UMTRI-85-16

EFFECTS OF SEATWINGS AND SEATBELTS ON THE RESPONSE OF FORKLIFT TRUCK OPERATOR DURING LATERAL DYNAMIC TIPOVERS

Nabih M. Alem, Ph.D.
Project Director

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109

Final Technical Report

June 1985

Prepared for

Caterpillar Tractor Company
100 N.E. Adams Street
Peoria, Illinois 61629

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECTS OF SEATWINGS AND SEATBELTS ON THE RESPONSE OF FORKLIFT TRUCK OPERATOR DURING LATERAL DYNAMIC TIPOVERS.		5. Report Date June 1985
		6. Performing Organization Code
7. Author(s) Nabih M. Alem		8. Performing Organization Report No. UMTRI-85-16
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute Ann Arbor, Michigan 48109		10. Work Unit No.
		11. Contract or Grant No. DRDA 85-2373-P1
12. Sponsoring Agency Name and Address Caterpillar Tractor Company 100 N.E. Adams Street Peoria, Illinois 61629		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The main objective of the study is to experimentally compare the dynamic response of the seated operator of a forklift truck during lateral tipovers while seated in a traditional seat to the response while seated in a seat which has been modified by the addition of a seat belt and side seat wings.

A state-of-the-art Side Impact Dummy was used as a surrogate to the human operator. Typical lateral self-restraint force of 125 lbs. that would be produced by the average male operator was laterally applied to the dummy. The tipover experiments were conducted at tipover velocities of 2.0 and 2.8 rad/sec. The probability of brain injury was based on the Head Injury Criterion (HIC) which is computed from measured head accelerations.

Test results indicate that, regardless of the tipover velocity, the seat with seatbelt and seatwings allowed the head to strike the ground at severities that would result in a high probability of life-threatening brain injury, but that this probability was significantly reduced by increasing the lateral self-restraint force. On the other hand, the results indicate that under identical test conditions of the traditional seat, the probability of life-threatening brain injury was negligible.

17. Key Words	18. Distribution Statement		
Forklift Trucks, Rollover accident, Forklife Truck injury, seat design, protection system			
19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-69)

ACKNOWLEDGMENTS

This research project was conducted by the University of Michigan Transportation Research Institute under a sponsored research contract from Caterpillar Tractor Co. during the six-month period ending in February, 1985. Contributions of the following persons are gratefully acknowledged.

Dr. John W. Melvin, of The University of Michigan, acted as a biomechanics consultant and technical advisor to the Project.

Dr. James H. McElhaney, of Duke University, acted also as a bioengineering consultant and a technical advisor to the Project.

Members of the Engineering, Research and Technical Facilities of Caterpillar Tractor Co. contributed to the engineering design and manufacture of the tipover fixture and test device, and to the design of the tests.

The experiments were performed with the technical assistance of **Mr. Marvin Dunlap** in maintaining the electronic equipment, **Ms. Paula Lux** in the signal and data processing, and **Mr. Jean Brindamour** in the photographic coverage.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

An experimental study was conducted at the University of Michigan Transportation Research Institute (UMTRI) and sponsored by Caterpillar Tractor Co. to investigate the dynamic response of a seated forklift truck operator during lateral tipovers. The focus of the investigation was to compare the dynamic response of the operator in a traditional seat, shown in Figure 1, to the operator's response in a seat which had been modified by addition of a seat belt and shoulder side restraints ("side wings") as shown in Figure 2. The dynamic responses of the operator's head and the probability of life threatening head injury were results of specific interest. This document is the Final Technical Report.

Fork lift trucks were the subject of this investigation. The results do not necessarily apply to other types of vehicles, machines or mobile equipment. Each type of vehicle or machine must be considered in the light of its dimensional constraints, dynamics and applications.

In this **introduction** section of the report, some background is given, the research objectives are defined, then a capsule summary of the results is presented, followed by a list of planned research activities.

The **test parameters** are discussed in section 2 of the report, followed by a description of the test matrix.

In section 3, the **test fixtures and devices** used in conducting the experiments are described. These include the tipover fixture, truck and overhead guard, seats and associated hardware, self-restraint device, the instrumentation, and the side-impact test dummy.

The **dynamic response measurements** of the experiments are discussed in section 4. This includes a description of the signals used for measurement and their processing and analyses methods. The criteria for

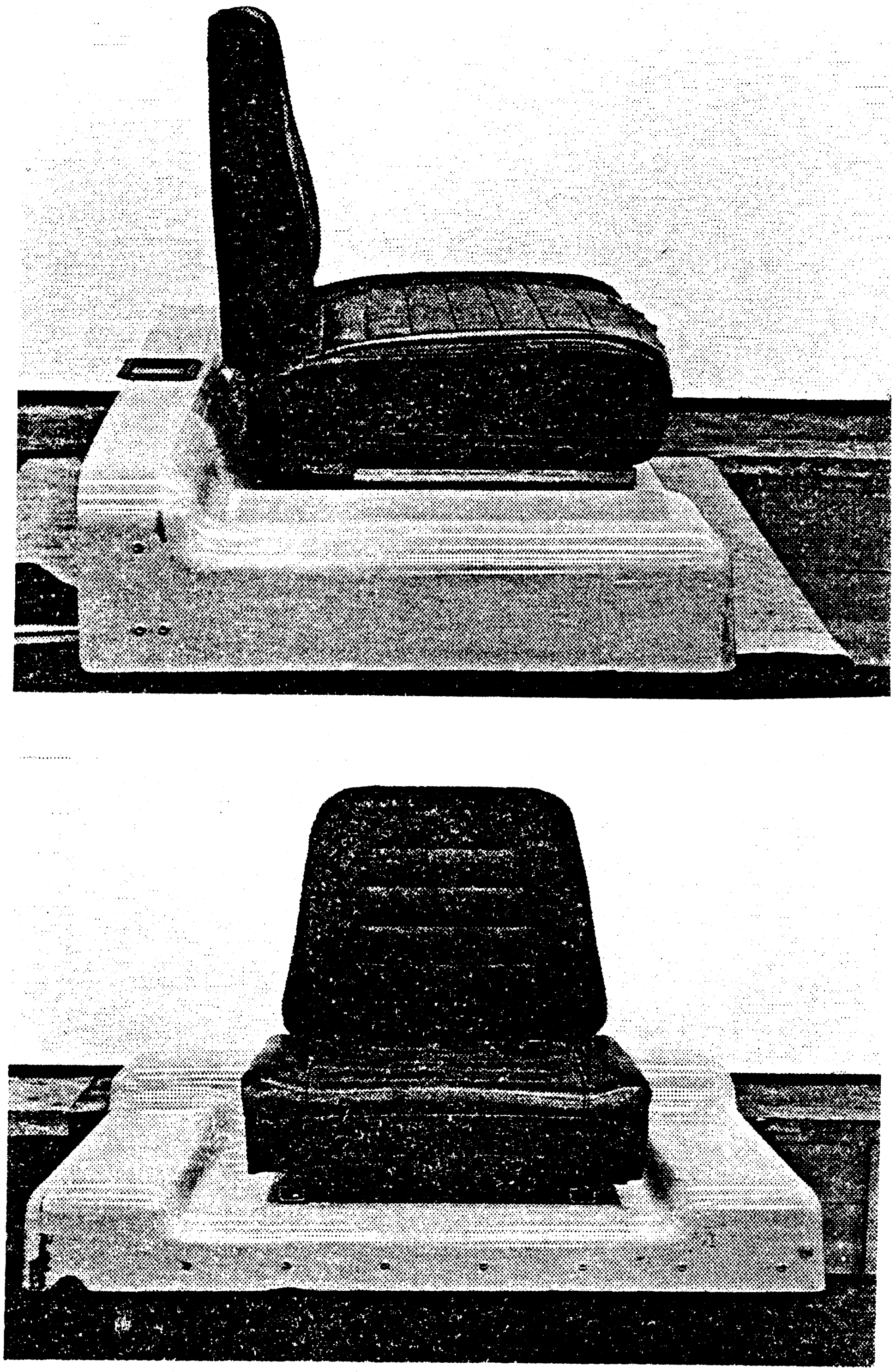


Figure 1. The traditional forklift truck seat

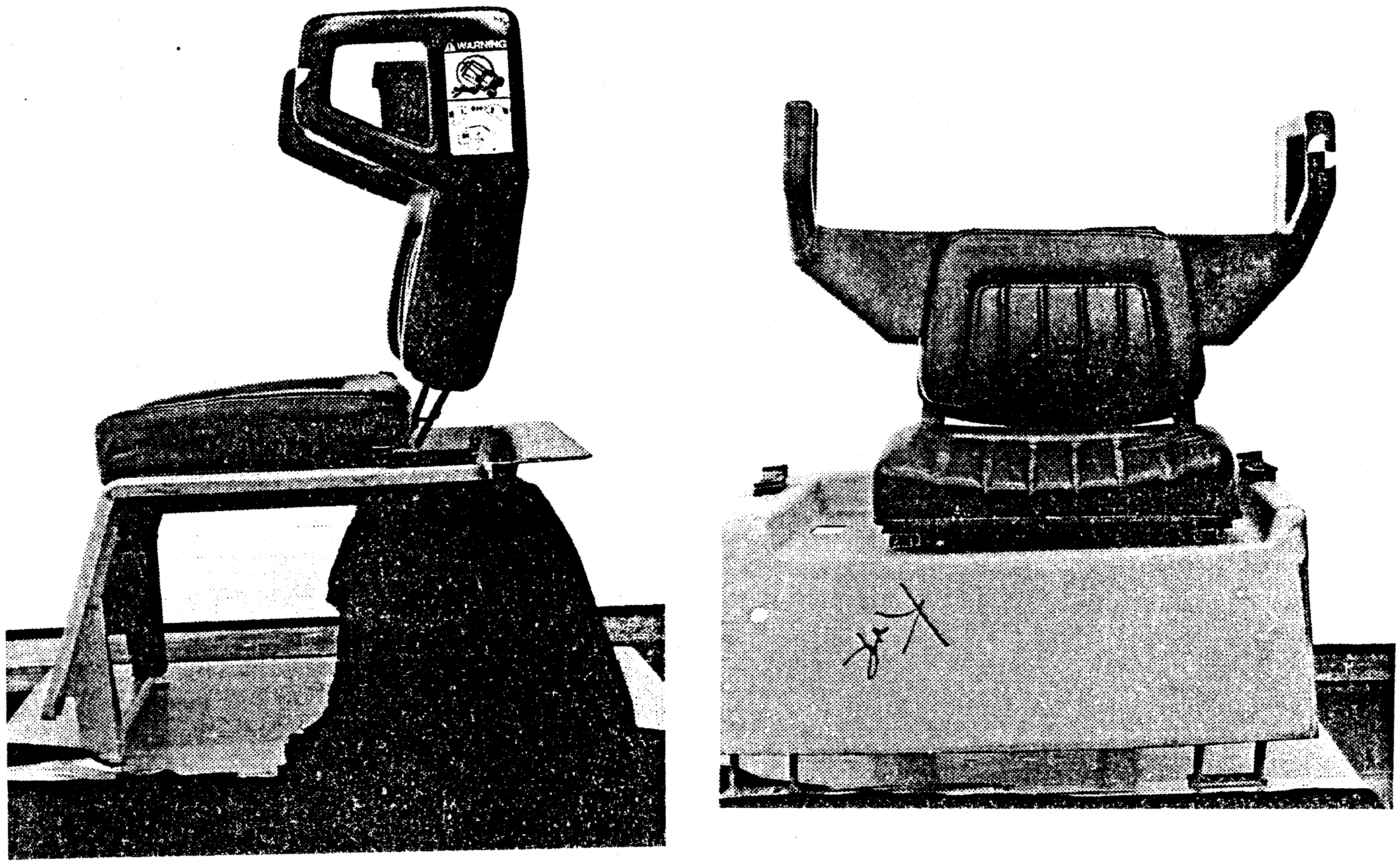


Figure 2. The seat with seatwings and seatbelts

evaluating the severity of impact and potential injury are also discussed in this section.

Finally, the **discussion of results**, presented in section 5, includes tables summarizing the results and a discussion of the findings. This discussion focuses on the technical validity of the tests and results, and the effects of adding wings and seatbelts on the test dummy response.

The **processed signals** are included in this report in the Appendix. These are grouped by signal type, each of which contains the signals generated from all the tests.

1.1 Background

In 1980, the Industrial Truck Association (ITA) conducted a study to simulate the overturning of forklift trucks and to measure and record the response of the test dummy. The results of the study, in which some 36 tipover tests were conducted, are given in a report to ITA[1].

One of the objectives of the 1980 ITA study was to evaluate the effects of restraint systems on the kinematics of the operator during truck overturns. This could be accomplished only if the performed tests were repeatable, i.e., if the results of the tests could be reproduced under "identical" test conditions. Because of testing difficulties, this objective was not achieved. This was one of the reasons which prompted ITA to undertake a second study[2] which was performed in 1982 at UMTRI, known then as the Highway Safety Research Institute, or HSRI.

Although many of the objectives of the second ITA study were met, the repeatability of the dynamic tests remained an elusive goal. The HSRI report indicated that, because many factors influence the outcome of each experiment, it is "very difficult to obtain repeatable results

---

[1] A.I. King, "Operator Restraint Test Program." Final Report, January 1981. A.I. King, Inc., Southfield, Michigan.

[2] J.W. Melvin, N.M. Alem, and C.B. Winkler, "Operator Restraint Testing Program - Phase II." Final Report No. UM-HSRI-82-6-1, February 1982. Highway Safety Research Institute, Ann Arbor, Michigan.

from the limited number of tests conducted in this study." The report cautioned that "although some conclusions may be drawn from these test results, the conclusions must necessarily be test-specific, while general conclusions are usually based on the results of a set of repeatable tests."

One of the difficulties encountered in the HSRI/ITA study was the variability in the timing of events leading up to the dummy's motions relative to the truck, and the truck motions itself once a test sequence was initiated. This variability persisted even when all test parameters were supposed to be identical, leading to the conclusion that one or more parameters cannot be absolutely controlled, or that the factors influencing the experiment were too complex to be handled in one experiment.

Another factor that was difficult to control was the hand grip on the steering wheel, because the anthropomorphic (human-like) dummy used in those tests was not designed for this purpose. To simulate this grip in the 1982 ITA study, the hands were tied to the steering wheel with a single strand of 40-lb test nylon fishing line. However, this "grip" broke at inconsistent force levels, and did not provide, as it should, any lateral resistance to motion of the upper torso.

A third shortcoming was the specific dummy used in both the 1980 and 1982 ITA studies. The HSRI report indicated that "the construction of the dummy can exert a strong influence on the nature of the dummy/ground interaction." "For example," the report continued, "the stiff shoulder structure, used in all automotive test dummies, is not well suited to lateral impacts." In some of the 1982 dynamic tests, "the head of the dummy did not contact the ground even though there was a strong shoulder contact. A human operator would most likely have incurred a head impact under the same conditions due to the lateral flexibility of the human shoulder structure." This is not surprising, since this dummy, known as Part 572 Anthrpomorphic Test Device (ATD), was designed and intended primarily for frontal collision testing.

The problems encountered in these studies were not the results of poor experimental techniques but rather were due to the general complexity of the truck overturn and dummy/truck dynamic interaction process. These problems were addressed in the current UMTRI/Caterpillar study, which is the subject of the present report.

The unpredictability of the truck motion was eliminated in the current study by constructing a "tipover fixture" capable of overturning a wide range of truck sizes in a controlled manner to produce consistent and realistic truck tipover dynamics. The inconsistencies of the lateral self-restraint of the operator, which was simulated in the two ITA studies by the hand grip on the steering wheel, were eliminated in the current study by introducing a controllable and repeatable device that applied a constant force level directly to the shoulder. The distortion resulting from the unrealistic shoulder structure of the dummy was eliminated in this study by using a Side-Impact Dummy (SID) which is designed specifically for lateral impacts.

After the development of the test fixture and methods was completed, the current study was then focused on comparing the operator's dynamic response during lateral tipovers under two situations: 1) when the operator, while seated in a traditional seat, holds onto the steering wheel, versus 2) when the operator takes the same action in a seat which had been modified by the addition of a seat belt and shoulder side restraints ("side wings"). The seat belt and side wings are specific modifications of a traditional truck seat.

Since the tipover speed determines the test severity and also is a factor influencing the timing of events leading to the interaction between the operator and the truck structure, the comparison of the two restraint situations (seat only vs. seat with wings/belts) was conducted at two tipover speeds that are near the lower and upper ends of the range of known tipover speeds.

Finally, the data generated from these experiments were analyzed using standard methods, and the results of the analyses were evaluated using well established criteria. Thus, for example, potential injury to the head was assessed using the Head Injury Criterion (HIC) based on measured head acceleration response.

1.2 Objectives

The main objective of the current study is to compare the dynamic response of the seated operator of a forklift truck during a lateral tipover while seated in a traditional seat to the response while seated in a seat which had been modified by the addition of a seat belt and side wings. The study is to incorporate a realistic range of tipover speeds and a realistic representation of the operator restraining himself in the truck. The primary basis for comparison is to be the Head Injury Criterion (HIC) and the probability of life-threatening head injury.

First, it was necessary to develop the experimental devices and procedures to produce realistic and repeatable test conditions which would provide the technical basis for drawing valid conclusions from the tests.

1.3 Capsule Summary

Table 1. Summary of Head Injury Probabilities

Seating Configuration	**Lower-Severity Tipovers**	**Higher-Severity Tipovers**
Traditional Seat Only	0 %	0 %
Seat with Wings/Belts	85-100 %	100 %

- The test conditions selected for the tipover simulations represented realistic conditions of real-world forklift truck overturn accidents.

- The lateral force applied to the dummy realistically simulated the self-restraint action that the operator may take during actual truck overturns.
- The use of the Side-Impact Dummy provided a more human-like lateral dynamic response than other previously used dummies.
- Standard and widely accepted practices of testing, measurement, analyses, and injury prediction were employed in the project.
- Regardless of the seating configuration, higher-velocity tipovers produced higher and potentially more injurious test dummy response than did lower-velocity tipovers.
- Regardless of the tipover velocity, a seat belt and wing-back seat allowed the head to strike the ground at angles and severities that would result in a high probability of life-threatening brain injury, as shown in Table 1 above.
- In the case of seat with seat belt and side wing back, the HIC value and the probability of life-threatening injury were significantly reduced by increasing the lateral self-restraint force.

1.4 Research Activities

To achieve the project's objectives, much of the activities consisted of preparatory design, fabrication, and trial runs to debug the system. Once system failures were eliminated, repeatable tests could be conducted without malfunction of the hardware or equipment. Thus, the work conducted in this study consisted of the following activities, which were substantially as initially planned.

- Design and fabricate a tipover fixture that is capable of tipping the truck an angle of 90 degrees on its side, with a programmable tipover speed that could be selected and repeated at will.
- Select two seats to be tested: a traditional forklift truck seat and a modified seat with wings and seatbelts.

- Install a truck shell and overhead guard on the tipover fixture and allow provisions for interchanging two types of seats and their respective engine hoods, i.e., the seat mounting surface..
- Design a self-restraint device which would apply a constant lateral force to the shoulder equivalent to the operator's grip on the steering wheel.
- Acquire and prepare a Side-Impact Dummy to be used as the test subject simulating the truck operator. Install the calibrated transducers (measuring instruments) in the dummy.
- Prepare the test site and instrumentation: install a floor bedplate for the tipover fixture and provide air and hydraulic supplies; install umbilical cables from test site to instrumentation room; prepare and calibrate electronic signal conditioning, recording, and playback equipment; select data digitizing, analysis, and plotting computer software; and install high-intensity flood lights for photographic coverage.
- Analyze full-scale truck tipover films from the 1982 ITA tests to determine realistic tipover speeds at which the current tests would be conducted.
- Determine a realistic self-restraint level that represents the forces applied by an "average" truck operator through his grip on the steering wheel.
- Conduct four series of tests representing the combinations of two tipover speeds and two seating configurations. All other parameters, such as self-restraint force and initial position, should remain substantially unchanged from test to test, and from group to group.
- Process the test data to document the truck angular motion, velocity, and deceleration; document the dummy head and chest acceleration signals; and film in slow motion the tipover sequence of events.
- Study the processed data: to determine the validity of the tests and the repeatability of the outcome; to assess the injury

potential in each test using the Head Injury Criterion (HIC) and the Mean Strain Criterion (MSC); and to compare the performance of the two seating configurations at the two tipover speeds.

- Present and discuss the findings of the project in this Final Technical Report.

2.0 TEST PARAMETERS

In conceiving an experiment, the test engineer must consider all the factors that influence the outcome of the experiment, and either try to control these factors or understand their role in affecting the sequence of events that occur. The effects of these factors, which are referred to as the "parameters" of the test, are sometimes difficult to isolate. One common technique in isolating the effects of a single parameter is to hold all other parameters to a given value or state, while varying only the single parameter of interest. Such an approach is generally called a "parametric" study.

Two important parameters at the core of the present study were the severity of truck tipover crash and the level of self-restraint the truck operator exerts by holding the steering wheel during the crash. A third parameter of interest is the seat configuration, i.e., whether wings and seatbelts are added to a traditional seat or not. These parameters are discussed in the next sections.

2.1 Dynamics of Truck Overturn

In order to understand the dynamics of a forklift truck tipover, the sequence of events may be divided into 4 phases or time periods, as diagrammed in Figure 3. These phases are marked by three critical events: (1) the separation of tires from the ground on one side of the vehicle; (2) the truck's center of gravity passing over the contact tires; and (3) the truck's side touching the ground. The time periods between these critical events are described below.

PHASE 1. In order to steer a vehicle in a curved path, it is necessary to impose an external force on the vehicle. Without an externally applied force, the vehicle and occupant would continue to move along a straight line (Newton's First Law of Motion.) This externally applied force is the lateral friction force of the ground on

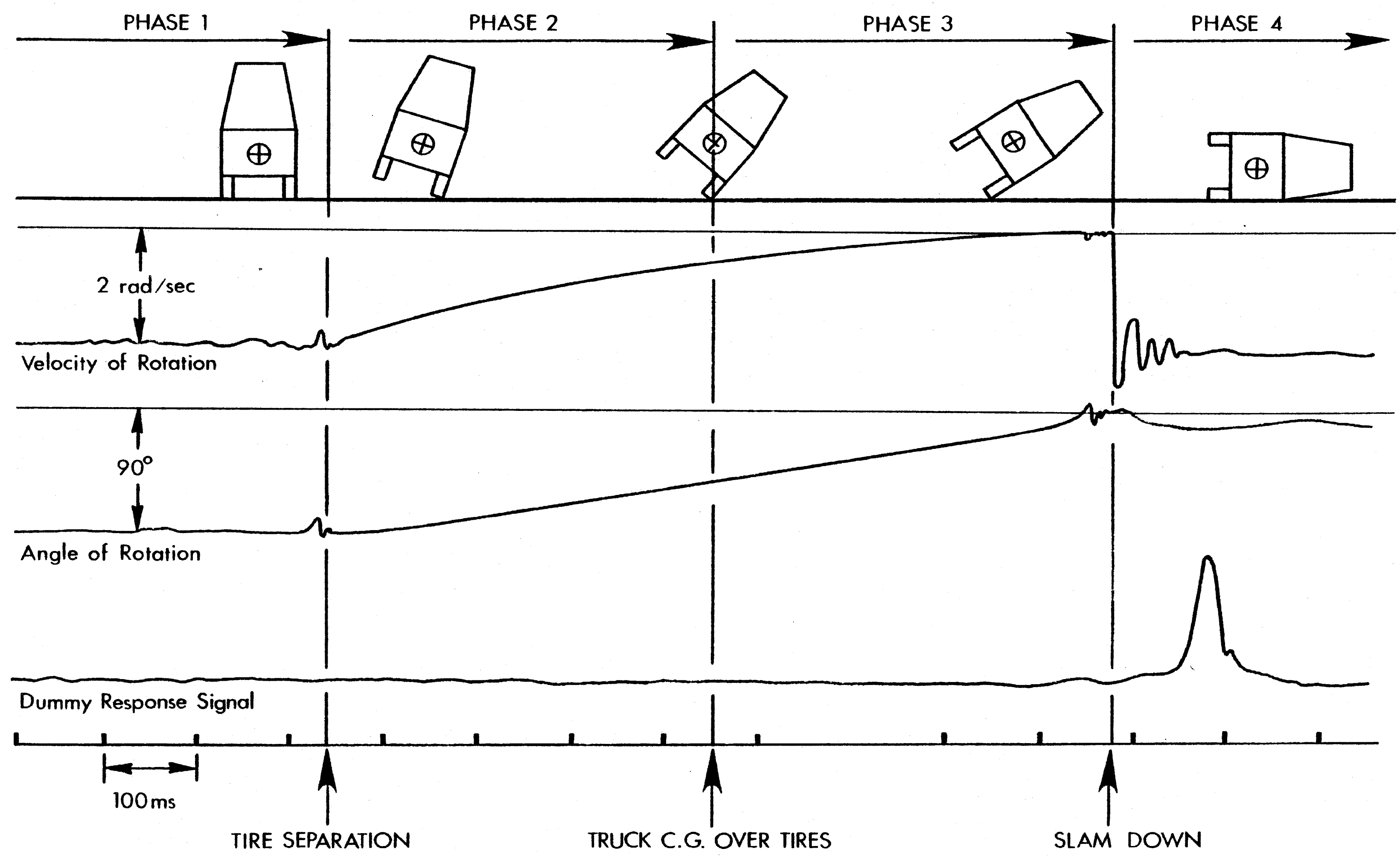


Figure 3. Time-history of the phases of a truck tipover

the tires. The lateral friction forces are centripetal forces, i.e., acting toward the inside (center) of the curve, as shown in Figure 4.

When the vehicle is steered along the curved path, it is accelerated laterally. The magnitude of this lateral acceleration depends on the ground speed of the vehicle along the curved path and on the radius of the turn itself. The lateral force required to produce this acceleration depends on the lateral acceleration and the mass of the vehicle (Newton's Second Law of Motion.) But the magnitude of the lateral force available is limited by the total mass and the coefficient of friction of the tire/ground interface. Thus, the magnitude of the lateral acceleration cannot exceed 0.6 to 0.7 g's, depending on the specific ground surface.

If the tire friction force acted at the center of gravity of the vehicle, the vehicle would not tip over on its side. However, the friction forces and the inertia mass reaction to acceleration are separated by a finite distance, the height above the ground of the center of gravity, as shown in Figure 5. The force and the mass reaction acting on two distinct points of a body form what is known as a "couple" which exerts a torque (or moment) on the body, causing it to rotate. Thus, under the right combination of speed, radius of turn, total mass, tire friction, and c.g. height, the resulting moment applied to the vehicle causes the tires on one side to lift off the ground and, possibly, results in a complete tipover of the vehicle.

PHASE 2. This phase begins with the separation or lifting of the tires off the ground on one side of the vehicle while tires on the other side remain in contact with the ground. For the tipover to occur, the tipping torque, described above, must be sustained at least until the truck c.g. goes beyond the vertical plane passing through the contact tires. This "critical" position of the truck may not be attained because of changes in the radius of turn and/or the truck speed. In these cases, the truck simply returns to its normal four-tire contact with the ground. Any attempt to possibly regain control over the truck motions must be taken by the operator during this phase, before the truck position reaches the critical point.

