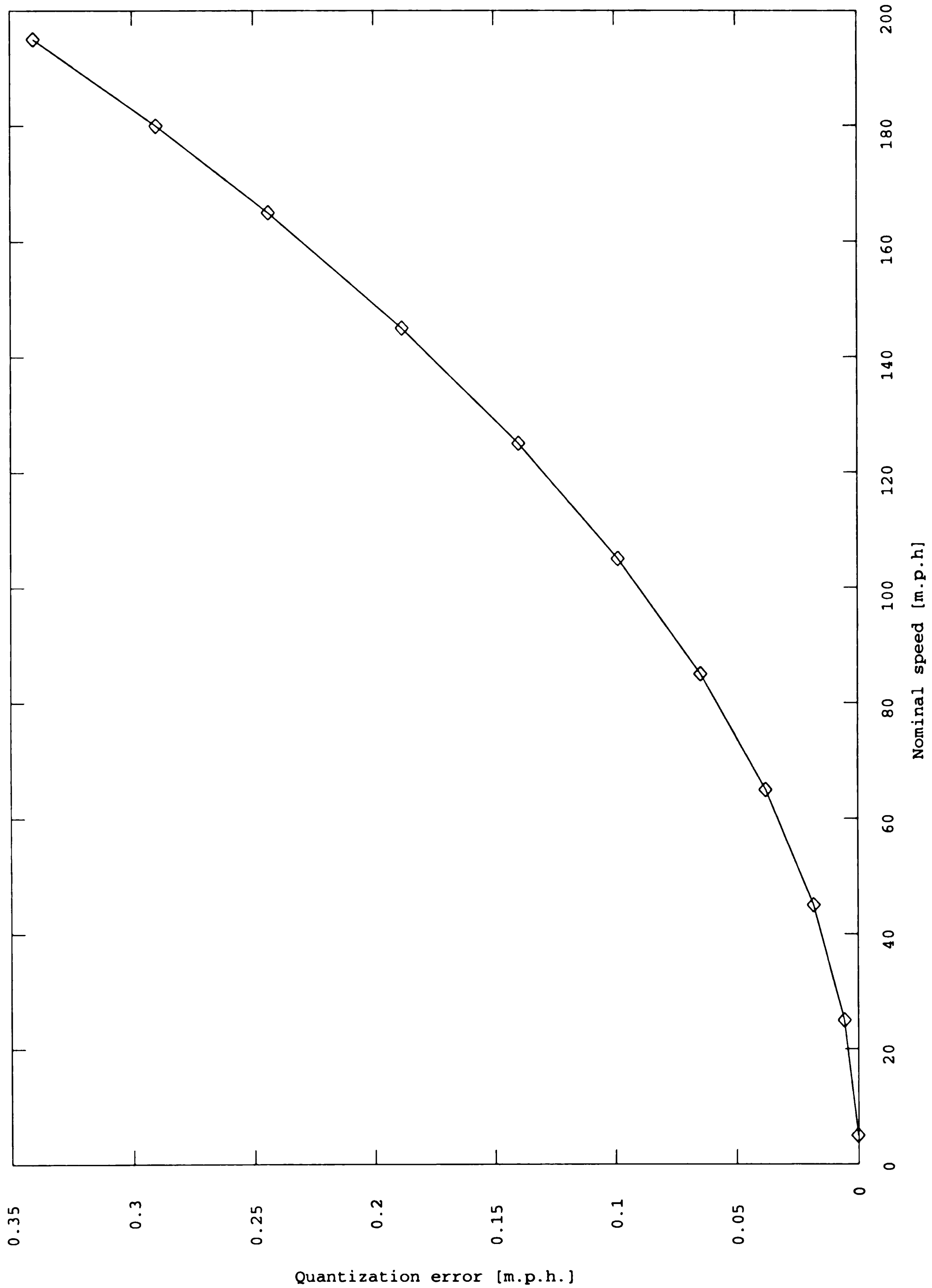

Fig. 5.1: Quantization errors of the MSU AR-LSMD speed simulator

With the present control logic the time resolution of the simulated target pulses is 8 μs. In the case of the AR-LSMD that we tested this corresponds to a maximum uncertainty of less than 0.33 miles per hour in the speed being simulated when operating at the upper edge of the Michigan guidelines, that are among the most stringent in the United States. Figure 5.1 shows the error introduced by the time quantization of our simulator as a function of speed and referred to a beam separation of 400 millimeters.

Another possible change to the Simulator is the addition of a third ETS channel to allow the operation in conjunction with a 3 beam AR-LSMD. This possibility was foreseen in the design of the Control Unit, so that such modification will simply require a third ETS box and minimal and straightforward modifications to the assembly firing routines.

With this much flexibility, the ETS concept appears to be the optimal solution to the problem of simulating a target for an AR-LSMD both for the precision that it allows and for the low cost of this solution, especially when compared with possible alternatives.

For these reasons, we hope that the ETS will find large acceptance among laboratories and institutions involved in the testing and certification of laser speed measurement devices.

5.3: Performance of the AR-LSMD under test

From our findings it is clear that the current version of this AR-LSMD has design limitations that do not make it fit for use in Michigan under the currently established guidelines. This notwithstanding, we believe that the concept of across-the-road Laser Speed Measurement is viable and, if properly implemented, can provide very accurate readings.

The main problem with the current device is the pulse repetition rate used in the laser modulation. From our tests it appears that to resolve speed within one mile per hour at 195 m.p.h. the pulse rate has to be increased at least five times, bringing the period of the modulation signal down to 24 μs or less. If this is not possible due to the duty cycle requirements of the laser emitters an alternative would be to increase the measurement base of the Ar-LSMD: a wider beam spacing would allow a slower pulse rate.

Once a combination of beam spacing and pulse rate is chosen such that the resolution of the device is brought up to compliance with the current Michigan guidelines, the error introduced by skipping a pulse needs to be addressed.

With the current modulation scheme there will always be a chance to skip a pulse due to a target entering the measurement range immediately after the falling edge of a start pulse: to minimize this chance the dead time between the sampling of the start beam and the sampling of the stop beam should be reduce as much as possible, so that the average cumulative error will fall into the requirements.

Finally, the present design lacks of a practical way to detect the geometrical distortions of the measurement range that we discussed in chapter 2 of this thesis. The present device is supplied with a ruler that has two phosphorescent detectors separated by 0.4 meters to be used to check the beam parallelism This device, while functional, is very impractical to use in full daylight, when the luminescence produced by the two infrared laser is too faint to be distinguished. We believe that such a device could be vastly improved by using two active infrared detectors at the ends of the beam gauge. A pair of visible LEDs will then indicate if both beams are illuminating the detectors at the same time.

The device that we tested has a bubble level in the base of its tripod that can be used to verify that the unit is set up without any vertical tilt, but no automatic cutoff to invalidate a measurement if the unit is actually tilted. This could be a potential weakness of this LSMD that could be used to legally challenge the readings taken by the Autovelox. While such cutoff would not affect the accuracy of the unit when properly employed, it would make the Autovelox simpler to use in the field and possibly easier to defend from challenges.

We believe that the problems that were detected in the current version of the AR-LSMD that we evaluated were not detectable with the testing apparatus being used by the manufacturer, and the data that we collected using the Electronic Target Simulator will be valuable to correct the design of this device.

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/17/94

Simulated Speed: 5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/17/94

Simulated Speed: 25 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/17/94

Simulated Speed: 4 5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	-1	44	0	78	0
11	-1	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	-1
14	0	48	0	82	-1
15	0	49	-1	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	-1	52	0	86	0
19	-1	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	-1
25	0	59	0	93	-1
26	0	60	5	94	0
27	0	61	-1	95	-1
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/17/94