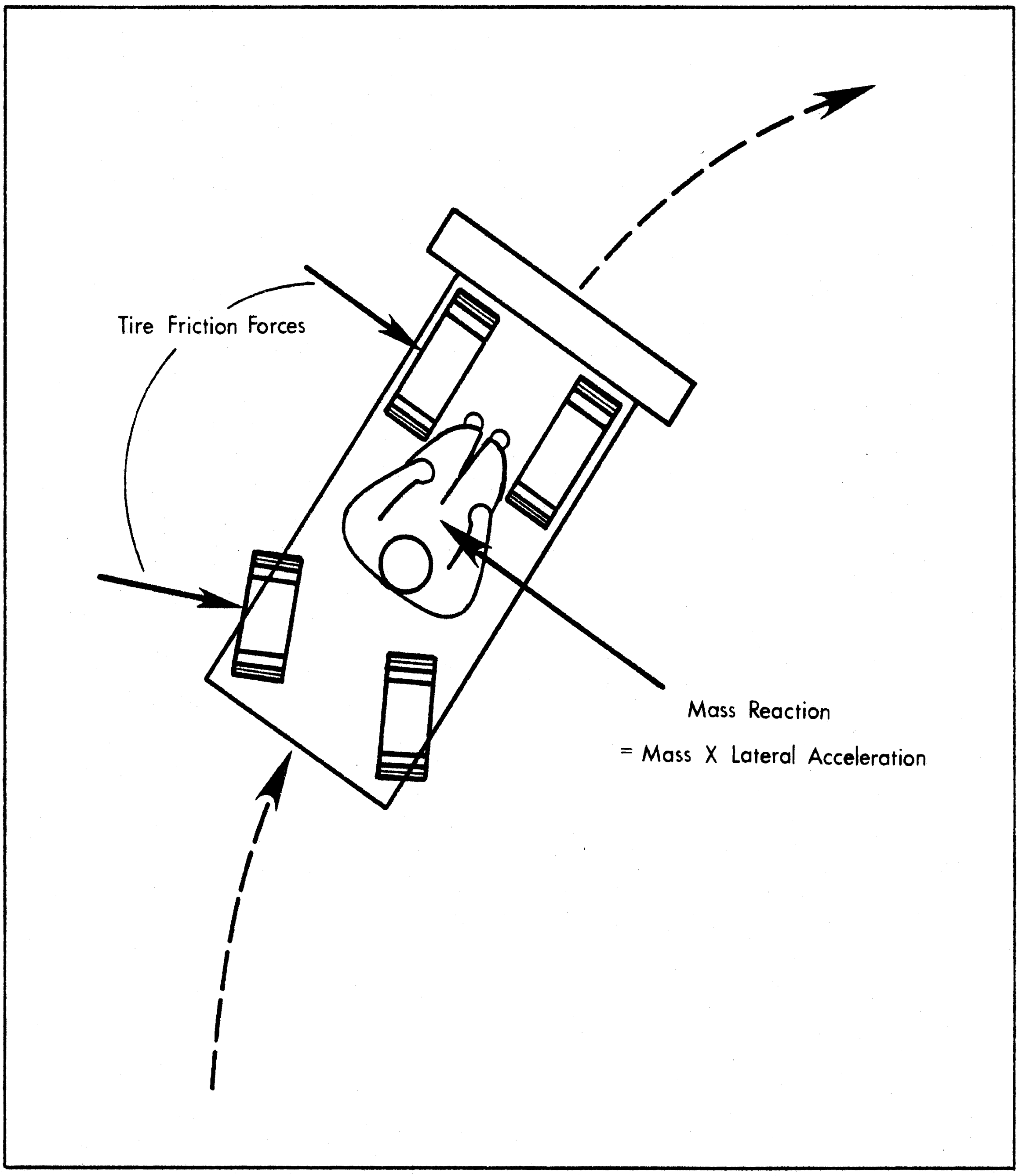


Figure 4. Top view of a truck in a right-hand turn

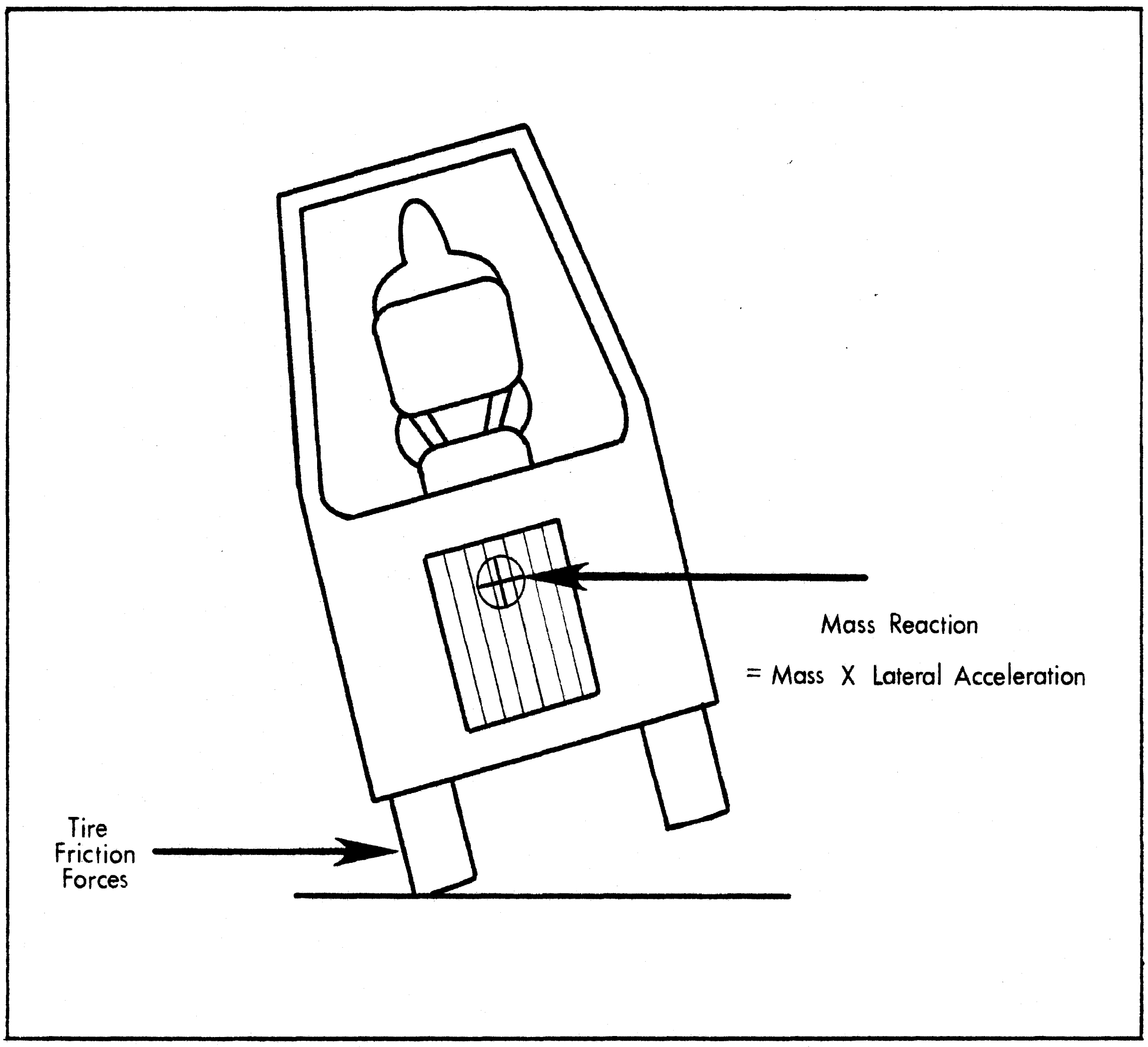


Figure 5. End view of a truck in a right-hand turn

PHASE 3. If there is sufficient energy and momentum left in the truck when it reaches this critical position, then the third phase of the tipover begins. The residual momentum is aided by gravity itself to carry the truck through the full rotation until its side slams down on the ground.

The final speed that the truck reaches at the moment of slamdown depends on the height of its center of gravity and on the truck momentum during the previous two phases of tipover, among other factors. How hard the truck's side strikes the ground may therefore be determined by how fast the truck is rotating.

During this phase, the operator may be able to take some actions that affect his motion, but not the motion of the truck itself. Therefore, the duration of this phase is an important consideration, since actions taken by the operator during this phase may increase or decrease his potential injuries.

PHASE 4. The truck and operator motions do not come to a complete stop instantaneously, no matter how abrupt the slamdown. Thus, this phase may last as much as 250 milliseconds (a quarter of a second), during which the truck and its occupant slow down from their initial velocities to zero velocity (or rest) over somewhat different periods.

The deceleration level, measured in units of gravity (g's), as well as the truck velocity at the first instant of impact, both define the severity of truck impact with the ground. This should be distinguished from the severity of the operator interactions with the truck structures and/or ground, which greatly depend on these structures, the actions or inactions of the operator, and on the timing of events that occur before, during, and immediately after the truck slamdown.

The slamdown is generally accompanied by horizontal "skidding" of the truck on its side structures along the ground surface. The skidding occurs because of residual kinetic energies and momentums that are no longer opposed by tire frictions, and are eventually dissipated by bouncing and scraping of the truck side structures on the ground. This is an important dynamic action that must be accounted for during tipover simulations, either by allowing the test truck to "skid" on slamdown, or by adjusting the location of truck structures to simulate such a skidding action.

2.2 Severity of Tipover

As explained above, the severity of truck crash is determined by the duration and level of impact deceleration. These, in turn, depend on the velocity at the moment of slamdown. Therefore, the slamdown velocity is a measure of the impact severity. There are two alternatives for describing the tipover velocity: (1) as the linear velocity of the center of gravity measured in miles per hour, or (2) as the angular velocity of the truck measured in degrees per second.

The two alternatives are equivalent, since the angular velocity is exactly equal to the linear velocity divided by the distance from the axis of rotation to the center of gravity. Because the angular velocity does not depend on that distance, it is simpler to use as an indication of the tipover severity.

One of the parameters (factors) that affect the experimental results is the severity of truck tipover, represented by the truck impact velocity. However, the effects of the impact severity on the operator's interaction and response cannot be isolated from experiments conducted at a single velocity. Therefore, the parametric study of these effects requires that at least two different velocity levels be chosen.

The selected slamdown velocities must be representative of real-world truck overturns. Because these are rarely documented, one must resort to full-scale simulations, such as the 1980 and 1982 ITA test series where high-speed movies of the events were taken.

Some of the ITA tests were selected for film analysis to determine the slamdown velocity. Accurate film measurements required that the truck be squarely facing the camera during the final moments before slamdown, and that the frame rate (frames/second) at which the camera was running be accurately known.

This reduced to five the number of tests that were analyzed. The results are shown in Figures 6 through 10. For each test, the truck angle with the ground was measured at each frame during the last 50 to 130 milliseconds before slamdown. Given the camera frame rate, the frame numbers were converted to time instants. The slamdown velocity was then estimated as the average slope of the angle-time plot for each test. The measured slamdown velocities ranged from 1.9 to 2.6 radians/second.

A value of 2.0 radians/second, which is at the lower end of the observed range, was chosen to be one of the tipover velocities at which the "lower-severity" tests would be conducted in the present study. Velocity for the "higher-severity" tests was selected to provide twice the energy stored in the truck prior to slamdown. Since this energy, known as the kinetic energy, is proportional to the square of the velocity, a velocity of 2.8 radians/second would increase the energy by 50 percent, producing the desired "higher-severity" tipovers.

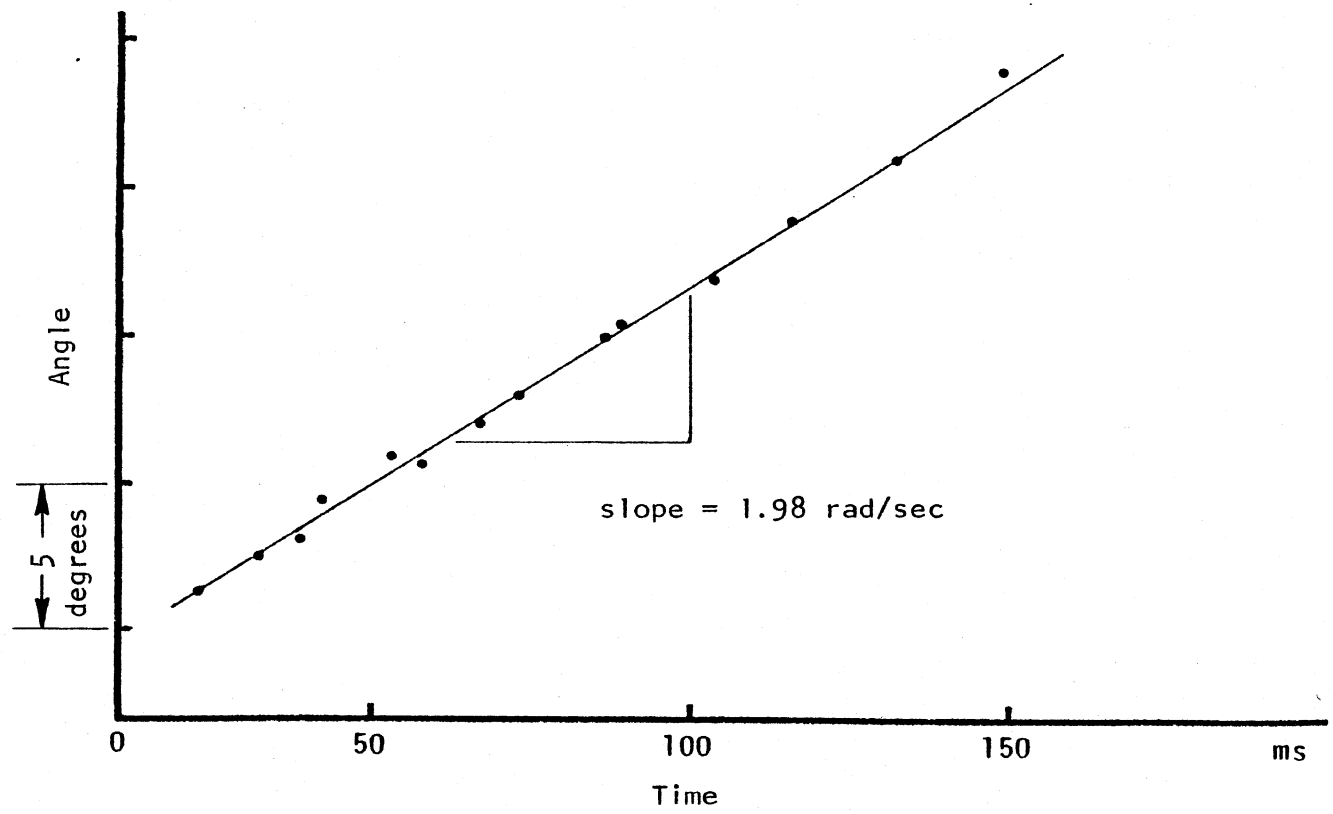


Figure 6. Angle and velocity, ITA Test E-4

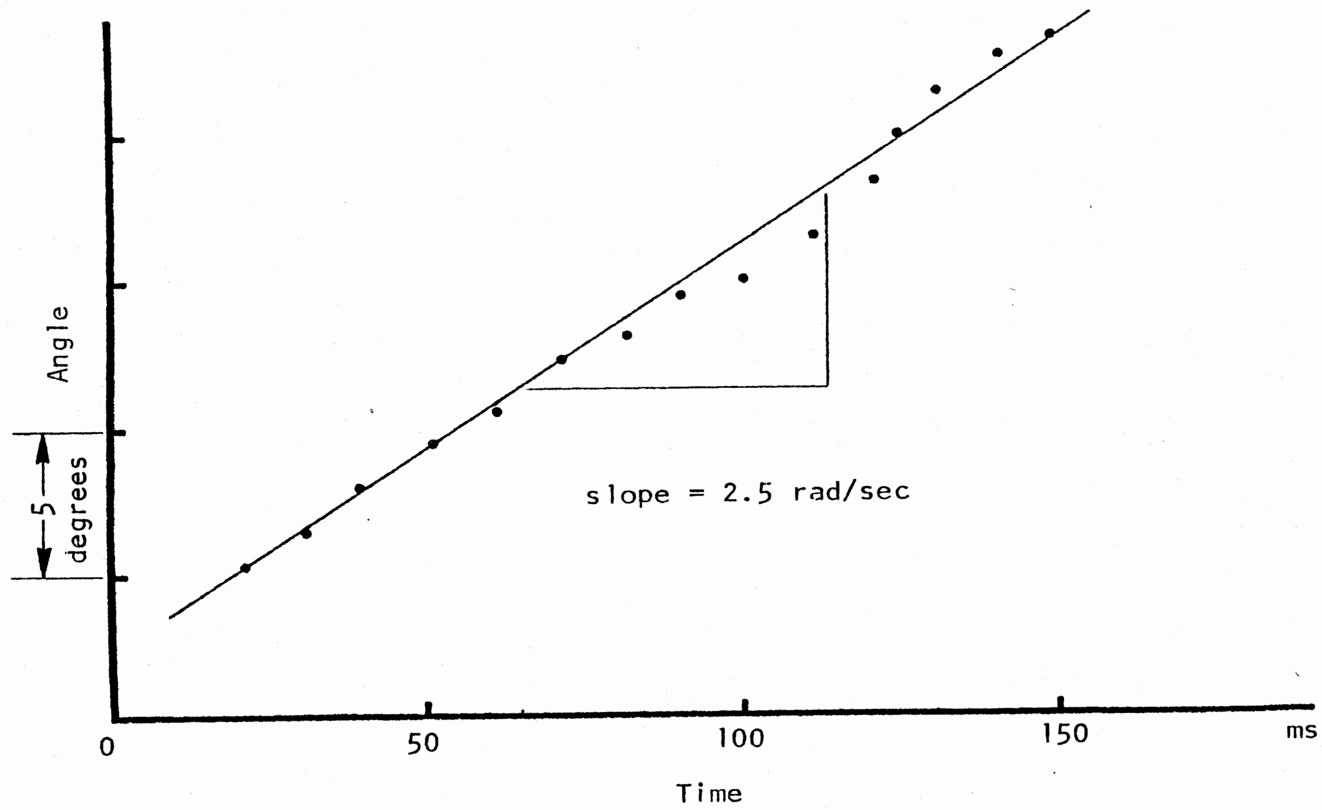


Figure 7. Angle and velocity, ITA Test E-5

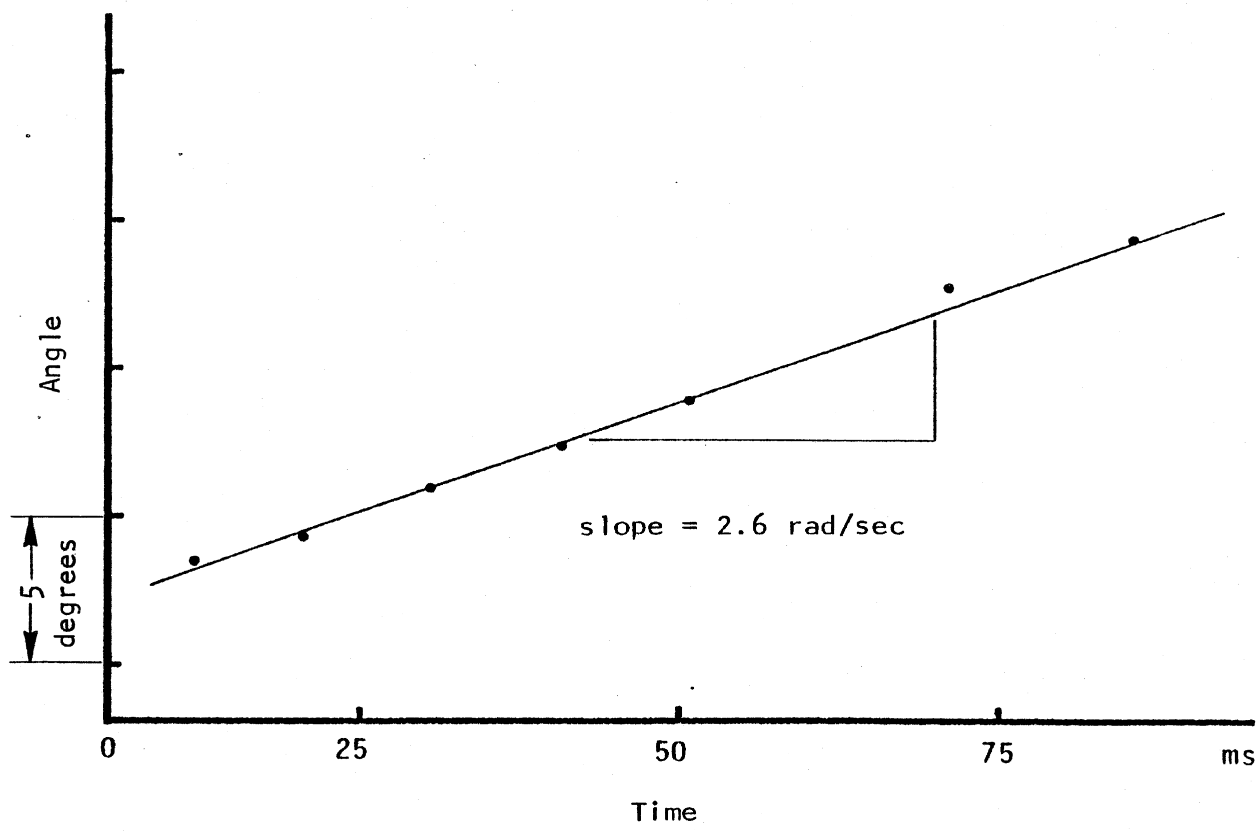


Figure 8. Angle and velocity, ITA Test E-6

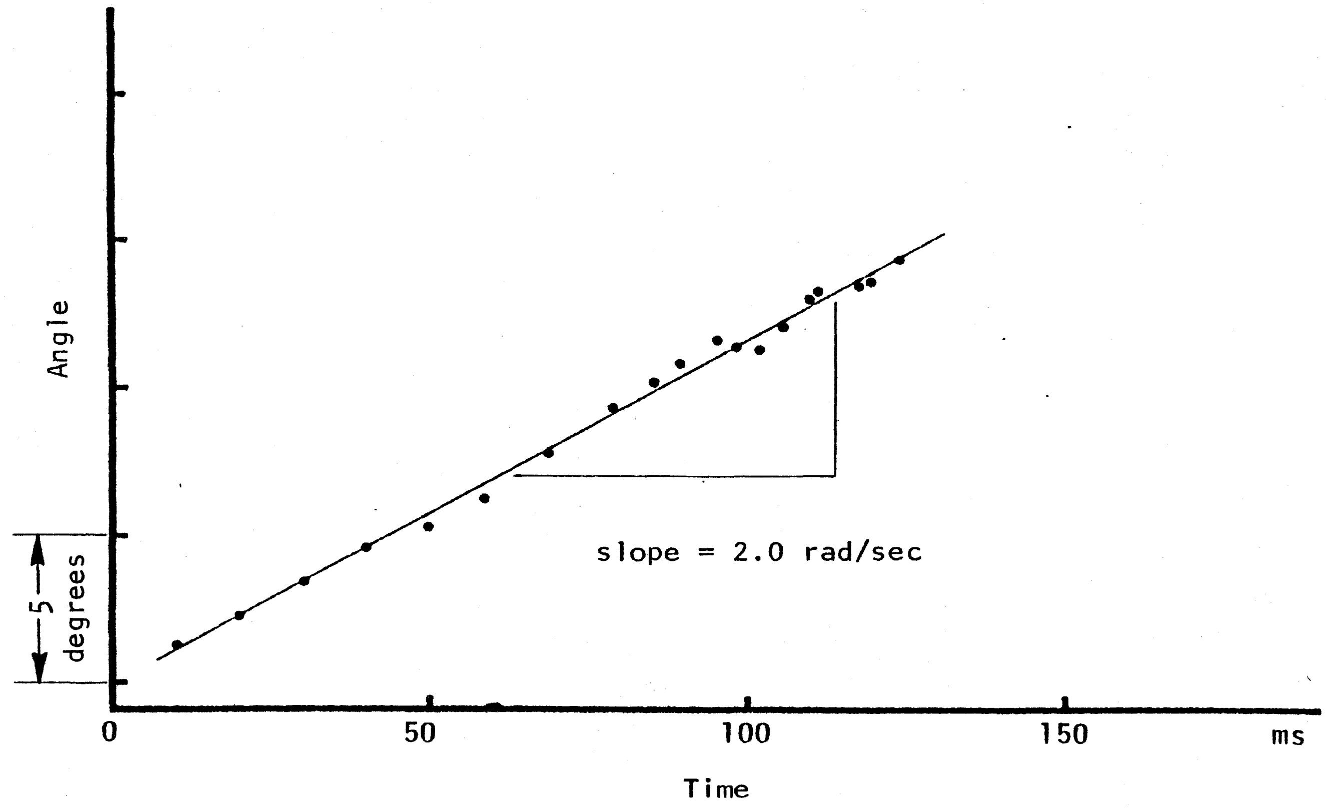


Figure 9. Angle and velocity, ITA Test E-7

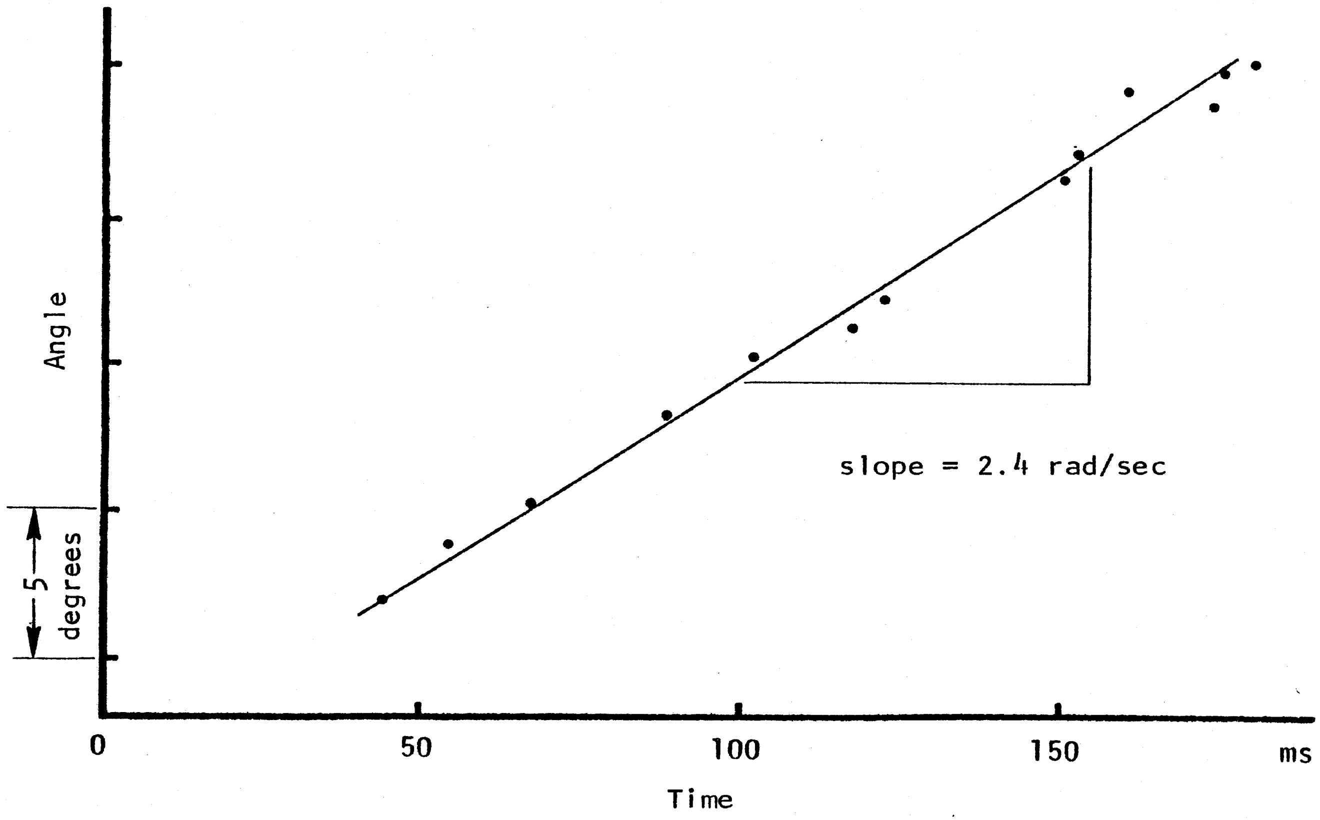


Figure 10. Angle and velocity, ITA Test S-9

2.3 Operator Self-Restraint

A key issue considered in this study was actions the forklift truck operator may take before, during, and/or after the truck tipover. Some of the common phrases used to describe these actions include "leaning" into the turn, "holding" on to the steering wheel, "pushing" against the seatback and cushion, "bracing" his feet against the truck floor, "standing" up during the overturn, and even "jumping" out of the truck. Although very graphic and descriptive, these common words are not sufficient for describing the complex phenomena to which they refer.