Simulated Speed: 65 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/18/94

Simulated Speed: 85 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	+1	37	0	71	0
4	+1	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	+1	77	+1
10	0	44	0	78	+1
11	+1	45	0	79	+1
12	+1	46	0	80	+1
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	+1	84	0
17	+1	51	+1	85	0
18	0	52	0	86	+1
19	+1	53	0	87	0
20	0	54	+1	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	+1
24	0	58	+1	92	0
25	0	59	+1	93	0
26	0	60	0	94	0
27	+1	61	0	95	0
28	0	62	0	96	0
29	+1	63	0	97	+1
30	0	64	0	98	0
31	+1	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	+1	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/18/94

Simulated Speed: 105 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	+2	41	+2	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	+2	48	0	82	0
15	0	49	+2	83	+2
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	+2	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	+2	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	+2	67	+2	101	+2
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/18/94

Simulated Speed: 125 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	0	69	-1
2	0	36	0	70	+2
3	-1	37	0	71	-1
4	0	38	-1	72	0
5	-1	39	-1	73	0
6	0	40	-1	74	0
7	0	41	-1	75	-1
8	+2	42	0	76	0
9	0	43	+2	77	0
10	-1	44	-1	78	0
11	0	45	-1	79	0
12	+2	46	+2	80	+2
13	0	47	0	81	0
14	-1	48	-1	82	+2
15	0	49	-1	83	0
16	0	50	-1	84	-1
17	0	51	+2	85	-1
18	-1	52	0	86	-1
19	-1	53	-1	87	-1
20	+2	54	+2	88	-1
21	-1	55	-1	89	0
22	-1	56	-1	90	0
23	-1	57	-1	91	-1
24	0	58	-1	92	0
25	0	59	+2	93	0
26	+2	60	0	94	+2
27	0	61	-1	95	-1
28	-1	62	-1	96	-1
29	0	63	-1	97	-1
30	0	64	0	98	+2
31	-1	65	-1	99	+2
32	0	66	-1	100	0
33	-1	67	-1	101	0
34	+2	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/18/94

Simulated Speed: 145 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	+2	69	+2
2	-1	36	+2	70	-1
3	-1	37	+2	71	+2
4	-1	38	-1	72	-1
5	+2	39	+2	73	+2
6	-1	40	+2	74	-1
7	+2	41	+2	75	+2
8	+2	42	-1	76	+2
9	-1	43	-1	77	-1
10	-1	44	+2	78	+2
11	+2	45	-1	79	-1
12	+2	46	+2	80	-1
13	-1	47	+2	81	-1
14	-1	48	+2	82	+2
15	+2	49	+2	83	+2
16	-1	50	-1	84	+2
17	+2	51	+2	85	-1
18	-1	52	-1	86	+2
19	-1	53	-1	87	-1
20	-1	54	+2	88	-1
21	+2	55	-1	89	+2
22	+2	56	+2	90	+2
23	+2	57	-1	91	-1
24	-1	58	-1	92	-1
25	+2	59	+2	93	-1
26	+2	60	+2	94	-1
27	+2	61	+2	95	+2
28	-1	62	+2	96	+2
29	+2	63	-1	97	+2
30	-1	64	+2	98	-1
31	+2	65	+2	99	+2
32	+2	66	-1	100	-1
33	-1	67	-1	101	+2
34	+2	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/21/94

Simulated Speed: 180 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+3	35	+3	69	-1
2	-3	36	-1	70	-1
3	-1	37	+3	71	-1
4	-1	38	+3	72	-1
5	-1	39	+3	73	-3
6	-1	40	+3	74	-1
7	-3	41	-1	75	-1
8	-1	42	-3	76	-1
9	-1	43	-1	77	-1
10	-1	44	-1	78	-1
11	-1	45	-1	79	+3
12	-3	46	-1	80	+3
13	-1	47	+3	81	-1
14	+3	48	+3	82	+3
15	-1	49	-1	83	-1
16	-1	50	-1	84	-1
17	-1	51	-1	85	-3
18	+3	52	+3	86	-1
19	-1	53	-1	87	-1
20	-1	54	+3	88	-1
21	-1	55	-1	89	-1
22	-1	56	-1	90	-3
23	+3	57	-3	91	+3
24	+3	58	-1	92	+3
25	-1	59	+3	93	-1
26	-1	60	-1	94	-1
27	-1	61	+3	95	-3
28	+3	62	-1	96	-1
29	+3	63	-1	97	+3
30	+3	64	-1	98	-1
31	-1	65	-1	99	-1
32	-1	66	+3	100	+3
33	-1	67	-1	101	-1
34	-1	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date:2/21/94