2.3.1 Dynamics of Self-Restraint. As explained earlier in section 2.1, it is necessary to impose an external force on a vehicle in order to steer the vehicle into a curved path, and without such a force, the vehicle would continue to move along a straight line. The same explanation applies to an object in the vehicle, except that the external force applied to the object is the lateral friction force of the seat on the object. An excellent demonstration of this is the "grocery bag" example: when you are driving a car, with a bag of groceries on the seat next to you, and make a sharp (small radius) or a fast (high speed) turn, the inert grocery bag tips over. What causes the grocery bag to tip over is the couple formed by the friction force between the bag and the seat, and the mass reaction to the lateral acceleration of the bag. Without the friction force, the grocery bag would not tipover, but would slide across the seat in the process of moving in its original straight path while the vehicle moves in the turn.

A person's reactions to the lateral force are different from those of an inert object. Thus, as the car driver who is making a turn, you hold onto the steering wheel to prevent your body from tipping over like the grocery bag or other inert object. In addition, you tense up the muscles of your arms, shoulder and back, increasing your ability to resist the forces and moments imposed on you. The result of your muscle action is to apply a lateral force to your torso, which counters the couple (or moment) which would otherwise cause you to tipover in the seat. The muscle action is in the same direction as the friction force of the seat on you buttocks, hence the sum of these forces is available to accelerate you laterally in order that you will stay in the car seat while your car travels around the curve. For example, in the 1980 ITA tests (King, 1981), when the human muscle action was represented by monofilament lines with total breaking strength of well under 100 pounds, the test dummy remained in the truck under the most severe turns that the vehicle could make.

The detailed biomechanical analysis of the individual and internal muscle forces and interactions is beyond the scope of this study. However, their net effect is clear: to resist the external forces. Therefore, the muscle forces may be represented by a single "resultant" force that has the equivalent effect. This resultant force, which is referred to throughout this report as the self-restraint force, is applied laterally to the operator's upper torso at the shoulder level and is directed from left to right.

Now it is necessary to determine the magnitude or level of the self-restraint force. To understand what this magnitude means, consider again the car passenger example. It was clear that some muscle action is necessary to resist the mass reaction resulting from the turn. How much muscle action is needed depends on the severity of the turn. Thus, if the car is turning at a very slow speed, or if the radius of the turn is very large, then the passenger barely needs to act at all to maintain his upright posture. However, as the severity of the turn increases, i.e., as the turn becomes sharper or faster, the passenger needs to exert more and more effort to maintain his upright position. Simply stated, the "magnitude" or "level" of the self-restraint force refers to "how much" muscle resistance the operator can exert and is a function of his muscle strength.

2.3.2 Published Muscle Strength Data. According to the classic work of Damon, Stoudt, and Mcfarland[3], many biological, psychological, environmental, and occupational factors affect muscle strength. Biological factors include age, sex, body build, body position, fatigue,

[3] A. Damon, H.W. Stoudt and R.A. McFarland, The Human Body in Equipment Design. Harvard University Press, Cambridge, Mass., 1971.

exercise, health, diet, drugs, and time of day. Environmental factors include temperature, humidity, altitude, and acceleration. Psychological factors include motivation and emotional state. Occupational factors include occupation, clothing, and personal and workspace equipment. The interested reader is referred to the above publication for detailed discussion of these factors. Only relevant parts of that discussion and data are presented here.

Two factors of concern in truck tipovers are the body position and emotional state of the operator. Body position is an important factor influencing strength. For example,

> In an upward movement of the arm, strength at the weakest position of the elbow flexion was only 44 per cent of that of the strongest position. Similarly, higher torques could be applied with the elbow at 90 degrees of flexion than at 150 degrees (next best) or at 30 degrees. Fortunately, when large forces must be overcome, people assume the position for which maximum strength can be exerted. This is not necessarily the one in which lesser forces can be most easily maintained.

Body position is defined in relation to the point of application of the external forces that must be overcome, as well as the direction of this force relative to the body axes. In truck tipovers, the operator not only instinctively "leans into the turn" to provide himself with maximum strength, but also applies his muscle forces in the same "lateral" direction to overcome the external forces imposed on him. To do this, the operator must use his hands, arms, shoulder, and lower back muscles. As the position of the body changes, different muscle groups come into play, making it difficult to determine precisely the net magnitude of the forces from the published strength data.

The emotional state of the operator is also an important factor causing considerable variation in muscle strength. Two persons of identical muscular ability, or the same person at different times, may differ markedly in strength.

> It is well known that the body has reserves of strength which are not directly under the control of the will and are available only under stress. Fear, panic, rage, and excitement can temporarily increase strength, though skill and accuracy may suffer. When maximum pull with forearm was measured, there was an increase, over "normal" pull, of 26 per cent under hypnosis, and an increase of 23 per cent under posthypnotic suggestion. Less marked but still

statistically significant increases were observed when the maximum effort was preceded by a pistol shot, and when the subject was instructed to shout during the pull.

The biomechanical data compiled by Damon et al. are very extensive but not all directly applicable to lateral tipover situations. However, the "Forces Exertable on an Aircraft Control Wheel at Each of Sixteen Different Positions" table will be briefly discussed here.

33 U.S. Air Force men were used for measurement of the right hand, 15 for measurement of the left and both hands. Each subject sat in a standard cockpit mockup and exerted maximum force on a control wheel with grips 18 inches above the Seat Reference Point and some 15 inches apart. Measurements were made at several forward locations and at various degrees of rotation.

The forward locations of the control (steering) wheel ranged from 10.75 inches to 23.25 inches. The hand were positioned on the wheel at 0-, 45-, and 90-degree rotations. Forces exerted by the left, the right, and both hands were measured separately. The results of the 19-inch location and 0-degree rotation were extracted from the published data and are presented in Table 2. This configuration was the closest one to the truck operator holding on to the truck steering wheel. The reported maneuvers were rotating right, rotating left, pulling and pushing.

Table 2. Forces of the Hands on Aircraft Control Wheel

Force Direction	Mean Exertable Force (lbs)		
	Right Hand	Left Hand	Both Hands
Rotate Right	63	43	101
Rotate Left	44	66	102
Pull	106	96	196
Push	121	124	265

Source: Damon, Stoudt, and McFarland (1971)

During pulling or pushing against the control wheel, the forces are applied along the general direction of the arm muscles, whereas in rotating the wheel, the forces are applied in a direction perpendicular to the arm. Such lateral motion brings into action the same muscle groups that may be involved in lateral self-restraint action of the truck operator. The reported level of about 100 lbs represents, therefore, an estimate of such self-restraint forces.

Damon et al. pointed out the general magnitude of variability between people with regard to strength.

> In a group of young, healthy college men of various biulds, strength varied tenfold, with the 95th percentile 4 to 5 times stronger than the 5th.

The data presented in Table 2 are mean values, i.e., representing the average (50th percentile) person with regard to strength. The complete data set in Damon et al., from which Table 2 was extracted, indicates that the 95th percentile person (with regard to strength) can exert about two times the forces given in Table 2 under "Rotate Right" and "Rotate Left" headings.

2.3.3 <u>Estimates of Self-Restraint Levels</u>. To confirm and refine these estimates, a limited study was undertaken in which lateral forces were applied to test subjects laterally at the shoulder level while they held onto the steering wheel. The device used for applying force, described in section 3.5, was an air cylinder where the pressure could be adjusted to produce the desired force level. A loop of seatbelt material was wrapped around the subject's upper torso at the shoulder level, and the loop was tied to the air cylinder via a convenient pulley/cable system. Two volunteers (RH, age 36, and NA, age 44, both male and of average physical build) and the side impact dummy (SID) were the subjects in the experiments.

The experiments were designed to answer three questions. First, to what extent can the average male adult resist lateral forces being imposed on him if he is allowed to hold onto the steering wheel and brace himself against the seat cushion and back? Second, in the reverse situation where he encounters a passive force, how much force can he apply to overcome this resistance? Third, what are the effects of applying the force suddenly (short duration) as opposed to gradually? In addressing these questions, the effects of tensing or relaxing the muscles had to be considered. With this in mind, four types of tests were performed. In the tests, the volunteers were allowed to brace their feet in a forward direction against the floorboard and push themselves against the seat back. However, they did not use their feet or legs to brace themselves directly in the lateral direction.

Type 1. The two volunteers were instructed to tense up their muscles and resist as much as possible a gradually increasing level of the external force. The force and displacement time-histories were recorded. The force at the time the subject "gave in" and could no longer resist the applied force was then tabulated.

Type 2. With the belt looped around the shoulders and tied to the air cylinder, the volunteers attempted to move against two pre-set levels of cylinder forces. Each was allowed to "yank" three times with increasing effort until the cylinder moved and momentarily held. The highest observed force was then recorded and tabulated.

Type 3. The volunteers were instructed to tense up in anticipation of a sudden application of the lateral force. The force was applied by dropping a 50-lb dead weight a distance of about 15 inches. The force pulse in this type of test exhibited a "knee" which occurred at the moment the tensed muscles of the subject were overcome by the rapidly rising force pulse.

Type 4. The dead weight was dropped as in Type 3 experiments, except that the volunteer was instructed to relax his muscles and was given no warning of the moment of release. This experiment was repeated with the side impact dummy as the test subject.

The results of this limited study are presented in Table 3. It includes an indication of the test type and test subject, and reports the maximum self-restraint forces due to muscle tension as the "knee" of the force curve, as well as the "peak" force which is the sum of the muscle forces and inertial effects. The displacements shown in the

Table 3. Summary of Self-Restraint Measurements

Test Description			Muscles Force (lbs)	Total Force (lbs)	Displ. at Peak (inches)
Type	Configuration	No.			
1	Tensed, Resisting	RH-1	**110**	-	3.0
1	Tensed, Resisting	RH-2	**140**	-	3.5
1	Tensed, Resisting	NA-1	**120**	-	4.5
1	Tensed, Resisting	NA-2	**130**	-	3.0
2	Move against 200 kPa	RH-3	-	110	-
2	Move against 200 kPa	NA-3	-	110	-
2	Move against 300 kPa	RH-4	-	175	-
2	Move against 300 kPa	NA-4	-	175	-
3	Tensed, Drop Weight	RH-5	**125**	350	-
3	Tensed, Drop Weight	NA-5	**100**	260	6.0
3	Tensed, Drop Weight	NA-6	**120**	350	4.0
3	Tensed, Drop Weight	NA-7	**100**	330	4.0
4	Relaxed, Drop Weight	NA-8	-	320	5.0
4	Relaxed, Drop Weight	NA-9	-	350	5.0
4	Dummy, Drop Weight	SID-1	-	500	2.0
4	Dummy, Drop Weight	SID-2	-	575	2.0

table are the lateral motion of shoulders at the time peak forces are recorded.

In the absence of any muscle tension, as in Type-4 experiments, the reported total force represents the peak force required to overcome the inertia of the subject. The lower observed forces in volunteer NA tests may be attributed to his inability to totally ignore (as in SID's tests) the sudden jerk of the dropped weight. This would explain why the reported displacements of NA are about twice those of SID. Clearly then, these forces cannot be used to estimate the muscle action that an operator might exert for lateral self-restraint. In Type-2 experiments, volunteers NA and RH attempted to move the cylinder piston by "yanking" laterally against a preset level of pressure. Both subjects produced identical forces regardless of the preset piston pressure. This may indicate that the momentum generated by the "yanking" action combines with the muscle forces to overcome the preset cylinder force. Like Type-4 tests, these too cannot be used to isolate the effects of muscle actions.

The remaining experiments (Types 1 and 3) were conducted with the subject holding onto the steering wheel and tensing up his muscles. Type-1 may be described as quasi-static tests with gradual application of the external lateral force, whereas Type-3 tests may be called dynamic, since the application of the force was sudden. In the dynamic tests of Type 3, the force exhibited a knee in the rise portion of the curve, which may be attributed to the tensed muscles being overcome by the rising force, after which it reaches a peak between 260 and 350 lbs, a level similar to that observed in tests where the muscles were relaxed. The knee of the force curve was between 100 and 125 lbs. This range is not unlike the static Type-1 tests (100-140 lbs) where the subjects resisted a gradually applied force, and was very similar to the range reported (Table 2) in the aircraft steering wheel rotation experiments.

Based on this limited investigation and the preceding discussion of published data, it is estimated that a male truck operator of average strength can exert a lateral self-restraint force between 100 and 140 lbs. These are conservative estimates and would be higher for stronger men or for the average man during a realistically dangerous situation. Therefore, an intermediate level of 125 lbs was selected as a reasonable and conservative self-restraint force to be used in all the tipover tests in this project.

2.4 Passive Restraint Systems

Of great concern to the manufacturers and users of forklift trucks is the prevention, in the first place, of tipover accidents and the prevention or mitigation of injury to the operator, once a tipover accident occurs. Countermeasures that may be developed and implemented must of course be based on a complete understanding of the circumstances and conditions leading to the tipover accident, as well as on a thorough analysis of the mechanisms of interaction between the truck, the operator, and the ground after initiation of the tipover. The development and enforcement of accident prevention measures are within the field of industrial plant management, and are beyond the scope of the present study. However, understanding of the mechanisms of the operator's interactions with his physical environment is at the core of this study.

The two ITA studies of 1980 and 1982 demonstrated that, under the right combination of truck speed, radius of turn, and attachment of the test dummy to the seat and/or steering wheel, the dummy may separate from the seat and fall to the ground, followed by the overhead guard, which may then strike the dummy close to the ground.

This leads to the consideration of various concepts of "passive" restraint systems which would confine the operator to his seat inside the overhead guard area, while requiring no "active" participation on his part during the tipover. The use of a 2-point lap belt, a 5-point harness of the type used in aviation, a safety net of the type used in race cars, a variety of side restraints built into the seat back, and motor cycle helmets, are some of the concepts that have been considered for the protection of the truck operator during the tipover.

While confining the operator to his seat during a tipover is a major consideration in the conception, design, and implementation of a restraint system, other factors must also be considered. For example, one must consider the effects that the restraint system would have on the ability of the operator to perform his work safely and comfortably. Thus, the restraint system should neither reduce his visibility nor obstruct his reach for the controls, ultimately causing an accident.

The most critical factor to be considered, however, is the ability of the restraint system to provide protection against injury during the tipover accident. Thus, any restraint system intended to prevent one type of injury should not increase the risk of another type of injury.

One restraint system that has been considered is the subject of experiments conducted in the present study. Briefly, the system requires the use of a two-point lap belt attached to the traditional seat to prevent the operator from being separated from his seat during a tipover, and two side "wings" attached to the seat back to prevent the belt-wearing operator from laterally striking the ground. Each of the two components of this system (wings and seatbelts) is intended to deal with a different aspect of injury risk. The seatbelts are intended to keep the operator in his seat since, presumably, some injuries occur as a result of the operator's "jumping out" of the confines of the overhead guard. On the other hand, the use of the belt limits the operator's ability to adjust his posture and position in order to avoid or minimize his own injury risk.

The other component of this restraint device is the pair of wings attached to the seat back. If the operator is wearing his seatbelt in a tipover accident and, therefore, was attached to the seat, he would be forced to rotate with the truck as it tips over, resulting in a side impact with the ground. To prevent injury from this operator/ground impact, the wings were added.

Two questions came up when this system was analyzed. First, what are the side effects of wearing the seatbelts on the operator dynamic response during tipover? In other words, would the restriction of the motion of the hips by the seatbelts, while leaving the upper torso free to pivot, result in a more dangerous situation than the operator's freedom to actively and voluntarily assume the best position for his protection? Such danger may arise from an increase of the lateral velocity of the head and upper torso that, in turn, increases the severity of their impacts on the ground.

Assuming that the seatbelts do create the above problem, then one remedy would be to restrict the lateral motion of the upper torso by installing side "wings" on the seat back. Then, the second question to be addressed is the effectiveness of such wings in reducing the severity of impact. Answering these questions was among the goals of the present research study.

2.5 Test Matrix

The parameters discussed in the previous sections formed the basis for planning the tests in this project. To summarize, those are:

- The two tipover velocities: 2.0 and 2.8 radians/second which are near the lower and upper ends of the observed range of full-scale tipover velocities.

- The self-restraint force: a constant level of about 125 lbs to be maintained throughout the testing.

- The two seating configurations: a traditional seat without wings and seatbelts, and a seat with wings and seatbelts.

There were four test series (A,B,C,D) for the distinct combinations of two velocities and two seat configurations. Each test series consisted of 3 repetitions of the same test conditions, and all tests were conducted at the same lateral self-restraint force level. Two additional runs in test series C (seat with wings/belts at low severity) were conducted at different restraint levels: one representing about 40% reduction in the self-restraint level at which all other tests were conducted, the other representing about 28% increase of that level. The test matrix of the 14 tests is shown in Table 4.

Table 4. Matrix of Tipover Tests

Seating Configuration	Lateral Self-Restraint Force	Tipover Velocity Range	
		Lower 2.0 rad/s	**Upper 2.8 rad/s**
Traditional Seat Only	125 lbs	**B-1** **B-2** **B-3**	**A-1** **A-2** **A-3**
Seat with Wings/Belts	125 lbs	**C-1** **C-2** **C-3**	**D-1** **D-2** **D-3**
	75 lbs	C-XL	---
	160 lbs	C-XH	---

3.0 TEST FIXTURES AND DEVICES

In this section, the hardware used in conducting the experiments is described. This includes the hydraulic tipover fixture and landing platform, the truck itself and the overhead guard, the two tested seats and their associated hardware, the lateral side-restraint device, the anthropomorphic side impact test dummy, and the instrumentation and equipment used to monitor the response signals.

3.1 Tipover Fixture

The test fixture used to tip the truck on its side, diagrammed in Figure 11, was designed and fabricated at Caterpillar, then shipped to UMTRI laboratories where the tests were conducted. It consisted of a rotating platform, to which the truck was bolted, and a landing platform that simulated the ground surface. To tip the truck on its side, a powerful hydraulic ram pushed a short-arm lever attached below the rotating platform, causing it to pivot about a shaft and rotate 90 degrees. The rotation was stopped by two vertical towers that block motion beyond the desired 90-degree angle. The two towers were solidly anchored to the floor and simulated the impact of the truck with the ground.

The landing platform was a heavy 1/2-inch steel plate that was bolted to the floor at the appropriate height and angle to provide about a 1-inch clearance between itself and the side of the truck. The landing platform, therefore, was not intended for stopping the motion of the truck, but for providing a ground surface that the dummy may interact with.

3.2 Truck and Overhead Guard

The forklift truck used in the experiments was also provided by Caterpillar. To reduce the weight that the hydraulic ram was required to push, the truck was stripped of its engine, its counterweight, its

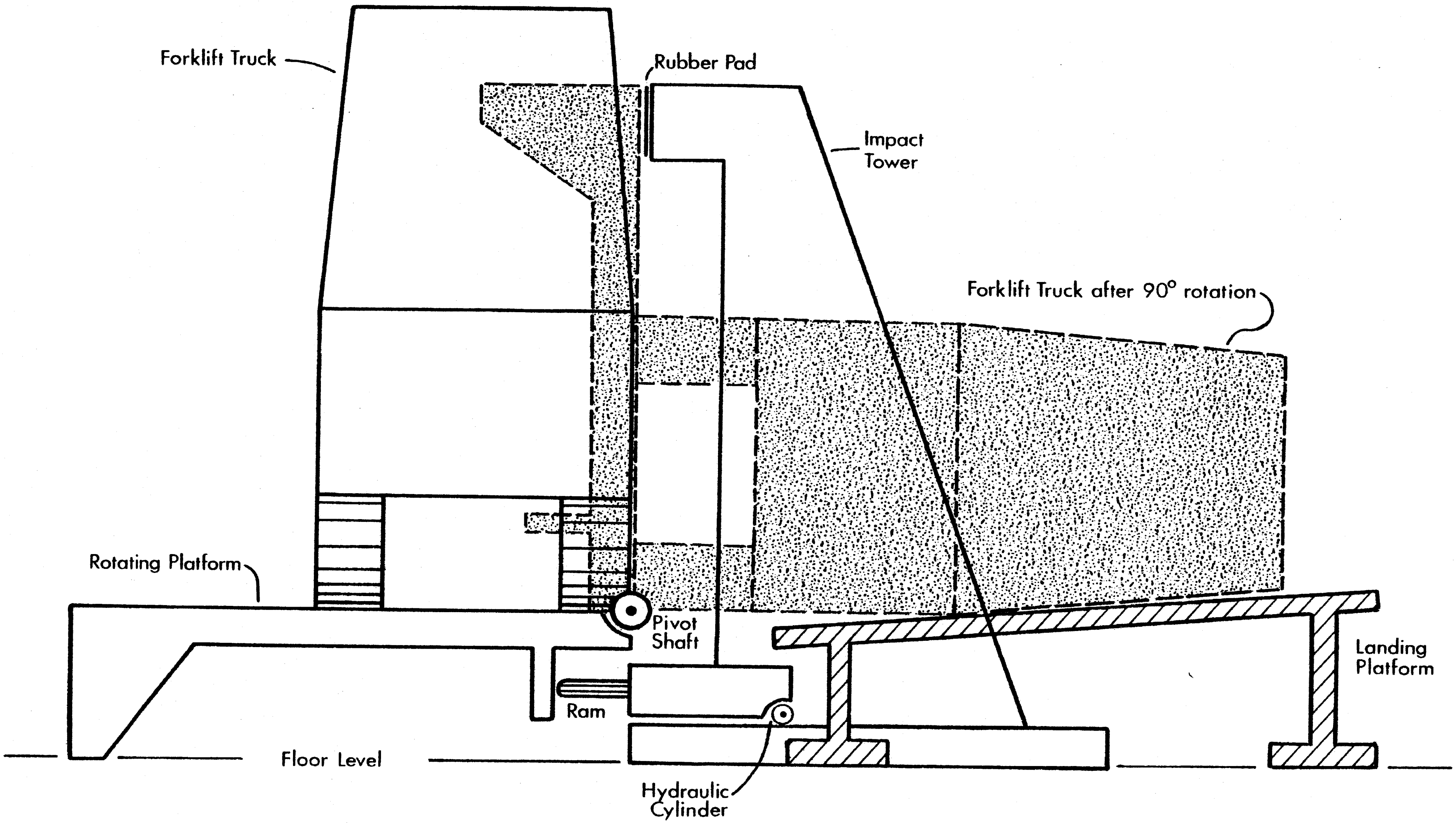


Figure 11. Diagram of the tipover fixture

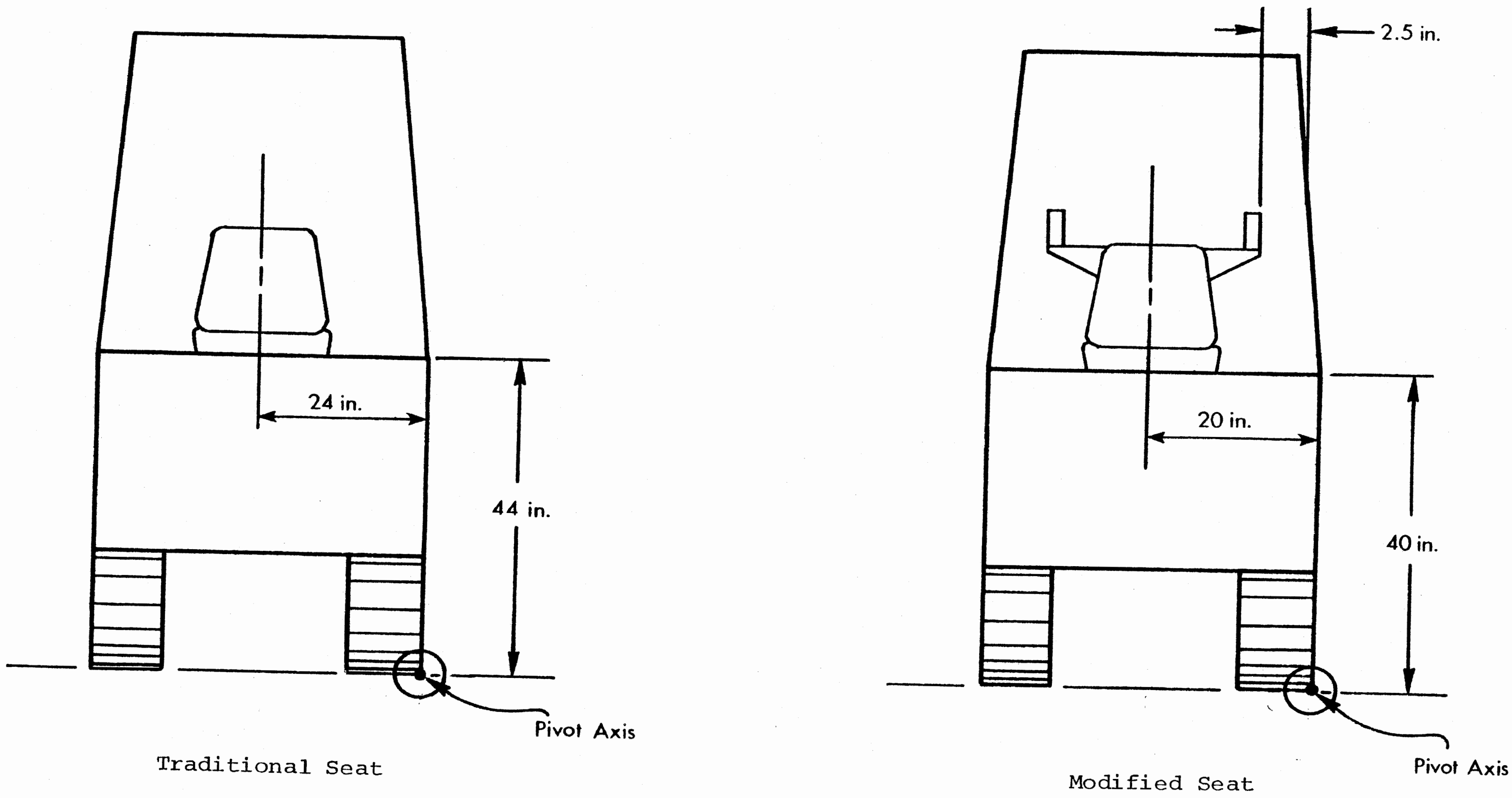


Figure 12. Relationships between seat, truck, and ground

forks, and much of the controls usually found in an operational forklift truck that have no bearing on the tipover experiments or their outcome.

The remaining shell was then modified to allow installation of two types of seats. Since the seats are typically attached to the engine hood, provisions were made to install the appropriate engine hood for each of the two seats. Every attempt was made to retain the structural properties of the tested seat/hood combination as found in production forklift trucks.

In addition to the structural properties of the tested seat/hood combinations, the geometric relationships were also retained between the seat, the truck and the landing platform (see Figure 12.) This was accomplished by positioning the seats and hoods vertically with respect to the front axle centerline and laterally with respect to the truck side and the outside of the legs of the overhead guard as per the trucks for which the seats and hoods were designed. The outside of the left wing of the seat with a winged back ranges from flush with the outside of the overhead guard legs to about three inches to the right (set in three inches) depending on the specific model on which it is installed. For the tests, the wing back seat was installed such that this dimension was approximately 2.5 inches. As stated in section 3.1, the landing platform was positioned so as to have the same geometric relationship to the side of the overhead guard of the simulated tipped over truck as the ground has to the side and to the overhead guard of a real tipped over truck, with the exception of the 1-inch clearance stated in section 3.1.

Only one overhead guard was used for both types of seats. Since the test dummy used in the experiments does not slump in his seated position as most people do, and because the truck could only pivot about a fixed shaft and not skid on the landing platform as it did in most of the full-scale ITA tests, these experimental limitations were accounted for by raising the overhead guard by about 5 inches.

3.3 Seat Hardware

Two commercially-available seating systems were tested. The first system, shown earlier in Figure 1, is available from Towmotor Corporation and is referred to as the traditional seat. It consists of the seat cushion and the seat back, and is attached to the engine hood with sliding tracks. The tracks provide fore-aft adjustment of the seat to fit the operator's needs. The engine hood is a fiberglass shell that can pivot about two pins to allow access to the engine. A latch closes when the seat is returned to the driving position. The latch and pivot pins were installed directly on the truck rigid structures.

The second seating system, shown earlier in Figure 2, is available from Clark Equipment Company and is essentially a modification of the traditional seat. In addition to a seat cushion and a seat back, a pair of side wings are attached to the seat back, and a lap belt is provided. The seatbelt is anchored to the seat frame at the bottom rear edges of the cushion near the seatback. Like the traditional one, this seat is mounted with sliding tracks which are bolted to the engine hood. However, the engine hood is made out of steel instead of fiberglass, and has different hardware for attachment to the truck's rigid structures. These attachments were duplicated in the tests where this seat was used.

3.4 Self-Restraint Device

To apply a constant-level side restraint force, a special fixture was designed, as shown on Figure 13. The fixture relied on a large-volume tank to produce a constant pressure level in an air cylinder to which the force was applied. The dummy's spine box was connected to the cylinder rod with a flexible steel cable which was looped around a pulley system to provide up to 42 inches of lateral displacement. The line of action of the steel cable was at the dummy's right shoulder.

During the tipover, the lateral motion of the dummy toward the left side of the truck (impact side) and away from the fixed cylinder pulled the cylinder rod, thereby compressing the air into the large-volume tank. Once the dummy's motions subsided, the compressed air tended to pull the dummy back in the opposite direction, an action which was judged to be unrealistic. To avoid this action, check (one-way) valves were installed between the tank and the cylinder to prevent the air from flowing back into the cylinder head.

Several calibration runs were conducted in order to determine the appropriate pressure level that would produce a constant 125-lb lateral

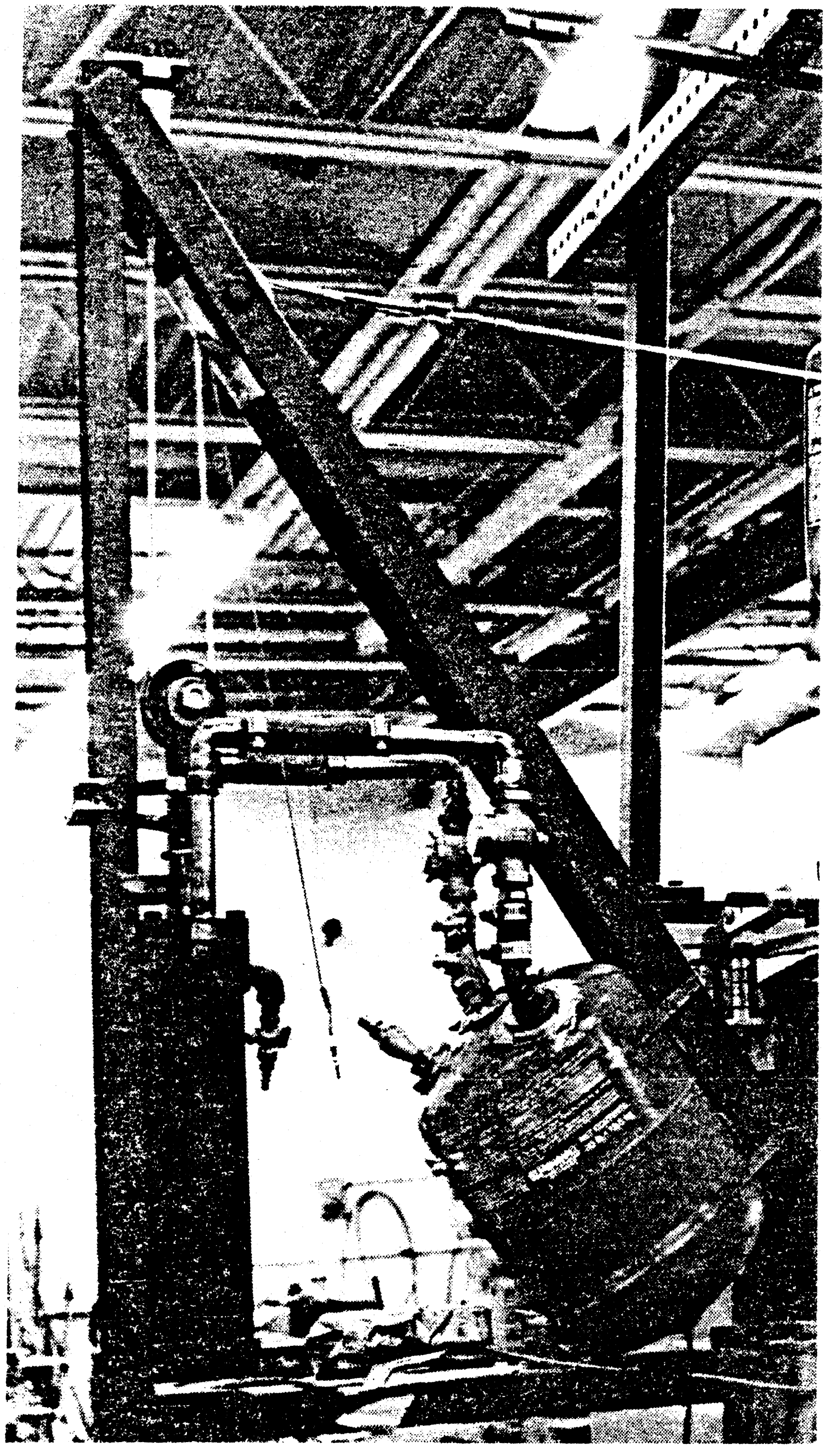


Figure 13. The self-restraint device

force. Once determined, all tests were run at that pressure level, but because of several factors, the average self-restraint deviated slightly from the nominal value, but not more than normal and statistically acceptable variations.

In the tests with traditional seat, there was no wing against which the dummy could press its right shoulder when the air cylinder was first pressurized. For the dummy to maintain a realistic position, similar to the initial position used in the winged seat tests, soft steel wire coiled in the form of a tension spring was used to counteract the air cylinder force. This coil provided up to 40 lbs of initial reactive force before permanently stretching to allow a more free motion of the dummy. This was supplemented by a steel cable which held the dummy in its initial position with respect to the vehicle until a release pin was automatically pulled as the tipover proceeded. Both the coiled steel wire and the steel cable were attached at one end of the left side of the top of the dummy's spine box and at the other end the upper side of the overhead guard. Thus, both the coiled wire and the steel cable pulled the dummy with the truck as it started to tip over, but when the release pin was pulled from the steel cable, the simulated muscle action provided by the air cylinder system could overcome the resistance of the coiled wire.

3.5 Test Instrumentation

Dynamic tests generate displacements, velocities, accelerations, and forces that result from motions and interactions. Because they vary with time, they are called dynamic quantities, and may be measured in inches, miles/hour, radians/second, g's, or pounds. The basic device that converts a physical quantity to a measurable electrical voltage, or signal, is called a transducer. Usually, the signal generated from a given transducer is very small and must be amplified before it can be recorded on a magnetic tape or displayed on a chart. Finally, the signal must be converted from a measured voltage back to the engineering units of the quantity that generated it. This crucial step requires the calibration of transducer, amplifier, and recording/playback equipment, a process that determines that conversion factor.

In the tipover experiments, several types of transducers, signal conditioners, and recorders were used to monitor the time-varying motions and forces. These are listed in Table 5. Thus, the rotation of the truck was measured with two transducers: one for the angle of rotation, the other for the rotational velocity. The impact deceleration of the truck was measured with an accelerometer mounted on the engine hood right under the center of the seat cushion, with its sensitive axis tangent to the rotation circle. No transducer was used to measure the linear velocity at that point. Instead, the measured acceleration was integrated to yield a time-history of that velocity. The self-restraint force was measured with a force transducer (load cell) mounted at the end of the cable being pulled by the lateral motion of the dummy. This lateral motion was monitored with a displacement transducer (string pot) that was pulled by a second cable attached at the same shoulder point as the first.

The most important measurements, however, were those of the head and chest accelerations of the test dummy. Two triaxial orthogonal clusters of linear accelerometers were installed at the centers of gravity of the head and chest. Each accelerometer was a piezo-resistive unit (Endevco Model 7264) rated at 2000 g's. The seismic mass inside an accelerometer is sensitive only in one direction, which is called the sensitive axis of the accelerometer. The mount for the triaxial cluster was designed such that the individual seismic masses are within 0.15 inches of each others, so that the resultant acceleration at the center of gravity can be computed from its three components. A cluster of three Endevco accelerometers is shown in Figure 14. The following is a brief list of all instrumentation hardware used in processing the test signals.

ACCELEROMETERS: *ENDEVCO* model 7264 and model 2264 piezo-resistive, uniaxial accelerometers, rated at 2000 g's. Used three for the head, three for the chest, and one for seat deceleration.

LOAD CELL: *INTERFACE* model SSM-NS-500, strain gauge-type, 500-lbs capacity. Used for the self-restraint force.

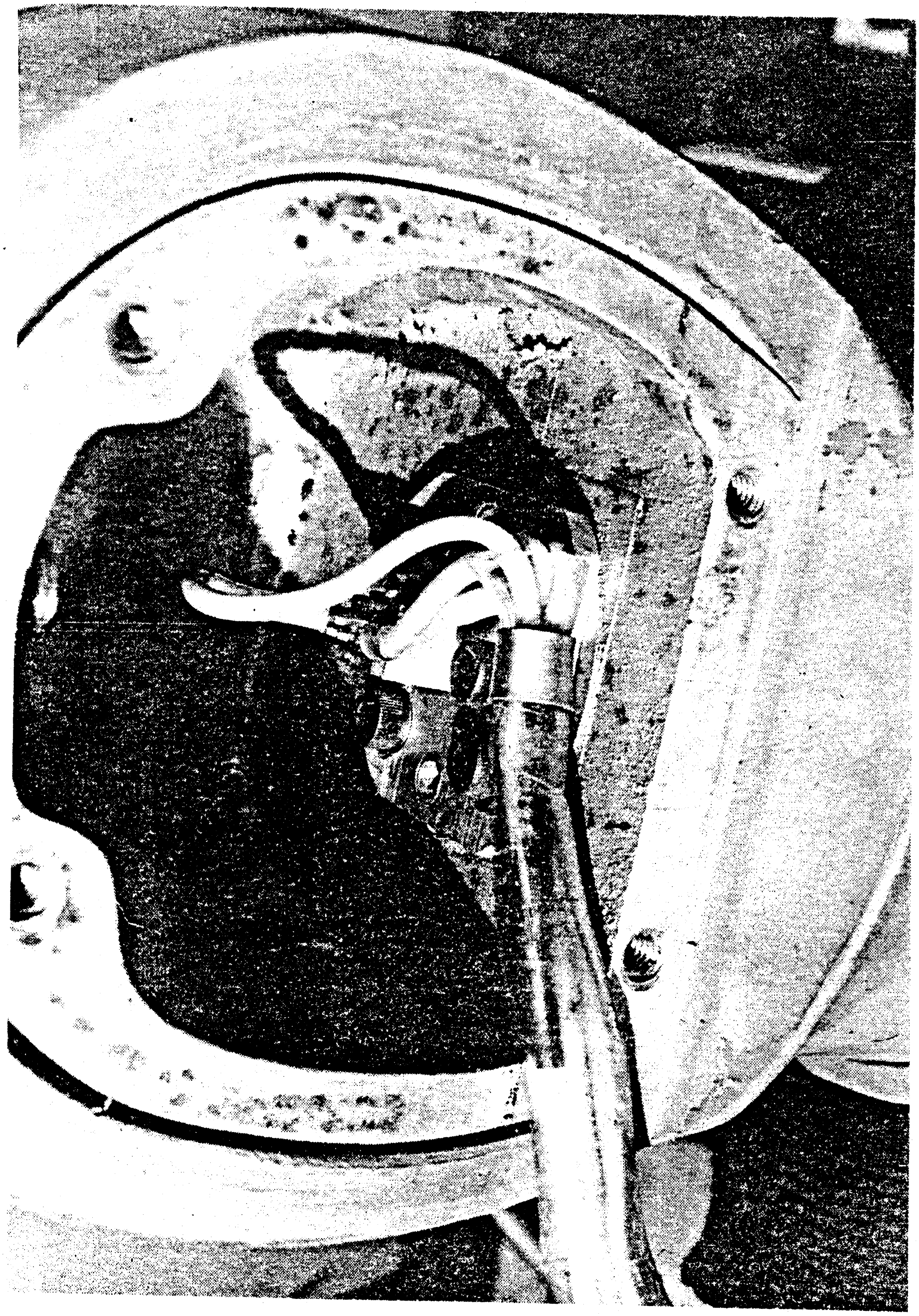


Figure 14. Head accelerometers triaxial cluster

POSITION/VELOCITY: *CELESCO* model DV-301-60A-50-6, string-pot type position transducer and generator-type velocity transducer. Used (1) for the truck rotation and (1) for the dummy lateral displacement.

AMPLIFIERS: *HONEYWELL* model 105 signal conditioning unit and HONEYWELL model 120 D.C. amplifier. Used with all accelerometers and the load cell.

TAPE RECORDER: *HONEYWELL* model 7600, 14-track IRIG standard, FM tape recorder. Recording at 30 IPS, play-back at 1-7/8 IPS. 10 kHz bandwidth.

ANALOG FILTERS: *BURR-BROWN* model LP-100-4B, low-pass, Bessel (linear phase), 4-pole filters with corner at 100 Hz. Used as anti-aliasing filters with effective corner at 1600 Hz for a 16:1 playback expansion.

DIGITAL PROCESSING: Processing of the signals was done using a *DATA GENERAL* NOVA/4X minicomputer. The signals were digitized at 8000 Hz sampling rate using an *ADAC* 16-channel multiplexed sample/hold digitizing board. Head and chest signals were digitally filtered by Class 1000 and Class 180 filters, respectively, as required by SAE J211b guideline. Other signals that are not specified in the guideline were filtered by Class 60 filter (truck velocity and acceleration,) and by the equivalent of Class 30 filter (lateral displacement and self-restraint force.) The filtered signals were then analyzed and plotted on a *ZETA* model 1556 incremental digital plotter.

3.6 Data Channel Calibration

The accuracy of acceleration measurement was an important aspect of the study. It was, therefore, necessary to calibrate all the electronic instruments used in processing the acceleration signal. The calibration procedures that are described here are accepted practices and were followed in the present research study. The data channel used for measuring acceleration consists of a transducer (accelerometer), a signal conditioning unit (amplifier), and a recording/display device (FM tape recorder). An end-to-end calibration produces an input/output relationship, which is a single number (such as g's/Volt) when all data channel components are linear. The calibration procedure described below assumes linearity of these components and is aimed at determining this input/output ratio.

Three-point static calibration was performed on the accelerometer and amplifier units before and after the test. For each point, a well-controlled constant acceleration level was generated using a centrifuge spinning at a known rate. The spin table was driven by a D.C. motor. Its speed was controlled by the 120 VAC line frequency, which is 60 Hz. Three speeds were selected: 600, 900, and 1200 RPM. The accelerometer was mounted on the spin table with its sensitive axis along the radial direction, so that it could sense the centrifugal component of the acceleration. Since this component is equal to the square of the angular velocity times the radial distance, with the radial distance pertaining to the seismic mass of the accelerometer, the "input" acceleration to the data channel was precisely known. The three levels are 41.2, 92.7, and 164.9 g's for the three spin rates.

The second component of the data channel that must be accounted for is the signal conditioning unit, which is a full-bridge strain-gage amplifier. By performing both the calibration and test using the same amplifier at the same excitation and gain settings, the need for separate calibrations of amplifier and accelerometer was eliminated. Thus, the input/output ratio determined from this calibration procedure was that of a larger segment of the data channel, which is the combination of accelerometer and amplifier.

The final segment of the data channel to be calibrated was the recording/display devices. The calibration output, which is a D.C. voltage level, is read directly on a digital voltmeter. This DVM is routinely checked against a precision D.C. voltage source, which is traceable to the National Bureau of Standards. The dynamic test itself was recorded on an FM analog tape recorder at 30 IPS, played back at 1 7/8 IPS, and displayed on a strip chart recorder.

To calibrate this segment of the data channel, which involves the tape recorder record and playback amplifiers as well as the strip chart playback amplifier, a computer-generated calibration signal was recorded on tape and played back into the strip chart, using the same recording and playback speeds as the test itself. The calibration signals consisted of three 85-ms long D.C. voltage levels of +2.5, 0.0, and -2.5 VDC. These levels were accurate to within 0.25 mV. The recorded calibration signals are played back onto the strip chart recorder, and input/output ratio, which should be equal to 1, was determined.

Deviations from unity were handled differently, depending on the method of read-out. Thus, a deviation of 2.5% (0.975-1.025) is normally tolerated for manual read-outs of test signals. When the deviation exceeded 2.5%, the recording and playback amplifiers were adjusted until their I/O transmission ratio was brought within the acceptable range. For digital read-outs, i.e., when the signals were digitized, the I/O ratio of the tape was combined with the accelerometer and amplifier I/O ratio to give a modified, end-to-end calibration number.

The transducer calibration as well as the signal conditioning, amplification, recording, playback, digitizing, plotting, and analyzing were done at the UMTRI instrumentation facilities. Part of these facilities is shown in Figure 15.

3.7 Side Impact Dummy

In experimental research, where humans may be exposed to dangerous or injurious situations, the use of human-like surrogates is a common practice. The surrogates, or "dummies," must be human-like in their physical characteristics and their ability to produce a dynamic human-like response, especially when their response is used to predict injury or evaluate the effectiveness of a restraint system in protecting humans. Such test dummies are generally called anthropomorphic test devices, or ATDs, because they are human-like in their response.

Automotive crash testing provided the impetus for the design and development of many of these test devices, with each design being an improvement over its predecessors. One of these designs was the General Motors Hybrid II Dummy, a highly repeatable test device. In 1973, a new Part 572 was added to Title 49 of the Code of Federal regulations[4] that established the Hybrid II as the test device of the National Highway

---

[4] Part 572, rule; Docket 73-8, Notice 2. Anthropomorphic Test Dummy - Occupant Crash Protection. 38 FR 20449, August 1, 1973.

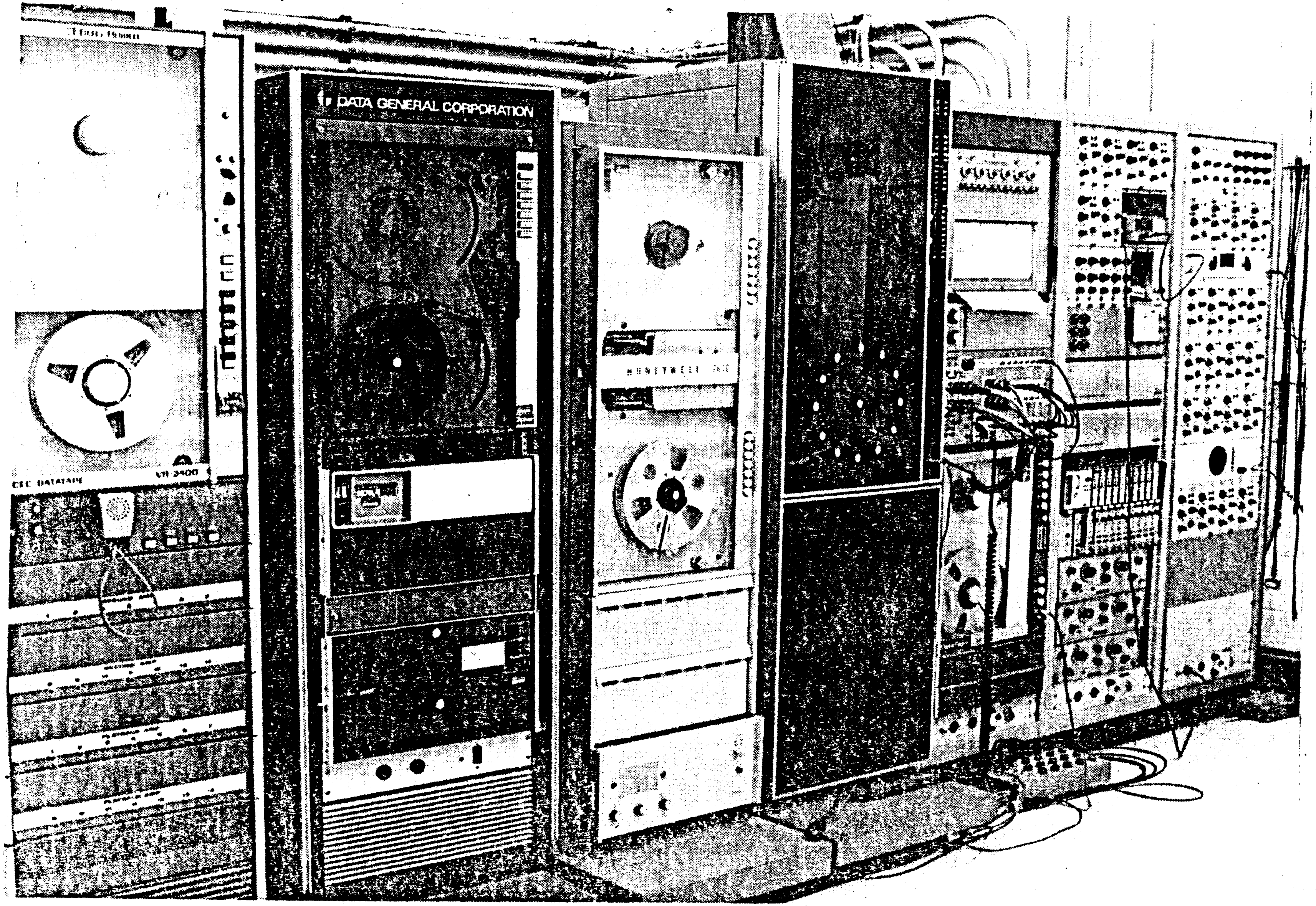


Figure 15. Partial view of the UMTRI instrumentation room

Traffic Administration, or NHTSA. The dummy, which became known as the "Part 572" ATD, was specified with detailed drawings and performance criteria.

The Part 572 ATD was intended primarily for frontal car crashes, and was found to be inadequate for use in car side impacts, a type of accident that was identified by NHTSA as a serious national problem. Subsequently, under a contract from NHTSA, a modified thorax[5] for Part 572 was developed at HSRI (now UMTRI) and the new test device became known as the NHTSA/HSRI Side Impact Dummy, or SID. The new thorax included modifications of the thoracic lateral dynamic stiffness, mass distribution, and rib linkages. The SID also included modification to the shoulder linkage that improved its lateral response. Thoracic response from impact tests conducted on this modified dummy compared favorably with cadaver response in similar tests, based on its ability to predict injury.

Later, additional modifications of the SID were introduced by NHTSA[6], primarily to solve mechanical failure problems with some of its components. The latest version of SID, shown in Figure 16, is the test dummy used in this project. With its human-like thorax, the problems caused by the unrealistic shoulder structure of Part 572 that were encountered in the 1982 ITA study (see section 1.1) were eliminated and the response of the test subject in lateral tipover experiments were more representative of those of a human truck operator.

The SID is a 50th percentile anthropomorphic test device. The use of a 50th percentile device is normal as a starting point for research and testing. The SID used was the current model manufactured by Alderson Research Laboratories, Stamford, CT.

---

[5] J.W. Melvin, D.H. Robbins, and J.B. Benson, "Experimental Application of Advanced Thoracic Instrumentation Techniques to Anthropomorphic Test Devices." Proc. Seventh International Technical Conference on Experimental Safety Vehicles, Paris, 1979.

[6] B.R. Donnelly, R.M. Morgan, and R.H. Eppinger, "Durability, Repeatability and Reproducibility of the NHTSA Side Impact Dummy." Proc. Twenty-Seventh Stapp Car Crash Conference, SAE Paper No. 831624, San Diego, October 1983.

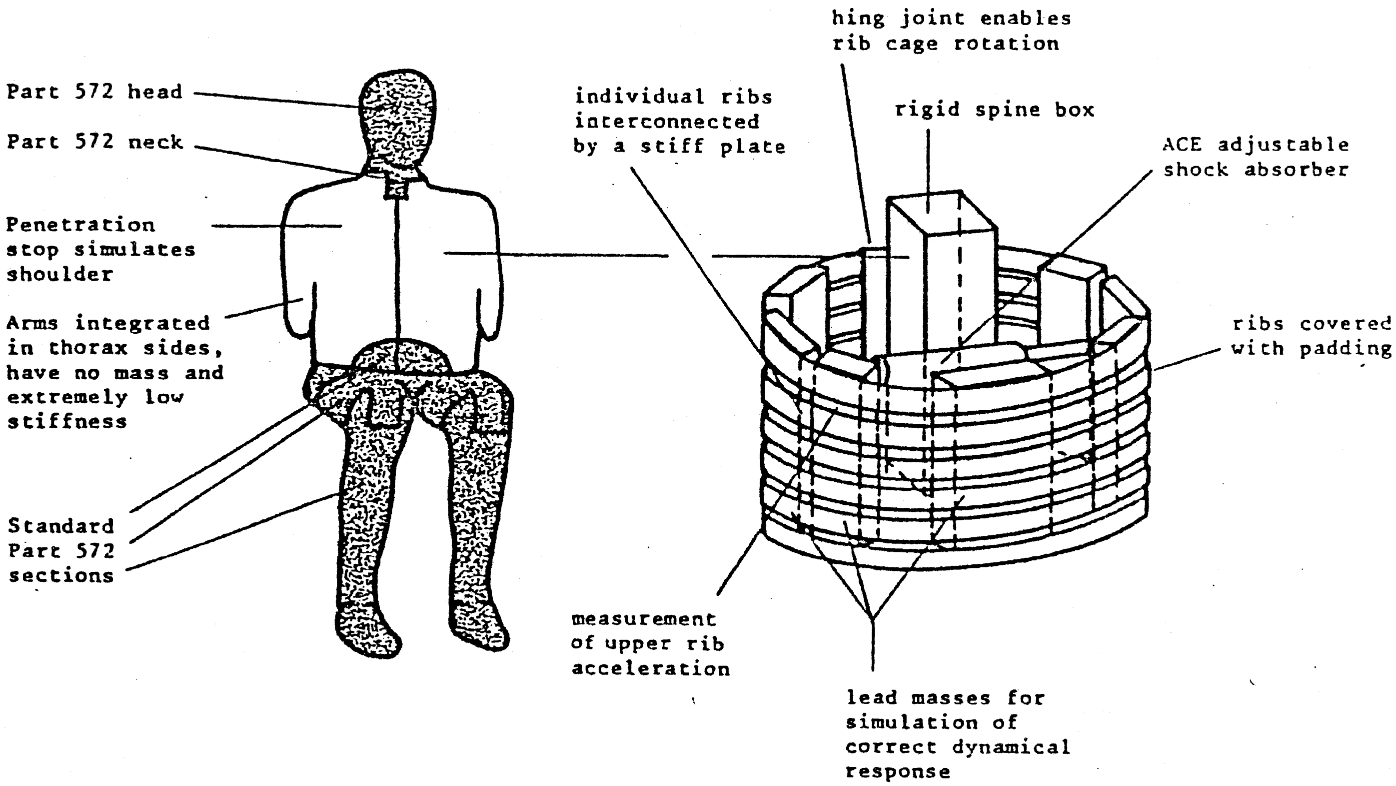


Figure 16. SID, the NHTSA side-impact dummy

Source: J. Maltha and E.G. Jansen, EEC Comparison Testing of Four Side Impact Dummies. Final Report EEC Phase IV, Contract NL9. Research Institute for Road Vehicles TNO, Delft, The Netherlands, October 1983.

4.0 DYNAMIC RESPONSE MEASUREMENTS

The tipover experiments are dynamic events lasting no longer than two seconds. The resulting interactions between the truck and the ground (landing platform) and between the test dummy and truck and ground last only about a quarter of a second, or 250 milliseconds.

Two methods were employed for documenting the forces and motions of the truck and test dummy: photographic and electronic. Photographic coverage consisted of taking color movies at the rate of 64 frames per second, so that when projected at normal (24 frames/second) projector speed, the filmed events appear in slow motion.

The forces and motions of the interactions were also recorded as electronic signals on a magnetic tape recorder for later processing and analysis. The signal processing techniques employed for this purpose are described in this section. The specific signals used to monitor the dynamic responses of the truck as well as the test dummy are described. Finally, the criteria used for evaluating the injury potential to the truck operator are presented and discussed.