Simulated Speed: 195 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	-1	69	-1
2	-1	36	+4	70	+4
3	+6	37	-1	71	+6
4	-1	38	-2	72	-1
5	-3	39	-1	73	+6
6	-1	40	-1	74	-2
7	-1	41	+6	75	-1
8	-1	42	-1	76	-1
9	+6	43	-2	77	-1
10	-1	44	-1	78	-1
11	-1	45	-1	79	-1
12	-1	46	-1	80	-1
13	-1	47	-1	81	+4
14	+4	48	-1	82	-1
15	-1	49	-1	83	-2
16	+4	50	-1	84	-1
17	-1	51	+6	85	-1
18	+6	52	-1	86	-1
19	-1	53	-2	87	-1
20	-1	54	-1	88	-1
21	-1	55	-1	89	-1
22	-1	56	-1	90	-1
23	-1	57	-1	91	-1
24	-1	58	-2	92	-1
25	+6	59	-1	93	-1
26	-3	60	-1	94	-1
27	-1	61	-1	95	-1
28	-1	62	-2	96	-1
29	-1	63	-1	97	-1
30	-1	64	-1	98	-1
31	+4	65	-1	99	-2
32	-1	66	-1	100	-2
33	-1	67	-1	101	-1
34	-1	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 5.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 25.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 45.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	0	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 65.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	0	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	0
11	0	45	0	79	0
12	0	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	0	86	0
19	0	53	0	87	0
20	0	54	0	88	0
21	0	55	0	89	0
22	0	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	0
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	0	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	0	64	+1	98	0
31	0	65	0	99	0
32	0	66	0	100	0
33	0	67	0	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 85.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+1	35	0	69	+1
2	+1	36	+1	70	+1
3	+1	37	0	71	+1
4	+1	38	+1	72	+1
5	0	39	+1	73	0
6	+1	40	+1	74	+1
7	0	41	+1	75	0
8	0	42	+1	76	0
9	0	43	0	77	+1
10	+1	44	0	78	+1
11	+1	45	0	79	0
12	+1	46	0	80	0
13	0	47	0	81	0
14	0	48	+1	82	0
15	0	49	+1	83	0
16	+1	50	+1	84	0
17	+1	51	+1	85	0
18	+1	52	+1	86	+1
19	+1	53	0	87	0
20	+1	54	0	88	0
21	0	55	0	89	0
22	0	56	+1	90	+1
23	0	57	+1	91	+1
24	0	58	0	92	+1
25	0	59	+1	93	+1
26	0	60	0	94	+1
27	0	61	0	95	0
28	0	62	+1	96	+1
29	+1	63	+1	97	+1
30	0	64	+1	98	+1
31	0	65	+1	99	+1
32	+1	66	0	100	+1
33	0	67	+1	101	+1
34	0	68	+1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 105.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+2	35	+2	69	+2
2	0	36	0	70	0
3	0	37	0	71	+2
4	+2	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	+2	41	0	75	+2
8	0	42	0	76	0
9	+2	43	+2	77	0
10	0	44	+2	78	0
11	+2	45	+2	79	+2
12	0	46	+2	80	+2
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	+2
16	+2	50	+2	84	0
17	0	51	0	85	0
18	+2	52	0	86	0
19	0	53	+2	87	+2
20	+2	54	+2	88	+2
21	0	55	0	89	0
22	0	56	+2	90	+2
23	0	57	0	91	0
24	0	58	0	92	0
25	+2	59	0	93	+2
26	0	60	+2	94	+2
27	0	61	0	95	0
28	+2	62	0	96	0
29	0	63	+2	97	+2
30	0	64	0	98	0
31	0	65	0	99	0
32	+2	66	0	100	0
33	0	67	+2	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 2/27/94