4.1 Signal Processing

Standard methods were used to process the signals in every tipover test conducted in this study. Whenever possible, these methods followed internationally accepted practices, such as SAE J211 standard[7]. The processing of signals consisted of five stages that are described below.

First, immediately before every tipover test and after all signal conditioning equipment was tuned, the "zero" level of every signal was recorded, and if necessary, a tape calibration signal was also generated and recorded.

Second, the electronic signals generated during the test were channeled to the instrumentation room where they were conditioned and

---

[7] S.A.E. Recommended Practice J211b, Instrumentation for Impact Tests. Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1980.

recorded on a 14-channel FM tape recorded at 30 inches/second (IPS) tape speed.

In the third stage, the tape was played back at 1-7/8 IPS tape speed in order to stretch the time of the signals by a factor of 16-to-1 and convert the analog (electronic) signals to digital form. The tape was played back twice: once to digitize the pre-test "zero" calibration signals, and once again to digitize the test signals themselves. Each signal was passed through Class 1000 filter before it was digitized. This is the highest-frequency filter specified by SAE J211. Lower-frequency filters were later applied to the appropriate digital signals. The digitizing rate was effectively 8000 samples per second for each signal, a rate recommended by the SAE J211 guideline. Once in the computer's memory, the digitized signals were corrected for any zero imbalance, then converted to engineering units such as pounds or g's and saved on digital magnetic tape for future analyses.

During the fourth stage, the digital signals were filtered according to J211 specifications, resultants were computed, then plotted on a digital incremental plotter. Depending on the signal, one of several digital filters are applied. Thus, Class 1000 was used for head accelerations, Class 180 for chest accelerations, Class 60 for truck deceleration and angular motion, and "Class 100" for the the lateral force and displacement signals. The "Class" is an SAE J211 designation for low-pass Butterworth filter, whose corner (half-power) frequency in Hertz is about 1.65 times the class designation, and whose roll-off rate is between 12 and 24 dB per octave. All the digital filters applied here had the sharper roll-off rate of 24 dB/octave.

The fifth and last stage of processing was to read off the processed signals their peaks, timing, and other pertinent values. Assessment of head injury was also done at this stage by processing the resultant head accelerations to extract the Head Injury Criterion (HIC) and the Mean Strain Criterion (MSC) as described in section 4.5.

4.2 Truck Motion and Impact

To determine and control the severity of impact, the truck tipover was monitored by measuring the platform angle (degrees), its angular velocity (radians/second), and the lateral linear deceleration at the base of the seat. The filtered rotations were plotted on a single page, with the angular velocity displayed in degrees/sec instead of radians/sec. Note that 180 degrees are equal to 3.14 radians.

The tests were conducted at two nominal velocities of 2.0 and 2.8 (115 and 160 deg/sec) that represented the lower and upper ends of the tipover severities of interest. Actual velocities, averaged over the last 50 msec before impact, deviated little from these nominal values.

The seat deceleration was filtered and plotted in g's as a function of time, along with seat linear velocity in miles/hour (mph). This linear velocity was obtained by integrating the deceleration pulse and was, therefore, initially set to zero. Although not strictly used as parameters to be controlled, both linear deceleration and velocity provided additional means to assess the severity of tipover impacts.

4.3 Lateral Force and Displacement

The self-restraint action was monitored by measuring the lateral force (pounds) applied at the shoulder of the test dummy as well as the lateral displacement (inches). The force signal was used to ensure that the applied force was within the estimated ability of the average person to apply muscle forces laterally as discussed in section 2.3. The displacement signal was intended to be combined with the force signal to compute the energy expended during the signal. However, this computation was later abandoned because of difficulties in the computer cross-plotting program.

Since both force and displacement measurements relied on a flexible cable arrangement, they could only record the "tension" of the cable but no "compression." Thus, the force signal could never become less than zero and always remained positive. Observed "negative dips" in the signal may be attributed to vibrations of the load cell mount at impact.

The time-history of the force signal is more complex than others and needs further description. Recall that an air cylinder was used to set the self-restraint level at a constant level. This required that the cylinder be pressurized prior to the test, thereby pulling the test dummy to the right side of the seat. In the tests with the winged seat, the right-side wings acted as a stop for the right shoulder, so that the dummy was pressed against the wing even before the test.

As the truck rotates, a momentary lapse of cable tension occurs until the dummy's motions re-tense the cable and the air cylinder piston begins to move. That is when the recorded force begins to rise, and depending on the static frictions present in the self-restraint system, momentarily overshoots the preset level of self-restraint force but soon settles at the preset value.

In the tests with the traditional seat, there were no wings against which the dummy was pressed when the air cylinder was first pressurized. To maintain an initial position similar to the one used in the winged seat tests, a coil of soft steel wire and a steel cable with a release pin were used to counteract the air cylinder force, as explained in section 3.4. This coil provided up to 40 lbs of initial reactive force before permanently stretching to allow free motion of the dummy.

Pressure in the air cylinder was set in all the tests at the same value of 450 kPa necessary to maintain the desired nominal 125 lbs self-restraint lateral force. However, the actual constant force levels, as measured from the processed signals, deviated slightly from the nominal value but were within an acceptable range.

4.4 Head and Chest Accelerations

The most commonly used indication of the dynamic response of a test dummy in an impact situation is the acceleration of its body parts. The acceleration is the rate of change of the velocity, which itself is the rate of change of displacement. Here, the word "rate" implies a change over a time, defined mathematically as the time-derivative. Thus, if displacement were measured in feet, the velocity would be in feet per second (ft/sec), and accelerations in ft/sec per second (ft/sec/sec). More commonly, accelerations are measured in units of gravity (g's) with 1 g equal to 32.2 ft/sec/sec.

Head and chest acceleration signals were measured in the posterior-anterior (P-A), right-left (R-L), and inferior-superior (I-S) directions of the body. Since these directions are orthogonal, the resultant (RES) acceleration was computed as the square-root of the sum of the squares of the P-A, R-L, and I-S components. The resultant and components were then plotted as functions of time, both for the head and for the chest.

4.5 Biomechanics of Head Injury

Head injury is one of the most significant type of injuries that can occur in an accident. Protection of the head from irreversible brain damage becomes, therefore, one of the most critical tasks for the safety design engineer. The following discussion is not an exhaustive treatment of this important area of biomechanics but is intended to provide a brief background on the subject. A comprehensive review of landmark literature and regulations relating to head injury may be found in a report by Hess, Weber, and Melvin[8]. References to works cited here may also be found in that report.

Most indexes of head injury are based on the Wayne State Tolerance Curve (WSTC), first suggested in 1960 by Lissner, Lebow, and Evans. The original WSTC included six points that represented the relationship between acceleration level and short impulse duration found to produce linear skull fracture in embalmed cadaver heads. Later, the tolerance data was augmented with additional cadaver impacts of longer durations, animal impact data, and with human volunteer acceleration data. The tolerance data suggest that, in general, humans can tolerate higher acceleration levels if the pulse duration is short, while only lower levels of acceleration may be tolerated if the duration is longer.

In 1961, C.W. Gadd suggested plotting the injury tolerance curve on logarithmic scales to achieve a straight-line fit. He also suggested that, if the head acceleration signal (raised to a power of 2.5) from an impact test near the threshold of injury were integrated over the pulse duration, then the number resulting from the integration could be used as an index to indicate the extent or severity of impact. The "2.5-

---

[8] R.L. Hess, K. Weber, and J.W. Melvin, Review of Literature and Regulation Relating to Head Impact Tolerance and Injury Criteria. Report No. UM-HSRI-80-52, Highway Safety Research Institute, The University of Michigan, Ann Arbor, July 1980.

power" was derived from the logarithmic slope of the tolerance curve, and impacts which fell on the tolerance curve produced an index of 1000 when their weighted acceleration signals were integrated. The Gadd Severity Index (GSI) was eventually adopted in 1966 by the Society of Automotive Engineers as an SAE J885a Recommended Practice.

Just as researchers were developing and recommending the use of alternate criteria, the National Highway Traffic Safety Administration (NHTSA) issued in 1971 a notice to FMVSS 208, the Occupant Crash Protection standard, requiring the use of the GSI and defining the head injury criterion as "a maximum head severity index of 1000, calculated according to SAE J885a."

The Fifteenth Stapp Car Crash Conference, held in the fall of 1971, included special sessions on head injury and became a forum for the discussion of head injury mechanisms, tolerance thresholds, and injury assessment criteria. At that conference, the GSI was reviewed, and several alternatives were suggested for its replacement. Alternatives included several simple one-mass and two-mass systems, as well as a modified weighted-acceleration calculation method. Two of the offered alternatives (the HIC and the MSC) were later refined and gained wide acceptance. These were used in the present tipover testing program, and are discussed next.

4.5.1 <u>HIC - Head Injury Criterion</u>. A mathematical critique of the GSI was presented in the 1971 Stapp Conference by J. Versace, who suggested an alternative method for calculating the injury index. Instead of integrating the weighted acceleration over the duration of its pulse, Versace multiplied the pulse duration by the weighted "average acceleration" computed over the duration of the pulse. This procedure is repeated for every pulse contained in the acceleration signal, and the largest computed index is retained as the final injury index.

NHTSA liked Versace's method because it was able to handle multiple impacts where the pulses were separated by relatively long periods of time, and to pick out only one pulse as the most severe, whereas the GSI would accumulate the effects of all pulses and produce an excessively large severity index. In June, 1972, NHTSA issued a new rule notice[9] to replace the GSI requirement in FMVSS 208 standard with a generalized version of the Versace index. Not formally labeled at that time, the new index soon became known as the Head Injury Criterion, or HIC.

Given the resultant head acceleration signal **a(t)**, measured in g's over the interval [0,T] seconds, the HIC is determined by evaluating the following expression for all possible combinations of t_1 and t_2 and retaining the maximum value. Thus,

$$HIC = \max \left[\int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} \cdot \left[t_2 - t_1\right]^{1.5}; \quad 0 \le t_1 \le t_2 \le T.$$

Since the HIC computation was largely based on the GSI, a level of 1000 was first estimated as the permissible HIC, then later confirmed by additional experimental head injury research. In adopting the HIC as a method and the value of 1000 as the criterion, NHTSA wrote:

> Some substantive objections were raised to the proposed method of calculating the head injury criterion. Several comments questioned the use of the resultant accelerations rather than the anterior-posterior accelerations used in the original development of the Wayne State University tolerance curve. Although the curve was originally based on anterior-posterior acceleration data, its validity for resultant accelerations appears to be confirmed by subsequent tests using resultant accelerations computed from biaxial accelerometers. Resultant accelerations have therefore been used in the amended criterion.
>
> The question of the permissible level was again raised with some commentors supporting a level of 1,500 even under the revised method of calculation. This agency's position is that adequate justification has not been demonstrated for a numerical increase in the severity level, although adjustments in the method of calculation adopted herein may have the effect of allowing greater cumulative accelerations than would have been allowed under the Gadd Severity Index. With a new calculation, the higher numerical level is less supported than before and it is accordingly rejected.

Although a HIC threshold value of 1000 has been used as a benchmark in evaluating protective systems, experimental and clinical data suggest that life-threatening head injuries may occur even when the computed HIC

---

[9] U.S. DOT/NHTSA, FMVSS 208 standard, rule; Docket 69-7, Notice 19. Occupant Crash Protection. 37 FR 12393, June 23, 1972.

falls short of the 1000 mark, and may not occur at all even when the HIC exceeds that mark.

Based on statistical analysis of existing head injury cases, Mertz[10] recently suggested the use of the HIC to determine the probability of injury rather than using it as a "pass/fail" criterion. Figure 17 summarizes this injury scaling for frontal head impacts. Lateral impacts are less tolerated by the human head than frontal impacts of the same level. Thus, a HIC of 1000 predicts that the human subject has about 15 percent chance of experiencing a life-threatening brain damage, whereas a HIC of 2000 would indicate a probability of 90 percent of suffering brain damage. A HIC that exceeds 2500 indicates a probability of over 99 percent of life-threatening brain injury, a near certainty.

4.5.2 <u>MSC - Mean Strain Criterion</u>. Head injury research did not stop with the adoption by NHTSA of the HIC. One of the alternative methods to both the GSI and the HIC was first suggested by Stalnaker and McElhaney in 1970. The method modeled the head as a two-mass system connected by a spring and a damper whose constants were derived from mechanical impedance data of the head. Impact to the head was simulated by applying the measured acceleration to one of the two masses, and calculating the spring length or the distance between the two masses. The severity of the impact was determined from the spring compression divided by its length, a strain ratio which was not to exceed a certain maximum, hence the Maximum Strain Criterion, or MSC.

Later in a symposium on human impact response in 1973, McElhaney, Stalnaker and Roberts[11] presented further refinements of the MSC model and compared its predictions to other indexes. Thus, the MSC was revised to represent the "mean" rather than "maximum" strain, where mean

---

[10] H.J. Mertz, "Injury Assessment Values Used to Evaluate Hybrid III Response Parameters." USG 2284 Part III, Attachment I, Enclosure 2. February, 1984.

[11] J.H. McElhaney, R.L. Stalnaker and V.L. Roberts, "Biomechanical Aspects of Head Injury." In Human Impact Response - Measurement and Simulation. Proc. of the Symposium on Human Impact Response, 2-3 October 1972, Warren, Michigan. New York: Plenum Press, 1973.

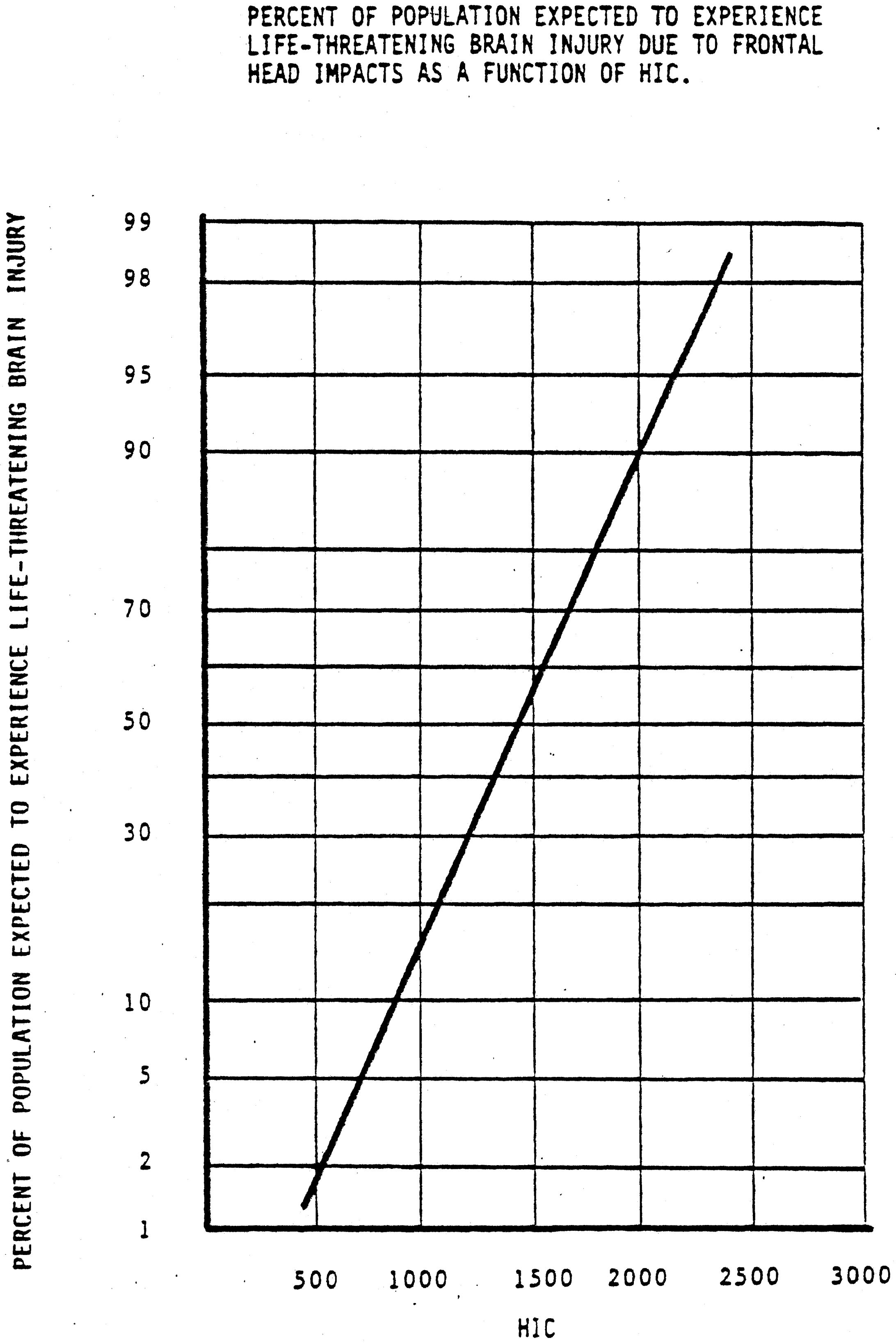


Figure 17. HIC prediction of brain damage in frontal impacts

strain was defined as the "displacement of one side of the head relative to the other, divided by the distance across the cranium." Other indexes derived from one-mass models were similar to the MSC in their predictions. The discussion that followed their presentation dealt with the understanding of brain injury mechanisms and the implications for head injury prediction. Part of that discussion is quoted here:

> *J.H. McElhaney:* The model we propose, which as we see predicts essentially the same things as many other models, is based on information from essentially rigid or almost hard impacts. Under these conditions we get a certain type of injury. We have certain injury mechanisms involved. We're starting to believe more and more, that this mechanism is cavitation whereas at one time we thought it might be just a gross deformation in the brain...
>
> We recognize particularly that as the pulse duration increases, there is a different mechanism of injury; and in fact, in the rigid striker impacts we see predominantly contracoup type injuries. When we pad this striker we don't see contracoup injuries anymore. We see minute hemorrhaging in much larger areas in the brain. Both of these injury types cause some difficulty in assessment. If the injuries occur in one region of the brain our pathologist tells us it's of no consequence; but if they occur in another region of the brain or tear a major artery, for example, it's very serious.

The simplicity of the two-mass MSC model has attracted researchers, since it can easily be adapted to other areas of the body, such as the chest. Research continues, however, in refining the constants of the head MSC model, and in improving its prediction capability.

There are five constants for the MSC model, derived from mechanical impedance and dimensions of the head. Since the head was found to have different physical and mechanical properties in different directions of the applied force, separate models were developed for the P-A, R-L, and I-S directions. For each model, five constants were determined: the length L across the cranium, the mass M1 of the impacted region, the mass M2 of the rest of the head, and the stiffness K and damping C of the head. While there is no MSC model to be used for the resultant acceleration, current research suggest that responses (strain signals) from the three MSC models be combined, much the same as three orthogonal components, to produce the MSC resultant response.

In this project, all three MSC models were applied using the head acceleration signals, measured in the P-A, R-L, and I-S directions, and

Table 5. Constants for the MSC Models

Model Constant	Head Direction			Units
	P-A	R-L	I-S	
Length, L =	7.68	6.06	10.00	inches
1st Mass, M1 =	0.60	0.40	1.00	lbs
2nd Mass, M2 =	10.00	9.00	10.00	lbs
Damping, C =	2.00	2.40	2.50	lb-s/in
Stiffness, K =	50000	26000	50000	lb/in

the "resultant" MSC was computed. Since these are intended to provide additional indication of the relative severity of head injury, the permissible levels of MSC indexes are not essential to the evaluation of the tests and, therefore, none of those levels is specified here and only the MSC indexes for the RES and L-R directions are included in the tabulations of results.

5.0 DISCUSSION OF RESULTS

Individual processed signals are given in the Appendix, but the most important parameters are extracted and presented in this section. There are four groups of tests that are separately tabulated:

B-tests: Lower (2.0 rad/s) severity, traditional seat only;

C-tests: " " " " seat with wings and seatbelts;

A-tests: Upper (2.8 rad/s) severity, traditional seat only;

D-tests: " " " " seat with wings and seatbelts.

The following sections contain definition of measured parameters, tables of the measurements, and a discussion of the findings.

5.1 Definition of Parameters

Each table of results contains five blocks of measured parameters that are related to an aspect of the experiment. The terms used to describe these parameters are described below; their values were read off the processed signals given in the Appendix.

Truck Rotation. The rotation of the truck is indicated by the angular **Velocity**, reported both in radians/second and degrees/second. The maximum **Angle** that the truck rotated is also reported. As an additional indication of the severity of impact, the **Peak Deceleration** level of the Seat is reported. Since this peak depends on the filter (SAE Class 60) used to process the signal, the **Peak Velocity** change from its initial value is reported in Miles Per Hour (MPH) and is a more consistent indicator of the severity of seat impact. The angular velocity may be used to compare the "lower" and "upper" impact severities and was nominally set at either 2.0 or 2.8 rad/sec.

Self-Restraint. The **Average** level of lateral self-restraint force is reported. The force signal generally reaches a temporary peak that lasts a very short time, before settling on this average value. This force is an indication of the consistency with which it was applied throughout the testing, and was nominally set at 125 lbs. When a transducer signal is not available because of instrumentation failure, a Loss Of Data is indicated by *LOD.*

Chest Acceleration. The reported values are peak accelerations in g's, measured in the posterior-anterior **P-A**, right-left **R-L**, and inferior-superior **I-S** directions at the chest center of gravity. The peak resultant **RES** is also reported.

Head Acceleration. The peak readings of the head accelerations at its center of gravity, measured in the **P-A**, **R-L**, and **I-S** are reported, along with the peak **RES** of their resultant.

Head Injury. Any indication of head **Contact** with the ground or with any other structure is reported, as determined from review of the slow-motion film of the test, or from the occurrence of an extremely short (less that 10 msec) head acceleration pulse. No Contact is indicated as **N/C**, in which case no further head injury assessment is carried out. In cases where head contact did occur, the **HIC** is computed and reported along with its **Duration**. The **Probability** of brain damage, based on the conversion chart given in Figure 17, is also reported. Probabilities are rounded to 0% when they are below 1%, and to 100% when they exceed 99%. As an additional injury assessment index, the **MSC** is also computed and reported, both for the **RES** and the **R-L** models.

5.2 Tabulations of Results

The results are given in Tables 6 through 10. Except for Table 8, all other tables are for tests that were conducted at the lateral self-restraint force nominal level of 125 lbs.

The dynamic response measurements of the test dummy are extracted and presented in Table 11. These are the HIC, probability of brain damage, and peak resultant accelerations of the head and chest. They represent the most appropriate parameters for comparing lower-severity impacts to upper-severity ones, and the effects of adding wings and seatbelts on the test dummy response.

5.3 Discussion of Findings

The activities and experimental design in this project were guided by several goals and some unanswered questions. Successful testing required that the test conditions selected for the tipover simulations represent realistic conditions of real-world forklift truck tipover accidents. Another requirement was the use of a state-of-the-art test dummy suitable for lateral impact. Since such a test dummy cannot simulate muscle action, sound experimental design required that the lateral force be applied at a realistic location and direction, and at levels that represent reasonably well the operator's self-restraint. Finally, the test matrix must be designed to bring out, in a reliable and repeatable fashion, the effects of the tipover severity on the dummy response, as well as demonstrate repeatedly the effects of seatwings and seatbelts. These issues were all addressed in the course of conducting the present research and the findings, supported in the body of the report, are summarized next.

TIPOVER FIXTURE. The fixture was designed to re-create the important phases of the tipover under a controlled laboratory environment. This greatly simplified the testing and eliminated the variability of tipover kinematics encountered in the ITA full-scale overturn experiments. This also imposes some limitation. For example, the effects of the forward motion of the truck on the response of the test dummy are not included. Such inclusion, however, would have complicated the test conditions and obscured the effects of specific parameters on the outcome. The test findings, therefore, can be attributed solely to the lateral rotation of the truck, without interference from other factors.

The test fixture simulated the impact of the truck on the ground by stopping the rotation at 90 degrees, but did not allow the truck to touch the ground, simulated by the landing platform. Instead, this platform was placed about an inch below the final position of the side of the truck, and interacted with the test dummy's head and shoulder in most of the tests.

Because the fixture allowed only the pivoting of the truck about the left-side tires/ground line and did not have a provision for allowing the truck to skid on slamdown, the horizontal skidding motion was accounted for by raising the overhead guard about three inches. This is well justified since, in reviewing the films of some of the ITA tests, the skidding was as much as 14 inches from the place of the initial slamdown.

<u>TIPOVER SEVERITY.</u> The severity of truck tipover was represented by the truck angular velocity, which was demonstrated to be an elegant and equivalent indication of severity. The velocity of 2.0 radians/second was selected from the lower range of full-scale tipover velocities that were determined from the ITA tests. A second velocity was necessary in order to study the effects of tipover severity on the performance of the two seating configurations. Thus, a velocity of 2.8 rad/sec was chosen to provide twice the kinetic energy of lower-severity tests.

<u>SIDE IMPACT DUMMY.</u> The use of SID provided the best surrogate of a human operator for these lateral tipover experiments. Except for an improved thorax and shoulder structures, the SID consists of a Part 572 ATD, a test dummy that is specified by NHTSA for crash testing and automobile certification.

Since the SID does not slump when seated, as most people do, the overhead guard was raised about two more inches to provide reasonable head room for the subject at the beginning of each test. This and the accounting for skidding amounted to a total of five inches that the overhead guard was raised, providing head room well within the observed skidding distances in the ITA full-scale tests.

<u>SELF-RESTRAINT.</u> The operator's action to restrain himself laterally in a tipover was simulated with a controllable, repeatable, and realistic device. The self-restraint level, which greatly depends on muscle strength, was estimated from published data and from a limited study of the lateral forces of two volunteers. The selected level of 125 lbs represented the average level of operator self-restraint, which can range from 100 to 140 lbs under conservative conditions.

PROCEDURES. Well-established and widely used practices were applied in the instrumentation, signal filtering, and analyses. Calibration procedures were followed when necessary or required. SAE and NHTSA guidelines were adhered to wherever they were needed. Good and sound engineering and scientific practices were always the guide for developing and implementing testing and analysis procedures.

REPEATABILITY. The care taken in conducting the experiments and in controlling the test parameters resulted in repeatable tests within each of the four test groups, as may be concluded from the tables of the results.

HEAD INJURY. The HIC was used as the primary indicator of head injury. The use of the MSC was included to provide an additional measure of the relative degree of injury potential. Both of these criteria are widely used and accepted as indications of head injury, and are described in the body of the report. The benchmark of a permissible level (HIC = 1000) may be used as a "pass/fail" criterion for injury. However, a more reasonable approach is to use the HIC to estimate the probability of experiencing life-threatening brain injury. Using this approach, the effects of tipover velocity and seating configurations are discussed here.

EFFECTS OF SELF-RESTRAINT. Table 8 presents a comparison of two tests (low-velocity, seat with wings/belts) run under identical test conditions except for the level of self-restraint force. The results indicate that, when the self-restraint force is about 70 lbs, the probability of head injury is near 100 percent, a certainty. When the self-restraint level was increased to the 125-lb nominal level, the probability of injury was slightly reduced but remained above 85 percent (Table 7). In order to eliminate the injury potential in this seating configuration and at this low velocity, it was necessary to increase the self-restraint force to 160 lbs. From the data, it is clear that the head would not have hit the floor had the self-restraint force been increased further.

EFFECTS OF TIPOVER VELOCITY. The results indicate that an increase of tipover velocity increases the severity of head injury. This is true for both types of seating configurations. The reader may examine the summary of results given in Table 11 to confirm this conclusion.

EFFECTS OF WINGS/BELTS. The results of the tests indicate that the presence of wings and belts did not reduce the injury potential of the subject. This may be explained by two factors. First, the restriction (by the seatbelts) of the hip from sliding out together with the upper torso toward the ground may have accentuated the motion of the upper parts of the body (shoulder, head) and resulted in a higher head/ground impact velocity. This pivoting of the upper part of the body about the restricted hips may also have exposed the head to an impact with the ground that has both L-R and S-I components.

The second factor is that the right seatwing (far side) forced the test dummy to "ride" the rotation until the truck stopped, at which point the kinetic energy transferred to the dummy during the rotation carried it to a full and hard impact on the left side, much harder than the retaining left seatwing can attenuate.

This brief discussion summarizes the findings of the research project. The following tables provide additional numerical results which may be further examined in greater detail.