Simulated Speed: 125.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+2	35	0	69	+2
2	+2	36	+2	70	-1
3	0	37	0	71	0
4	-1	38	0	72	-1
5	-1	39	-1	73	+2
6	+2	40	+2	74	-1
7	0	41	0	75	0
8	-1	42	+2	76	-1
9	+2	43	0	77	+2
10	+2	44	-1	78	-1
11	+2	45	+2	79	+2
12	+2	46	0	80	+2
13	0	47	0	81	0
14	0	48	-1	82	+2
15	0	49	-1	83	+2
16	0	50	+2	84	+2
17	-1	51	0	85	0
18	0	52	-1	86	-1
19	+2	53	0	87	0
20	0	54	+2	88	0
21	0	55	0	89	0
22	0	56	+2	90	-1
23	+2	57	-1	91	+2
24	-1	58	+2	92	0
25	0	59	+2	93	-1
26	-1	60	+2	94	+2
27	-1	61	+2	95	-1
28	-1	62	0	96	+2
29	-1	63	+2	97	0
30	+2	64	+2	98	0
31	0	65	+2	99	+2
32	-1	66	0	100	0
33	+2	67	0	101	+2
34	-1	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/5/94

Simulated Speed: 145.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+2	35	+2	69	+2
2	-1	36	-1	70	-1
3	-1	37	-1	71	-1
4	-1	38	-1	72	-1
5	+2	39	-1	73	+2
6	+2	40	+2	74	+2
7	+2	41	+2	75	+2
8	+2	42	-1	76	+2
9	+2	43	-1	77	-1
10	-1	44	-1	78	-1
11	+2	45	+2	79	-1
12	+2	46	+2	80	+2
13	-1	47	-1	81	-1
14	+2	48	+2	82	-1
15	-1	49	-1	83	+2
16	-1	50	+2	84	+2
17	+2	51	+2	85	+2
18	+2	52	-1	86	+2
19	-1	53	-1	87	-1
20	+2	54	+2	88	+2
21	+2	55	+2	89	-1
22	+2	56	+2	90	+2
23	+2	57	+2	91	+2
24	+2	58	-1	92	+2
25	-1	59	+2	93	-1
26	+2	60	-1	94	+2
27	+2	61	+2	95	+2
28	+2	62	+2	96	-1
29	-1	63	+2	97	+2
30	+2	64	-1	98	+2
31	+2	65	-1	99	-1
32	-1	66	-1	100	+2
33	+2	67	+2	101	-1
34	+2	68	+2		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/4/94

Simulated Speed: 165.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	0	35	0	69	0
2	0	36	0	70	0
3	0	37	0	71	0
4	0	38	0	72	0
5	0	39	0	73	0
6	0	40	0	74	0
7	0	41	+4	75	0
8	0	42	0	76	0
9	0	43	0	77	0
10	0	44	0	78	+4
11	0	45	0	79	0
12	+4	46	0	80	0
13	0	47	0	81	0
14	0	48	0	82	0
15	0	49	0	83	0
16	0	50	0	84	0
17	0	51	0	85	0
18	0	52	+4	86	0
19	0	53	0	87	+4
20	0	54	+4	88	0
21	0	55	0	89	0
22	+4	56	0	90	0
23	0	57	0	91	0
24	0	58	0	92	+4
25	0	59	0	93	0
26	0	60	0	94	0
27	0	61	+4	95	0
28	0	62	0	96	0
29	0	63	0	97	0
30	+4	64	+4	98	+4
31	+4	65	0	99	0
32	0	66	0	100	0
33	0	67	+4	101	0
34	0	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/4/94

Simulated Speed: 180.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	+3	69	+3
2	+3	36	+3	70	+3
3	-1	37	+3	71	+3
4	-1	38	-1	72	+3
5	-1	39	-1	73	+3
6	+3	40	-1	74	-1
7	-1	41	-1	75	-1
8	-1	42	-1	76	+3
9	-1	43	-1	77	-1
10	-1	44	+3	78	-1
11	-1	45	+3	79	-1
12	-1	46	+3	80	-1
13	+3	47	+3	81	+3
14	-1	48	+3	82	+3
15	-1	49	+3	83	+3
16	-1	50	-1	84	+3
17	-1	51	+3	85	+3
18	-1	52	-1	86	-1
19	+3	53	-1	87	+3
20	+3	54	+3	88	-1
21	+3	55	+3	89	-1
22	-1	56	+3	90	+3
23	+3	57	+3	91	-1
24	-1	58	-1	92	+3
25	-1	59	-1	93	+3
26	+3	60	+3	94	+3
27	-1	61	+3	95	-1
28	-1	62	+3	96	-1
29	-1	63	+3	97	-1
30	-1	64	+3	98	-1
31	-1	65	-1	99	-1
32	-1	66	-1	100	-3
33	+3	67	-1	101	-1
34	+3	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/5/94

Simulated Speed: 195 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	-1	69	-1
2	-1	36	-1	70	-1
3	-1	37	+6	71	-1
4	-1	38	-1	72	-1
5	-1	39	-1	73	-1
6	-1	40	+4	74	-1
7	+6	41	-1	75	-1
8	-1	42	-1	76	-1
9	+6	43	-1	77	-1
10	-1	44	+6	78	+4
11	-3	45	-1	79	-1
12	-1	46	-1	80	-1
13	-1	47	-2	81	-1
14	-1	48	-1	82	-1
15	-1	49	-1	83	+6
16	-2	50	-1	84	-1
17	-1	51	-1	85	-1
18	-1	52	0	86	-1
19	0	53	-1	87	-1
20	-1	54	-1	88	+6
21	-1	55	-1	89	+4
22	-1	56	-2	90	-1
23	-1	57	-1	91	-1
24	-3	58	-1	92	-1
25	-1	59	-1	93	-1
26	-1	60	-1	94	-1
27	-1	61	-1	95	-2
28	-1	62	-1	96	-1
29	+6	63	-1	97	-1
30	-1	64	-2	98	-1
31	-1	65	-1	99	-3
32	-1	66	-1	100	-1
33	-1	67	-1	101	+6
34	+4	68	-2		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/5/94

Simulated Speed: 195.25 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	-1	69	+6
2	-1	36	-1	70	-1
3	-1	37	+4	71	-1
4	-1	38	-1	72	+6
5	-1	39	-1	73	-1
6	-1	40	-1	74	-1
7	+6	41	-1	75	-1
8	-1	42	-2	76	-1
9	-1	43	-1	77	+6
10	-1	44	-1	78	-1
11	+6	45	-1	79	-1
12	-1	46	+4	80	-1
13	-1	47	-1	81	-2
14	-1	48	-2	82	-1
15	-1	49	-1	83	-1
16	+6	50	+6	84	0
17	-1	51	+4	85	-1
18	-1	52	+6	86	-1
19	0	53	-1	87	+6
20	+4	54	-1	88	-2
21	-2	55	-1	89	-1
22	-1	56	-1	90	-1
23	-1	57	-1	91	+6
24	-1	58	+6	92	+6
25	-1	59	-1	93	-1
26	-2	60	-1	94	-1
27	-2	61	-2	95	+4
28	-1	62	-2	96	-1
29	+4	63	-1	97	-1
30	-1	64	-3	98	-1
31	-1	65	-1	99	-2
32	-1	66	-1	100	-1
33	+6	67	-1	101	-1
34	-1	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/4/94