Table 6. Results of B-(1,2,3) Tests

Lower Velocity Tests, with Traditional Seat Only

Measured Parameter	Measurements			Units
	Test B-1	Test B-2	Test B-3	
Truck Rotation: **Velocity**	**2.0**	**1.9**	**1.9**	**rad/sec**
	115	110	112	deg/sec
Angle	88	87	87	degrees
Seat: Peak Deceleration	19	29	29	g's
Peak Velocity	8.3	9.6	8.8	MPH
Self-Restraint: **Average**	**134**	**128**	**135**	**lbs**
Chest Acceleration: **RES**	**8**	**9**	**9**	**g's**
P-A	2	2	2	g's
R-L	8	8	9	g's
I-S	7	8	7	g's
Head Acceleration: **RES**	**5**	**6**	**5**	**g's**
P-A	2	2	2	g's
R-L	4	5	5	g's
I-S	3	4	4	g's
Head Injury: Contact	N/C	N/C	N/C	
Duration	N/C	N/C	N/C	msec
HIC (RES)	**N/C**	**N/C**	**N/C**	
Probability	**0**	**0**	**0**	**Percent**
MSC (RES)	N/C	N/C	N/C	
(R-L)	N/C	N/C	N/C	

Table 7. Results of C-(1,2,3) Tests

Lower Velocity Tests, Seat with Wings and Seatbelts

Measured Parameter		Measurements			Units
		Test C-1	Test C-2	Test C-3	
Truck Rotation:	**Velocity**	**2.1**	**2.1**	**2.1**	**rad/sec**
		120	121	120	deg/sec
	Angle	89	89	89	degrees
Seat:	Peak Deceleration	31	32	34	g's
	Peak Velocity	10.5	10.5	10.5	MPH
Self-Restraint:	**Average**	**134**	**141**	**136**	**lbs**
Chest Acceleration:	**RES**	**18**	**24**	**18**	**g's**
	P-A	6	8	3	g's
	R-L	17	21	18	g's
	I-S	9	11	7	g's
Head Acceleration:	**RES**	**438**	**534**	**385**	**g's**
	P-A	52	67	49	g's
	R-L	285	383	316	g's
	I-S	332	388	278	g's
Head Injury:	Contact	YES	YES	YES	
	Duration	0.875	0.875	1.125	msec
	HIC (RES)	**1997**	**3438**	**1815**	
	Probability	**90**	**100**	**85**	**Percent**
	MSC (RES)	1320	1575	1062	x 10^{-6}
	(R-L)	926	1188	857	x 10^{-6}

Table 8. Results of C-XL and C-XH Tests

Lower Velocity, Wings/Seatbelts, Different Self-Restraints

Measured Parameter		Measurements		Units
		Test C-XL	Test C-XH	
Truck Rotation:	Velocity	2.0	2.1	rad/sec
		115	120	deg/sec
	Angle	89	89	degrees
Seat:	Peak Deceleration	28	30	g's
	Peak Velocity	8.8	10.5	MPH
Self-Restraint:	Average	68	160	lbs
Chest Acceleration:	RES	24	16	g's
	P-A	4	6	g's
	R-L	23	16	g's
	I-S	10	6	g's
Head Acceleration:	RES	662	246	g's
	P-A	64	52	g's
	R-L	551	196	g's
	I-S	384	217	g's
Head Injury:	Contact	YES	YES	
	Duration	0.875	1.375	msec
	HIC (RES)	6425	600	
	Probability	100	3	Percent
	MSC (RES)	1939	610	$x 10^{-6}$
	(R-L)	1604	442	$x 10^{-6}$

Table 9. Results of A-(1,2,3) Tests

Upper Velocity Tests, with Traditional Seat Only

Measured Parameter		Measurements Test A-1	Test A-2	Test A-3	Units
Truck Rotation:	**Velocity**	**2.8**	**2.8**	**2.9**	**rad/sec**
		162	163	165	deg/sec
	Angle	89	89	89	degrees
Seat:	Peak Deceleration	43	45	44	g's
	Peak Velocity	9.0	13.5	13.2	MPH
Self-Restraint:	**Average**	**136**	**132**	**144**	**lbs**
Chest Acceleration:	**RES**	**19**	**15**	**22**	**g's**
	P-A	7	4	8	g's
	R-L	18	12	18	g's
	I-S	14	15	22	g's
Head Acceleration:	**RES**	**68**	**31**	**79**	**g's**
	P-A	44	13	34	g's
	R-L	43	24	62	g's
	I-S	31	16	48	g's
Head Injury:	Contact	YES	YES	YES	
	Duration	2.625	2.500	9.500	msec
	HIC (RES)	**26**	**4**	**64**	
	Probability	**0**	**0**	**0**	**Percent**
	MSC (RES)	157	74	251	$x 10^{-6}$
	(R-L)	111	63	202	$x 10^{-6}$

Table 10. Results of D-(1,2,3) Tests

Upper Velocity Tests, Seat with Wings and Seatbelts

Measured Parameter	Measurements			Units
	Test D-1	Test D-2	Test D-3	
Truck Rotation: **Velocity**	**2.9**	**2.9**	**2.9**	**rad/sec**
	165	168	166	deg/sec
Angle	89	89	89	degrees
Seat: Peak Deceleration	45	36	40	g's
Peak Velocity	13.5	12.3	12.6	MPH
Self-Restraint: **Average**	**125**	**135**	LOD	**lbs**
Chest Acceleration: **RES**	**29**	**56**	**51**	**g's**
P-A	6	10	11	g's
R-L	28	54	49	g's
I-S	14	18	15	g's
Head Acceleration: **RES**	**653**	**605**	**744**	**g's**
P-A	110	110	169	g's
R-L	595	561	665	g's
I-S	379	287	379	g's
Head Injury: Contact	YES	YES	YES	
Duration	1.375	0.750	1.625	msec
HIC (RES)	**6202**	**4362**	**8654**	
Probability	**100**	**100**	**100**	**Percent**
MSC (RES)	1898	1979	2262	$x\ 10^{-6}$
(R-L)	1769	1907	2142	$x\ 10^{-6}$

Table 11. Summary of Test Dummy Response

All Tests at 125-lb Nominal Lateral Self-Restraint

Tipover Severity	Seating Configuration	Test No.	Head Injury		Peak Resultant Acceleration, G	
			HIC	Prob.	Head	Chest
Lower Velocity 2.0 rad/s	Traditional Seat Only	B-1	N/C	0%	5	8
		B-2	N/C	0%	6	9
		B-3	N/C	0%	5	9
	Seat with Wings/Belts	C-1	1997	90%	438	18
		C-2	3438	100%	534	24
		C-3	1815	85%	385	18
Upper Velocity 2.8 rad/s	Traditional Seat Only	A-1	26	0%	68	19
		A-2	4	0%	31	15
		A-3	64	0%	79	22
	Seat with Wings/Belts	D-1	6202	100%	653	29
		D-2	4362	100%	605	56
		D-3	8654	100%	744	51

APPENDIX: PROCESSED SIGNALS

The appendix is divided into the following sections:

Section 1: Truck Rotation

Section 2: Seat Deceleration

Section 3: Lateral Self-Restraint

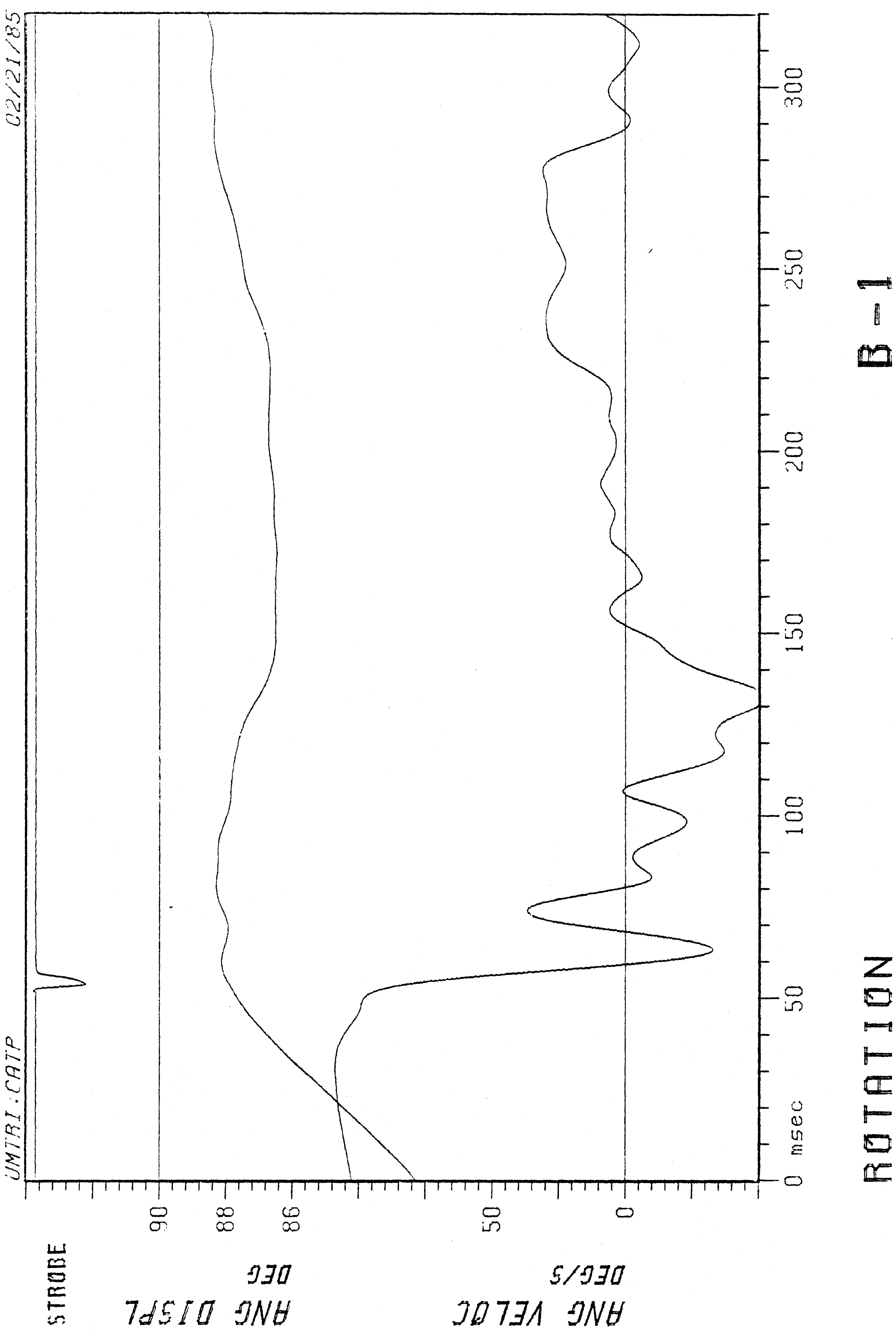
Section 4: Chest Accelerations

Section 5: Head Accelerations

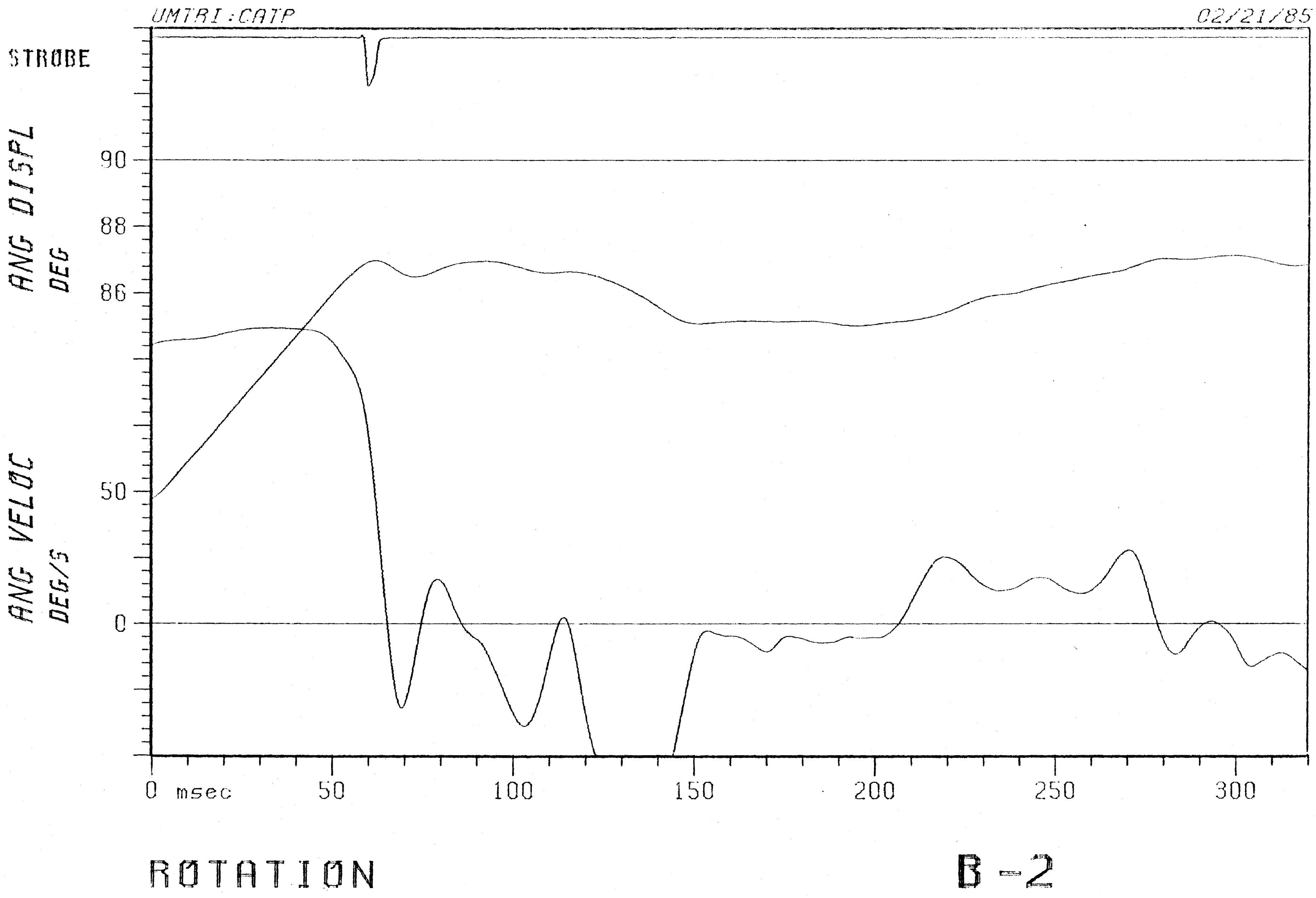
Section 6: Expanded Head Accelerations

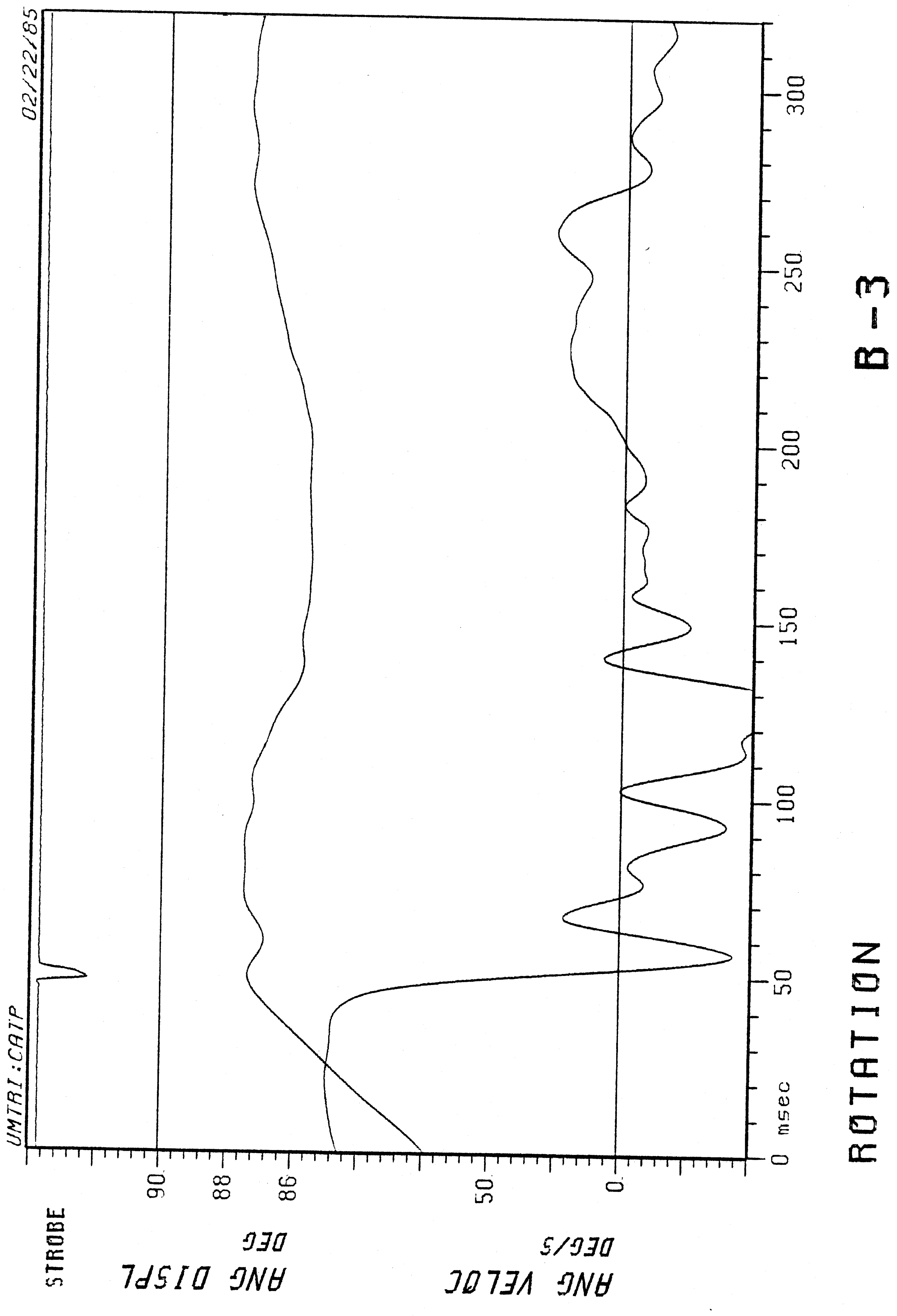
SECTION 1

Truck Rotation

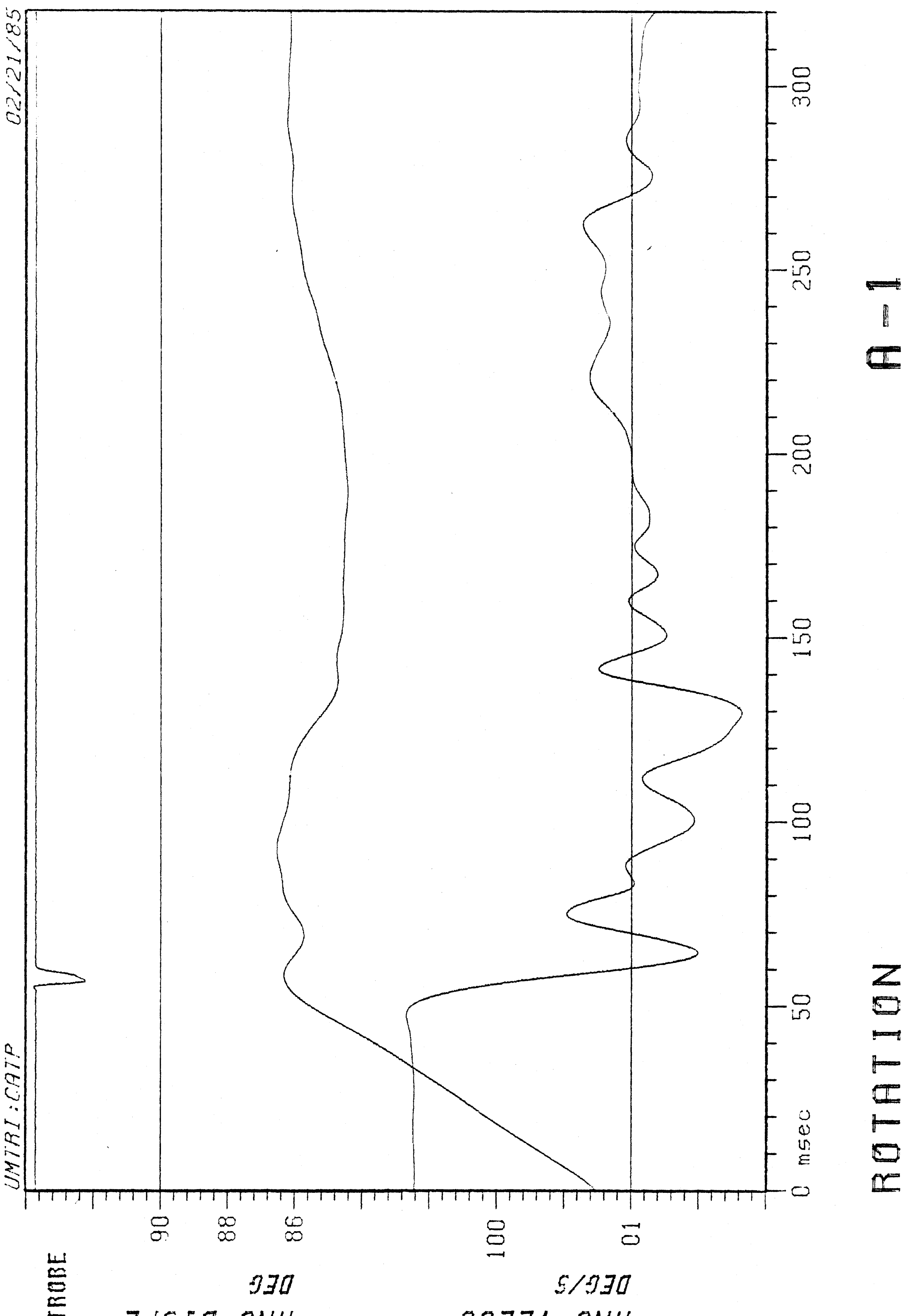


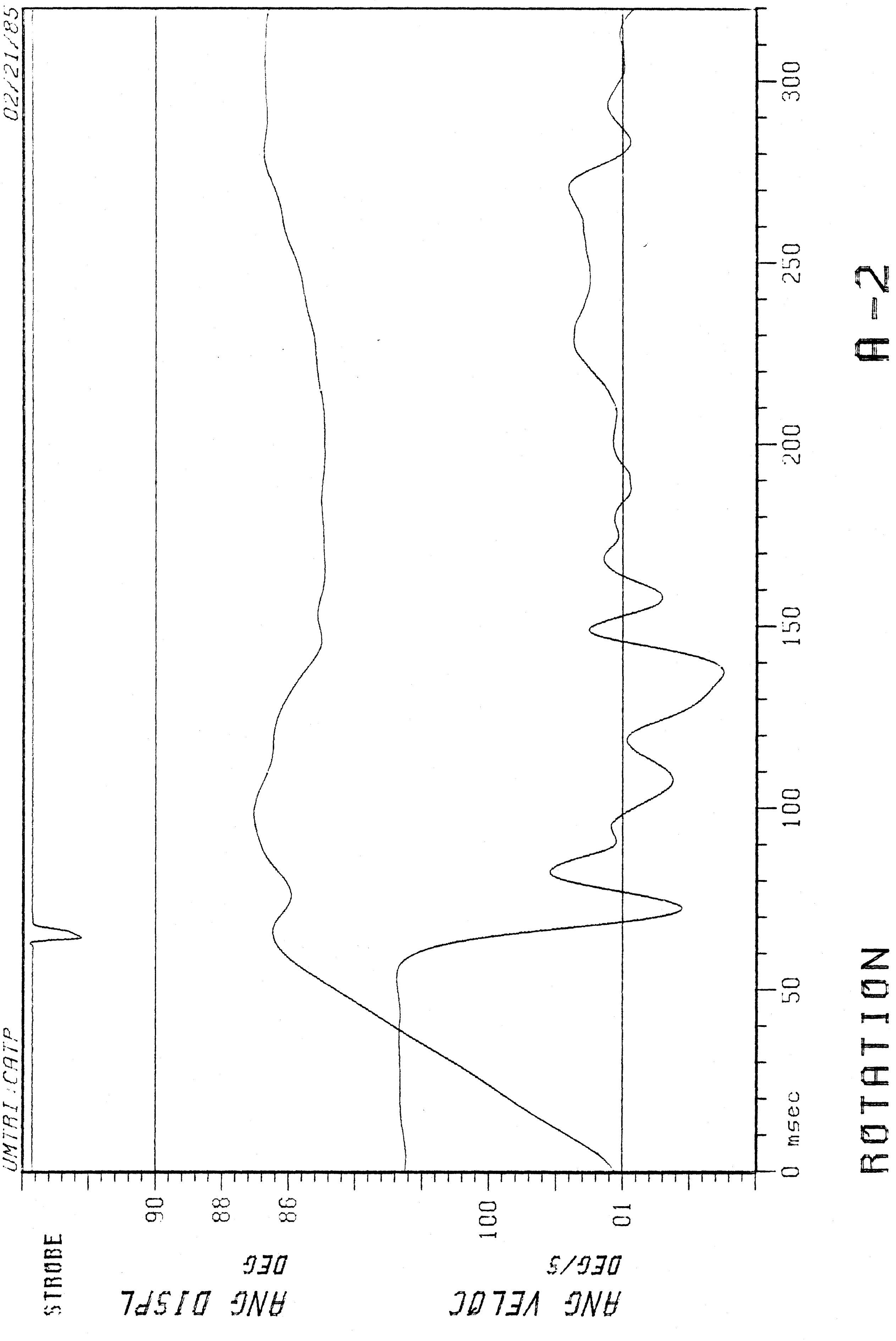
UMTRI:CATP
02/21/85
STROBE
ANG DISPL
DEG
90
88
86
ANG VELOC
DEG/S
50
0
0 msec
50
100
150
200
250
300
ROTATION
B-1