Simulated Speed: 195.5 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	-1	69	-1
2	-1	36	-1	70	-1
3	-1	37	+6	71	+6
4	-1	38	-1	72	-1
5	-1	39	-1	73	+4
6	-1	40	-1	74	-1
7	-1	41	-1	75	-1
8	-1	42	-1	76	-1
9	-1	43	-1	77	-1
10	-1	44	-1	78	-1
11	-1	45	-1	79	-1
12	-2	46	-1	80	-1
13	-1	47	-1	81	+6
14	+6	48	-1	82	+6
15	-1	49	-1	83	-1
16	-1	50	-1	84	-1
17	-1	51	-2	85	-1
18	-1	52	-1	86	-1
19	-1	53	-1	87	-1
20	-1	54	-1	88	-1
21	-1	55	-1	89	-1
22	-1	56	-1	90	-1
23	+6	57	-1	91	-1
24	+6	58	-1	92	+6
25	+4	59	-1	93	-1
26	+6	60	-1	94	-1
27	-1	61	-1	95	-1
28	-1	62	+6	96	-1
29	-1	63	-1	97	-1
30	-1	64	-1	98	-1
31	-1	65	-1	99	-1
32	-1	66	-1	100	-1
33	-1	67	-1	101	0
34	-1	68	-1		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/5/94

Simulated Speed: 195.75 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	-1	35	+6	69	+6
2	-1	36	+6	70	-1
3	+6	37	-1	71	-1
4	-1	38	-1	72	-1
5	-1	39	-2	73	-2
6	-1	40	-2	74	-1
7	+6	41	-1	75	+6
8	-1	42	-1	76	-1
9	-1	43	-2	77	-1
10	+6	44	-1	78	-1
11	+6	45	-1	79	-2
12	-1	46	-1	80	-2
13	-1	47	+6	81	+6
14	-1	48	-1	82	+6
15	-2	49	-2	83	-1
16	-1	50	+6	84	-1
17	0	51	-1	85	-1
18	+6	52	-1	86	-1
19	-1	53	-1	87	-1
20	-1	54	-2	88	+6
21	-1	55	-1	89	+6
22	+6	56	-1	90	+6
23	-1	57	-1	91	-1
24	-1	58	+6	92	-1
25	-2	59	-1	93	-1
26	+6	60	-1	94	-2
27	-1	61	-1	95	-1
28	+6	62	-2	96	-1
29	-2	63	-1	97	+6
30	-1	64	-1	98	-1
31	-1	65	+6	99	-1
32	-1	66	-1	100	-1
33	-1	67	-1	101	-1
34	-1	68	0		

Speed-Accuracy Testing

Laser Model/Serial No.: D1/1184 Date: 3/5/94

Simulated Speed: 196 m.p.h. Operating Temperature: +23 °C (+73 °F)

Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)	Run No.	Difference (m.p.h.)
1	+5	35	+5	69	+5
2	-2	36	-2	70	-2
3	-2	37	-2	71	-2
4	-2	38	-2	72	-2
5	-2	39	+5	73	-1
6	-4	40	-3	74	-2
7	-2	41	+5	75	-2
8	-2	42	-2	76	+5
9	+5	43	-2	77	-2
10	-2	44	-2	78	-2
11	+5	45	-2	79	-2
12	-2	46	+5	80	+5
13	+5	47	-2	81	-3
14	-2	48	+5	82	-2
15	-2	49	-2	83	-2
16	+5	50	+5	84	-2
17	-2	51	-2	85	+3
18	+5	52	-2	86	-2
19	-2	53	-2	87	-2
20	+5	54	+5	88	-2
21	+5	55	-2	89	-2
22	-2	56	+5	90	+5
23	-2	57	+5	91	-2
24	-2	58	-2	92	-2
25	+5	59	+5	93	-2
26	-2	60	-2	94	+5
27	+5	61	-2	95	-2
28	-4	62	+5	96	-2
29	-2	63	-2	97	-2
30	-2	64	+5	98	+5
31	+5	65	-2	99	+5
32	+5	66	+5	100	+5
33	+5	67	-3	101	-2
34	-2	68	+5		

References:

1. Motorola, Inc, "M68HC11 Reference Manual", Chapter 10, section 10.4, pp.10-27 to 10-37

2. Lassini, S. A. M., "AR Laser Speed Simulator Design", unpublished report

3. Michigan Speed Measurement Task Force, "Interim Standard and Specifications for the Procurement of Laser Speed Measurement Devices", pp. 4-8