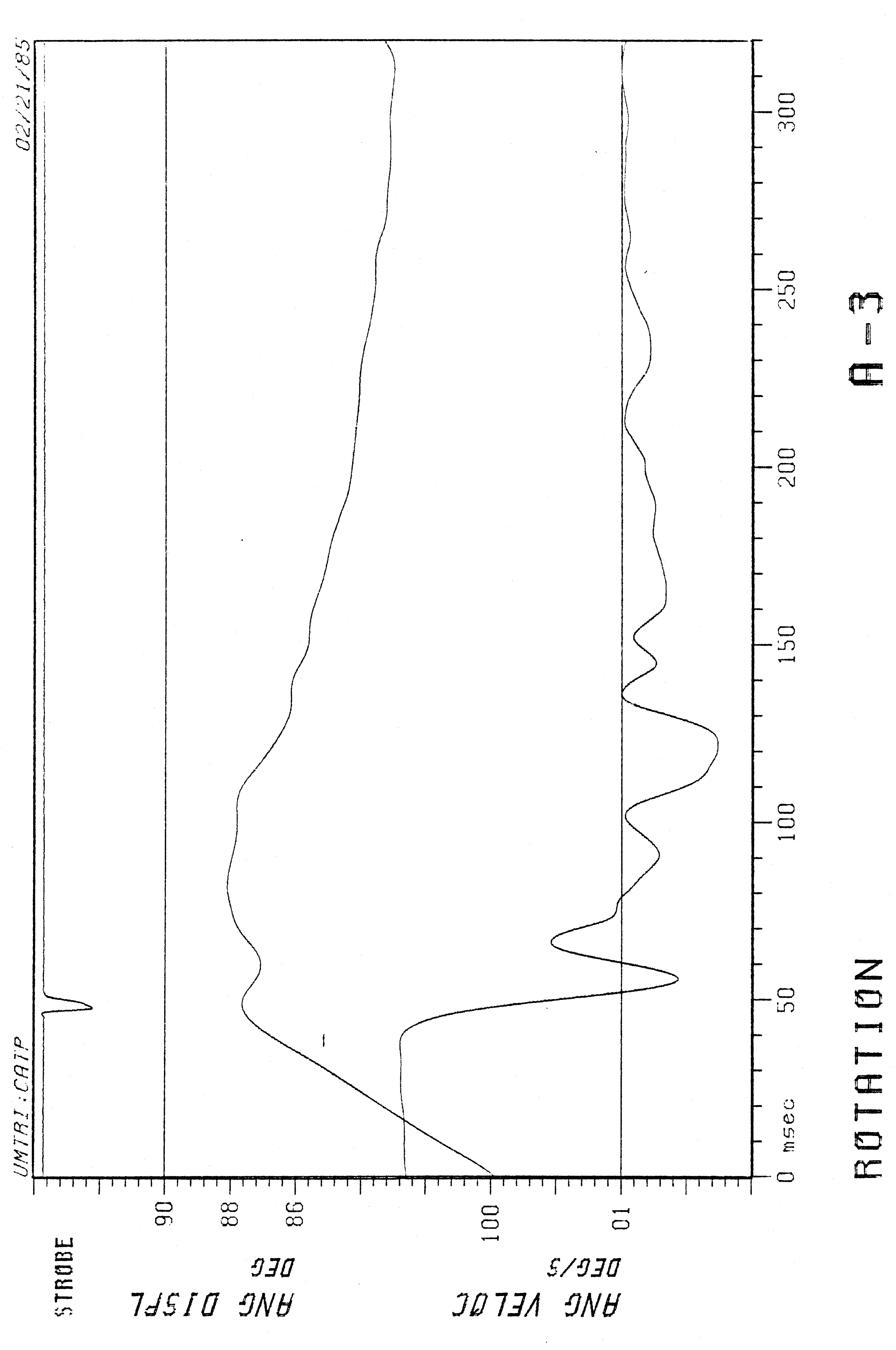

UMTRI:CATP
02/21/85
STROBE
ANG DISPL
DEG
90
88
86
ANG VELOC
DEG/S
50
0
0 msec
50
100
150
200
250
300
ROTATION
B-2

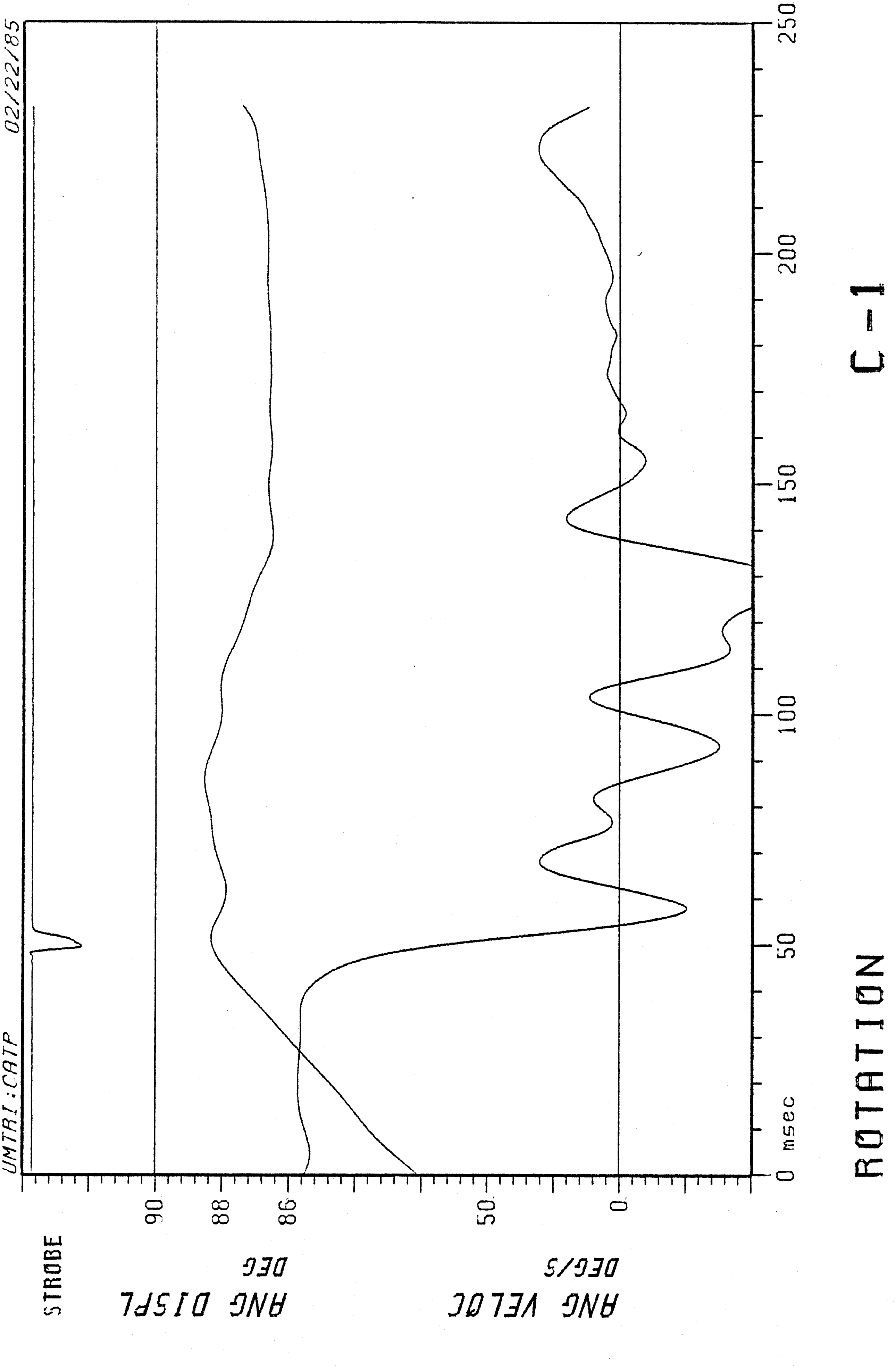


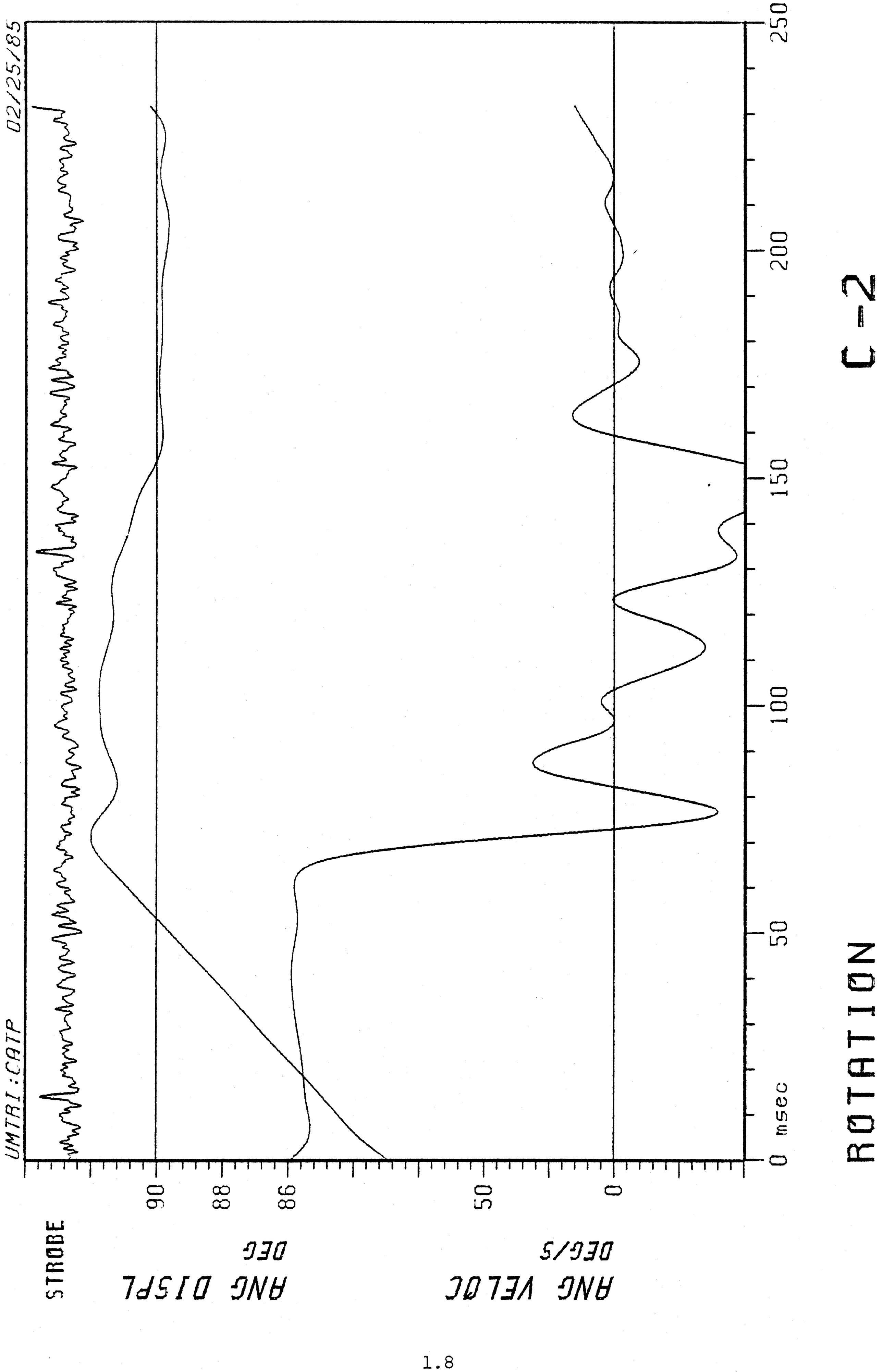
UMTRI:CATP
02/22/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
50
0
0 msec
50
100
150
200
250
300
ROTATION
B-3

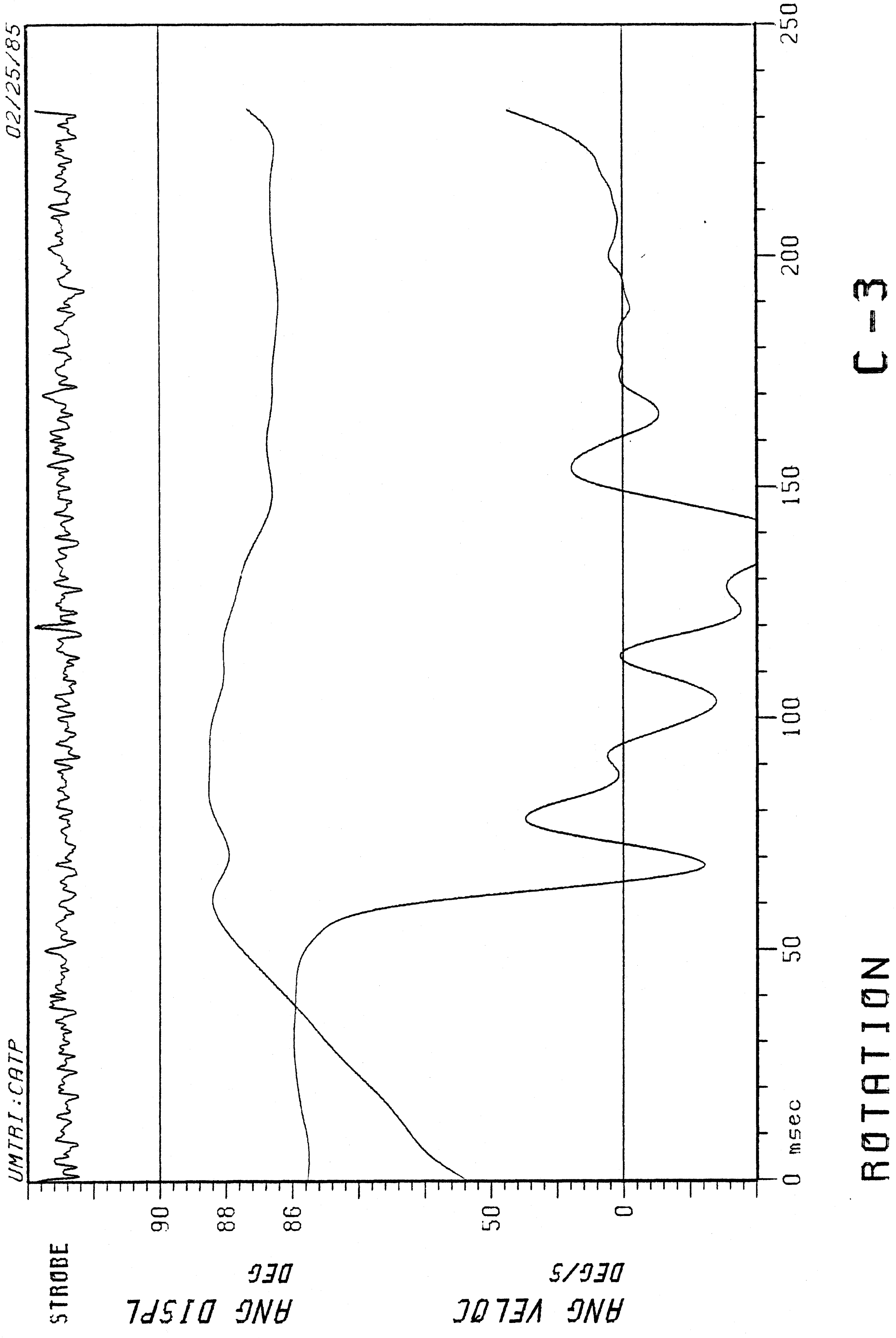

UMTRI:CATP
02/21/85
STROBE
ANG DISPL
DEG
90
88
86
ANG VELOC
DEG/S
100
01
0 msec
50
100
150
200
250
300
ROTATION
A-1


UMTRI:CATP
02/21/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
0 msec
50
100
150
200
250
300
ROTATION
A-2

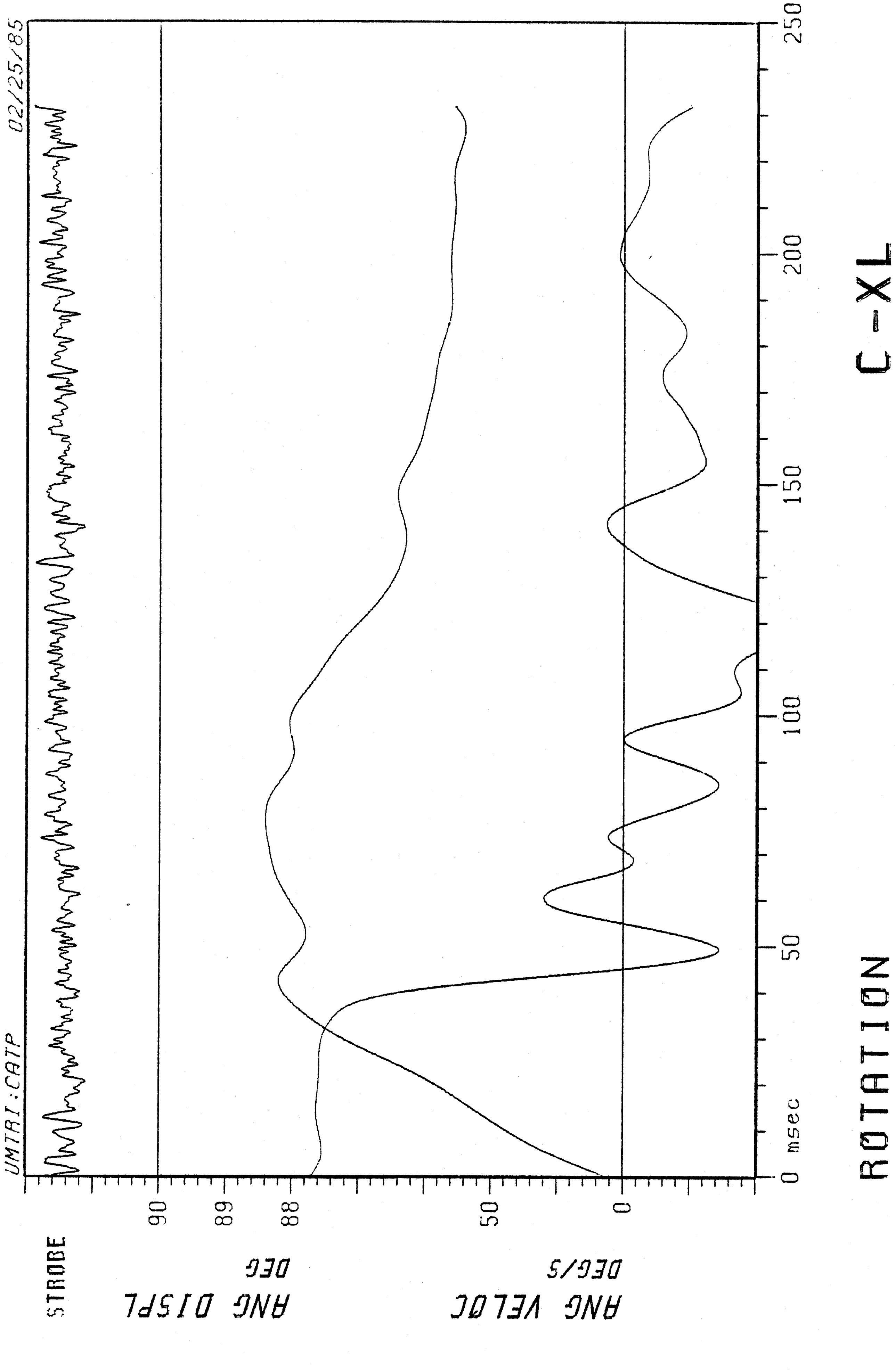

UMTRI:CATP
02/21/85
A-3
ROTATION
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
100
01
0 msec
50
100
150
200
250
300

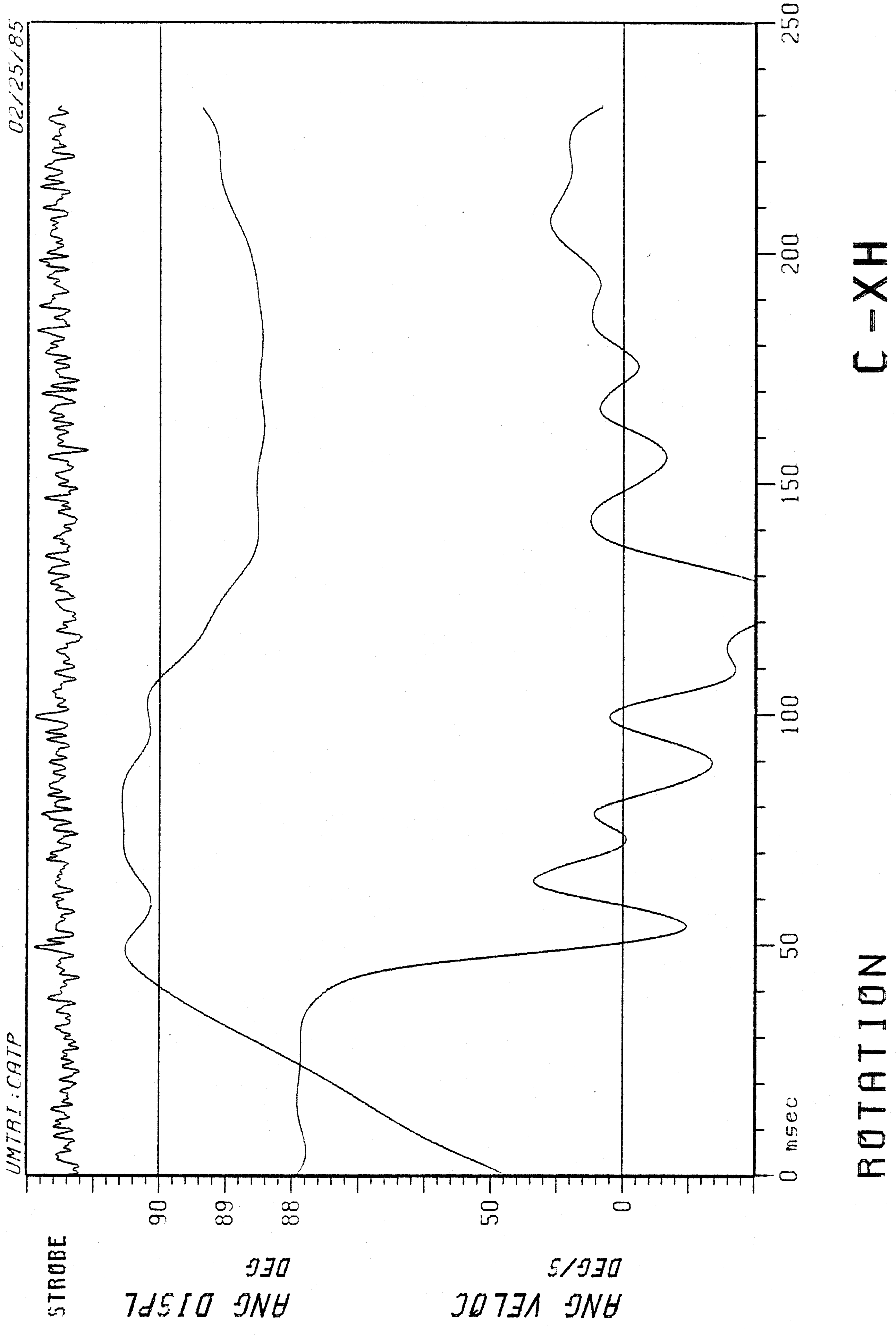

UMTRI:CATP
02/22/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
50
0
0 msec
50
100
150
200
250
ROTATION
C-1


UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
50
0
0 msec
50
100
150
200
250
ROTATION
C-2

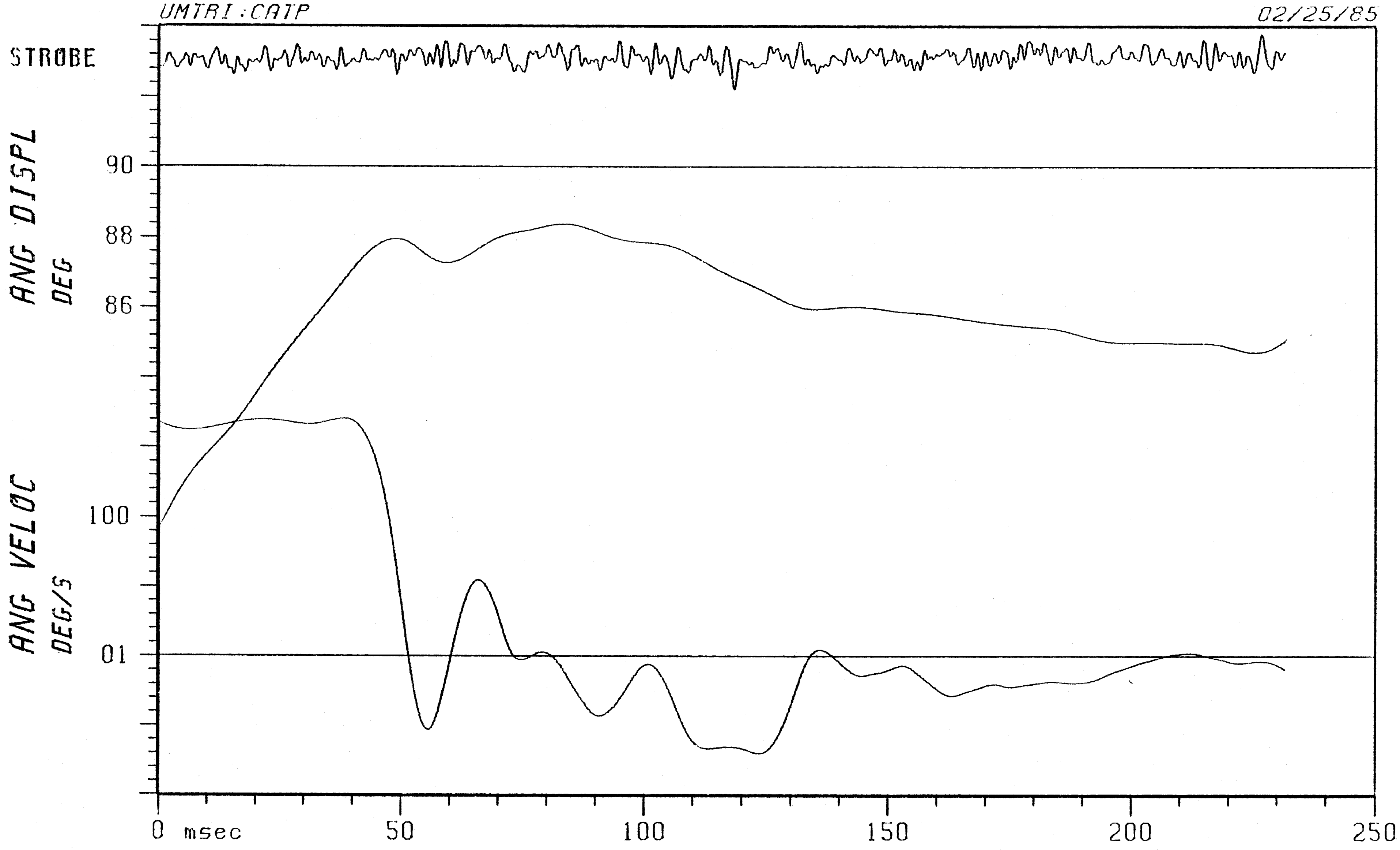


UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
50
0
0 msec
50
100
150
200
250
ROTATION
C-3


UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
89
88
50
0
0 msec
50
100
150
200
250
ROTATION
C-XL

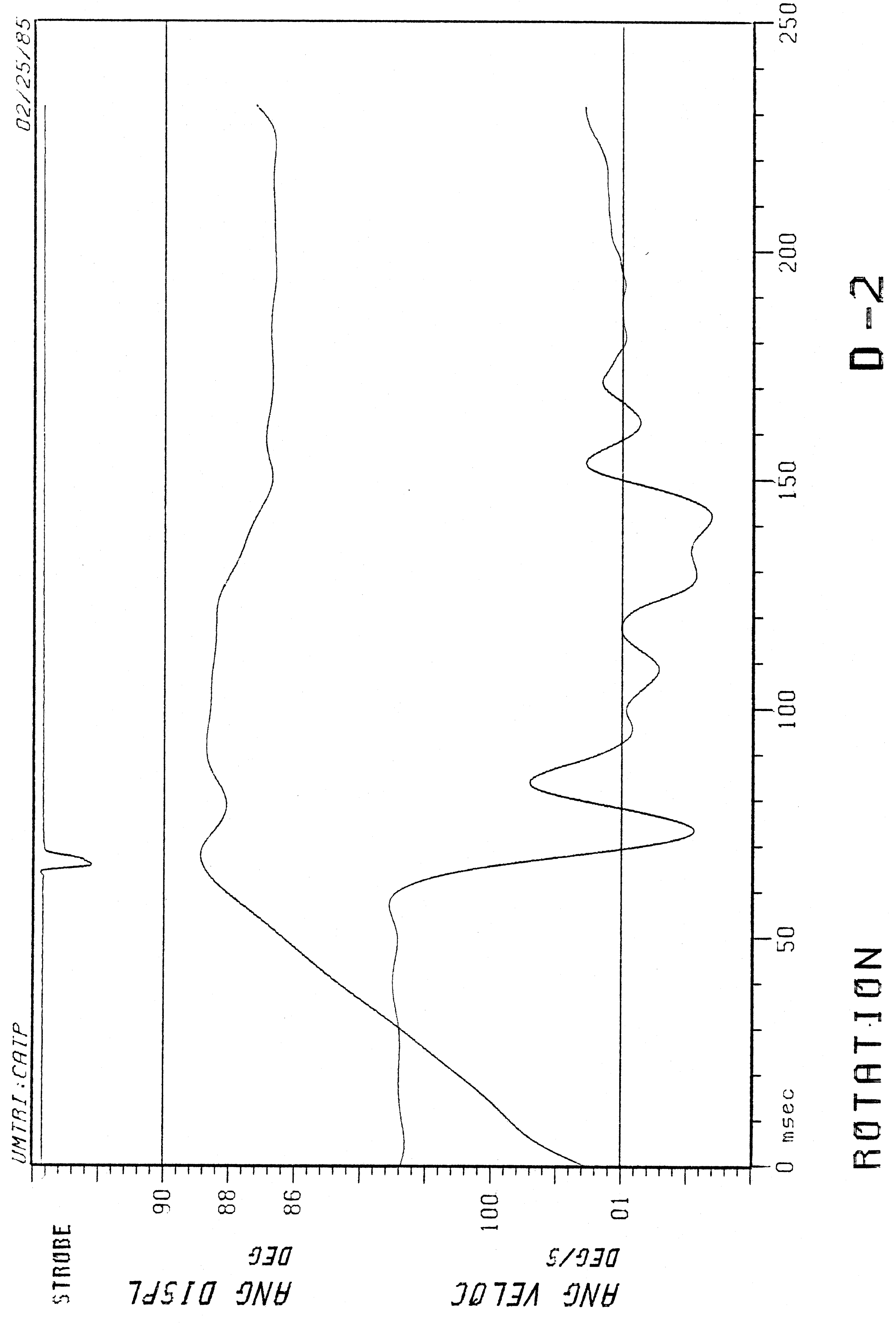


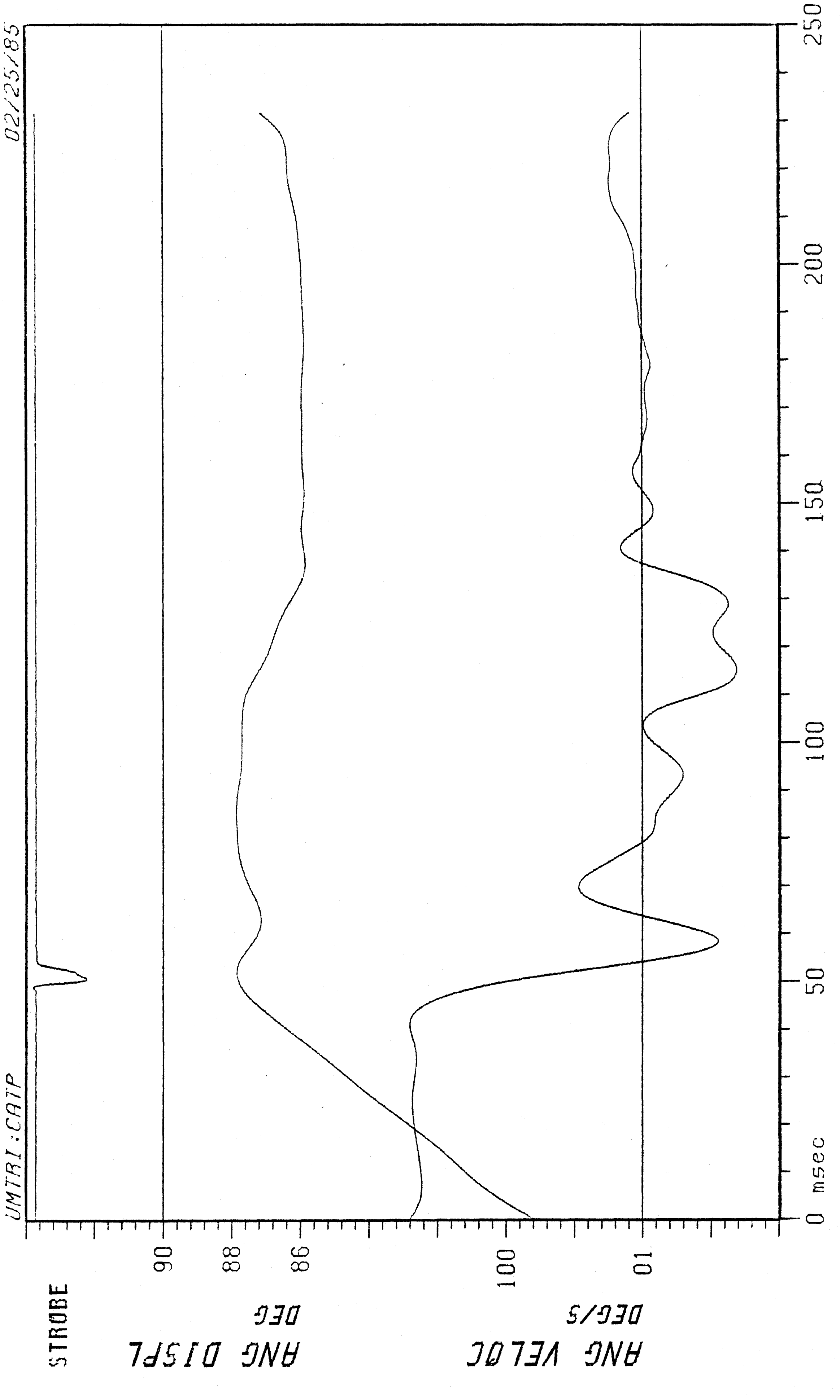
UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
89
88
50
0
0 msec
50
100
150
200
250
ROTATION
C-XH



UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
90
88
86
ANG VELOC
DEG/S
100
01
0 msec
50
100
150
200
250

ROTATION D-1

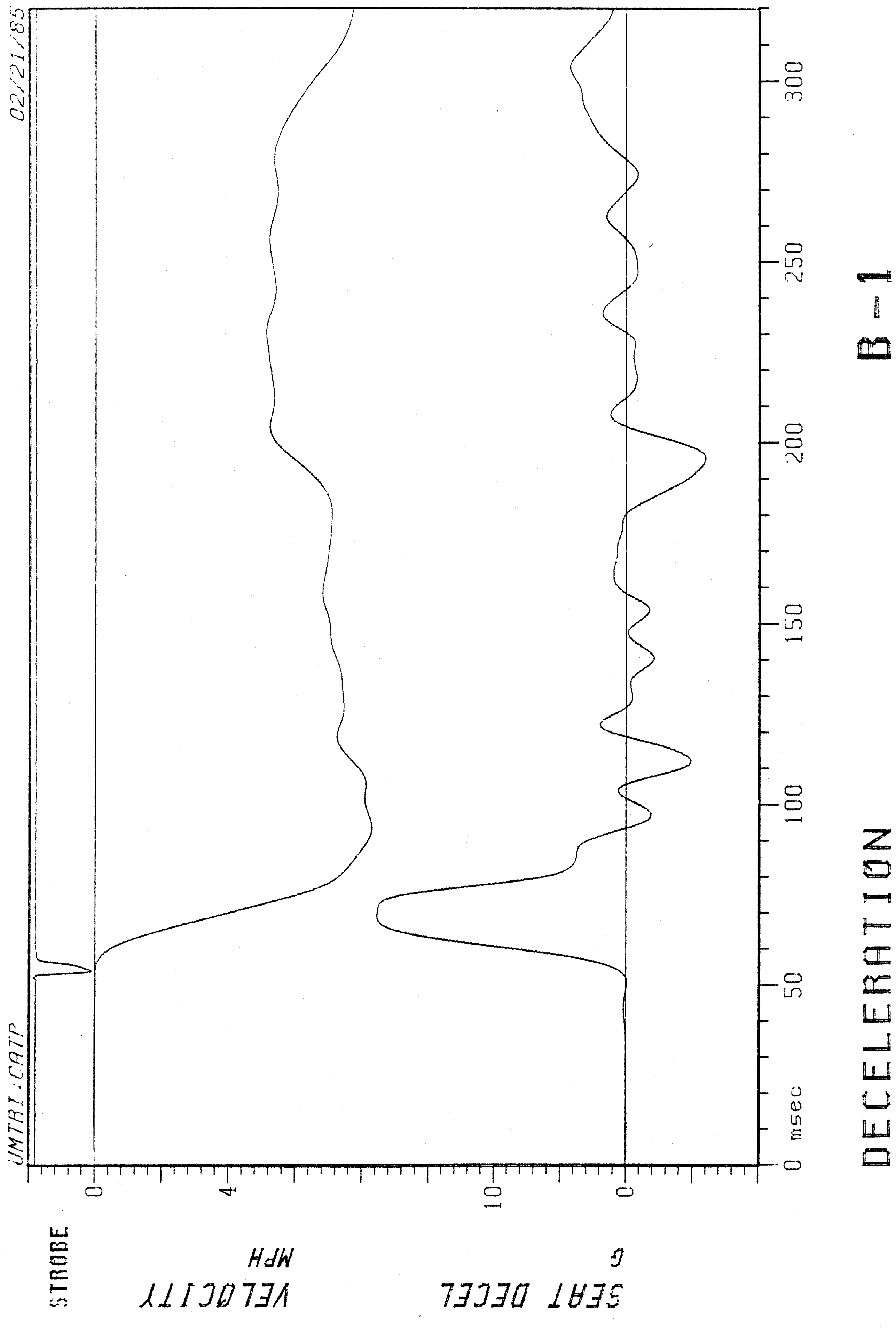

UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELØC
DEG/S
90
88
86
100
01
0 msec
50
100
150
200
250
D-2
RØTATIØN

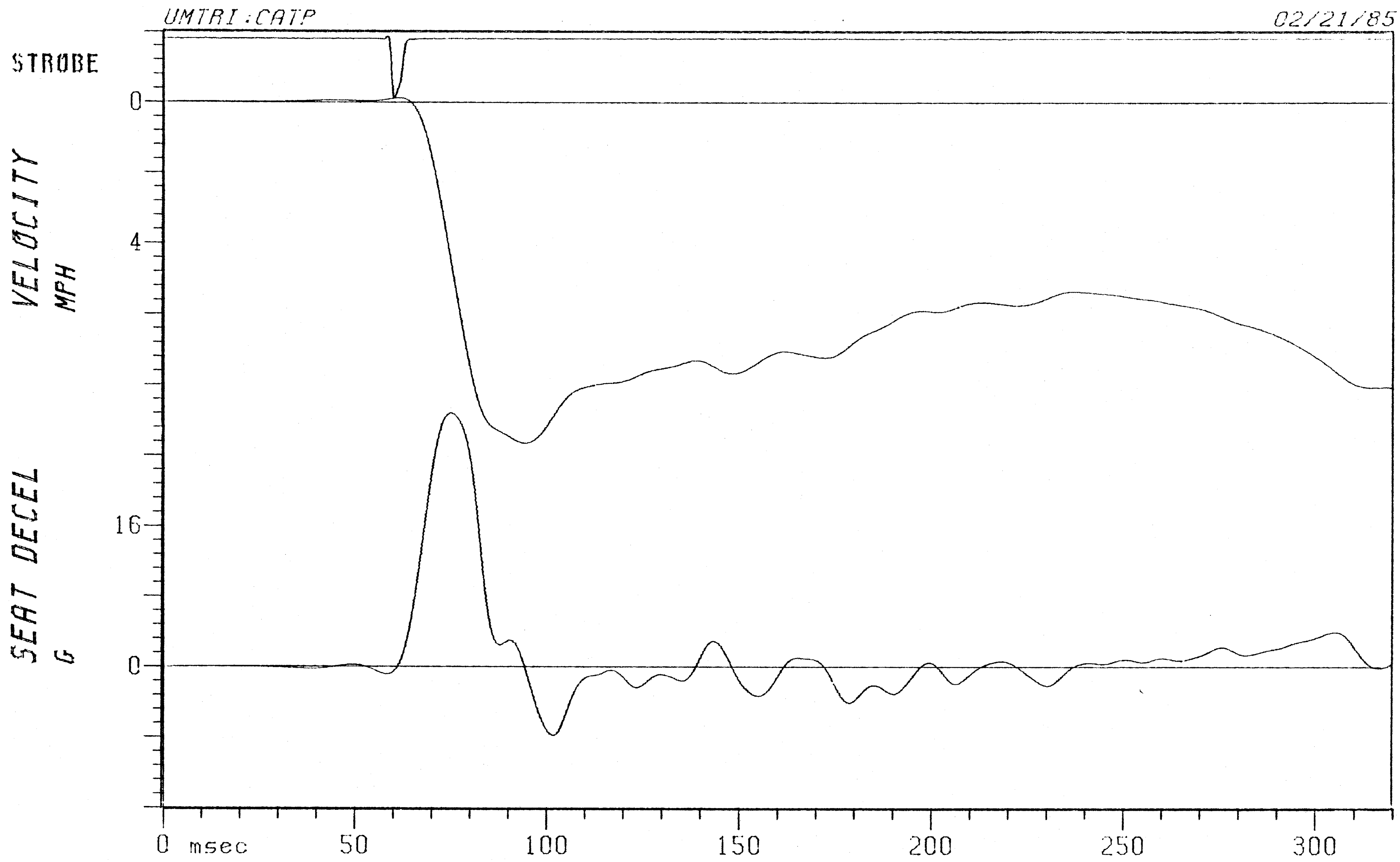

UMTRI:CATP
02/25/85
STROBE
ANG DISPL
DEG
ANG VELOC
DEG/S
90
88
86
100
01
0 msec
50
100
150
200
250

ROTATION D-3

SECTION 2

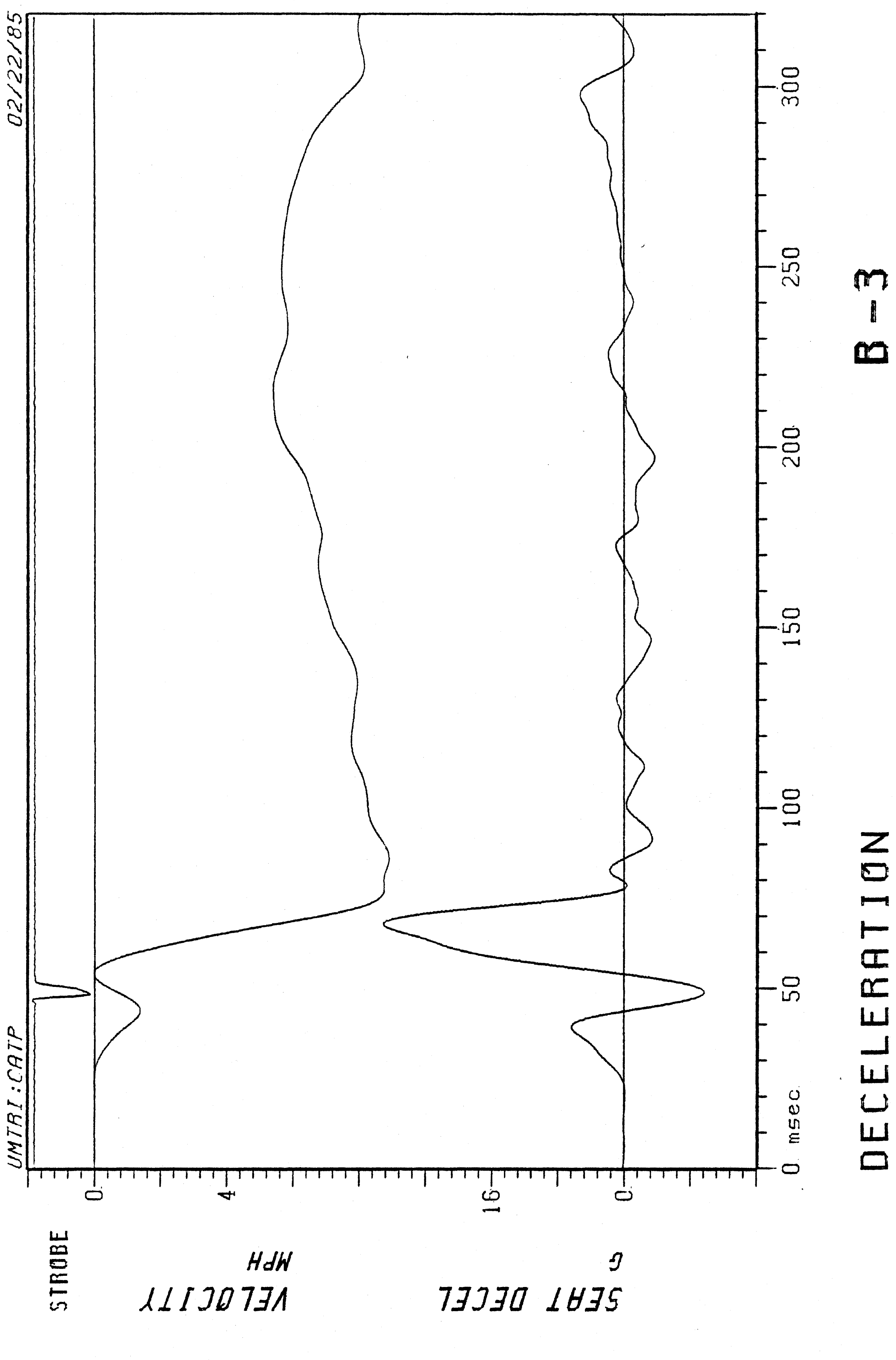
Seat Deceleration


UMTRI:CATP
02/21/85
STROBE
VELOCITY
MPH
SEAT DECEL
G
0
4
10
0
0 msec
50
100
150
200
250
300
DECELERATION
B-1

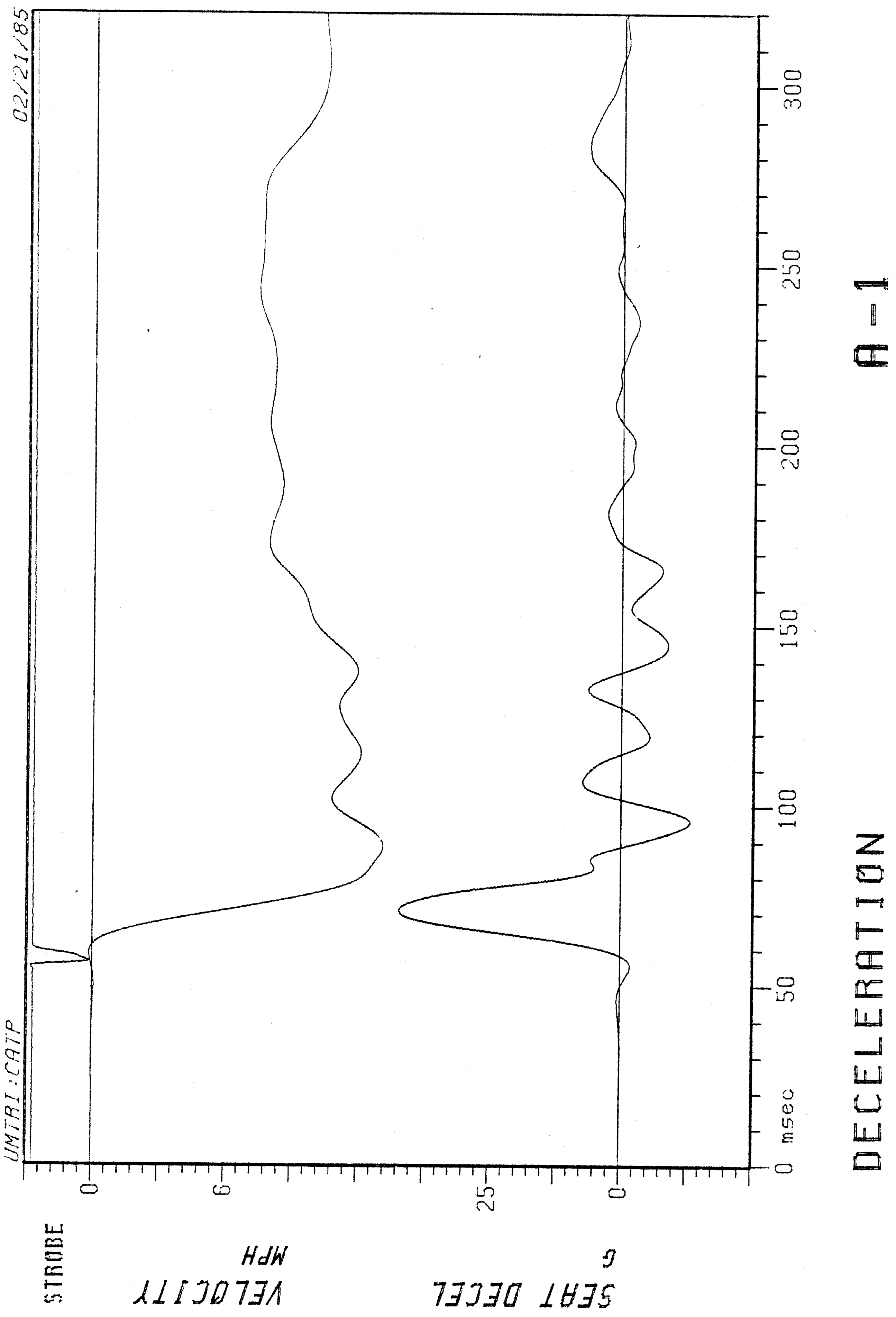


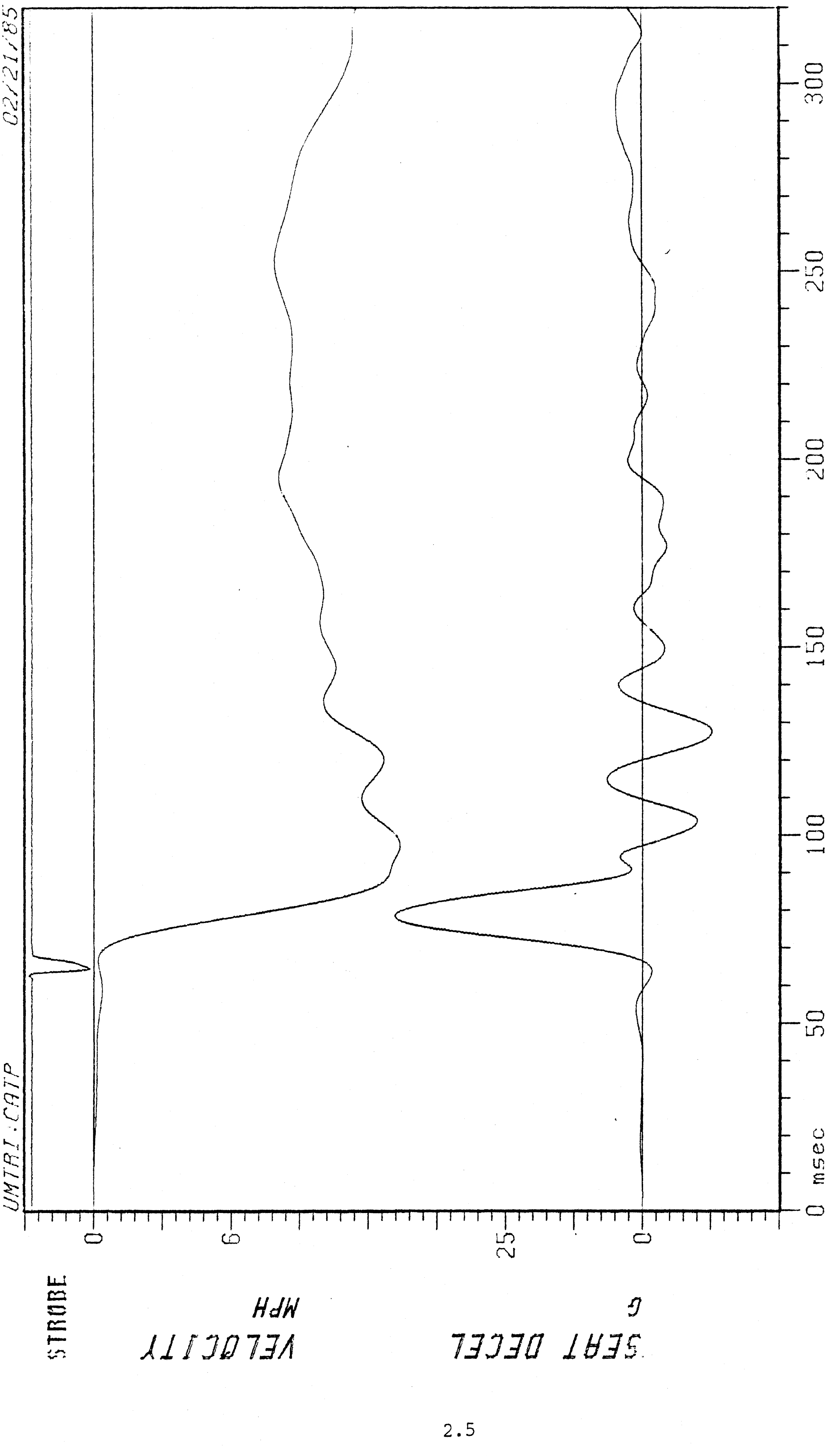
DECELERATIØN

B-2



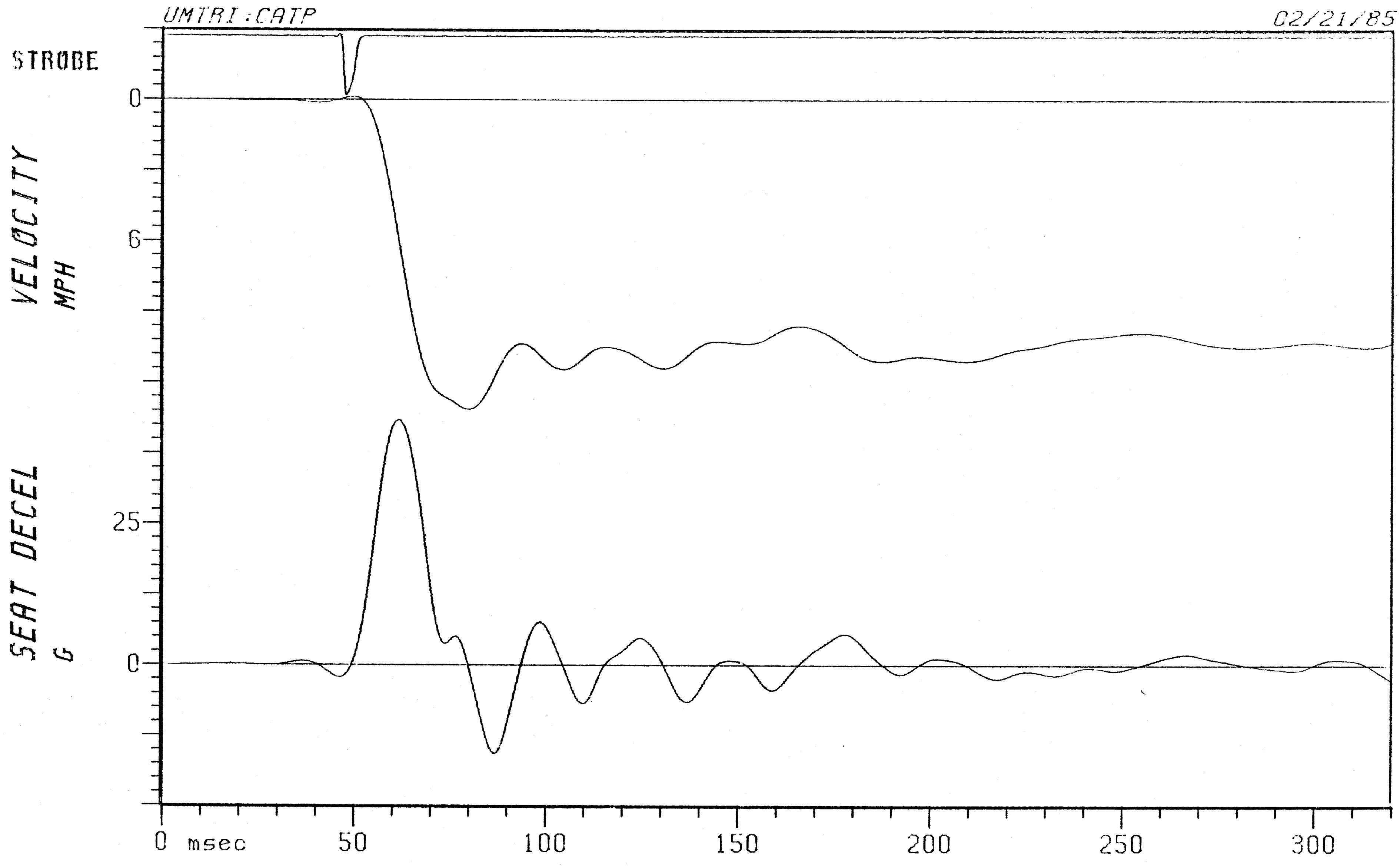
UMTRI:CATP
02/22/85
STROBE
VELOCITY
MPH
SEAT DECEL
G
0
4
16
0
0 msec
50
100
150
200
250
300
DECELERATION
B-3


DECELERATION
A-1
UMTRI:CATP
02/21/85
0 msec
50
100
150
200
250
300
STROBE
VELOCITY
MPH
0
6
SEAT DECEL
G
25
0



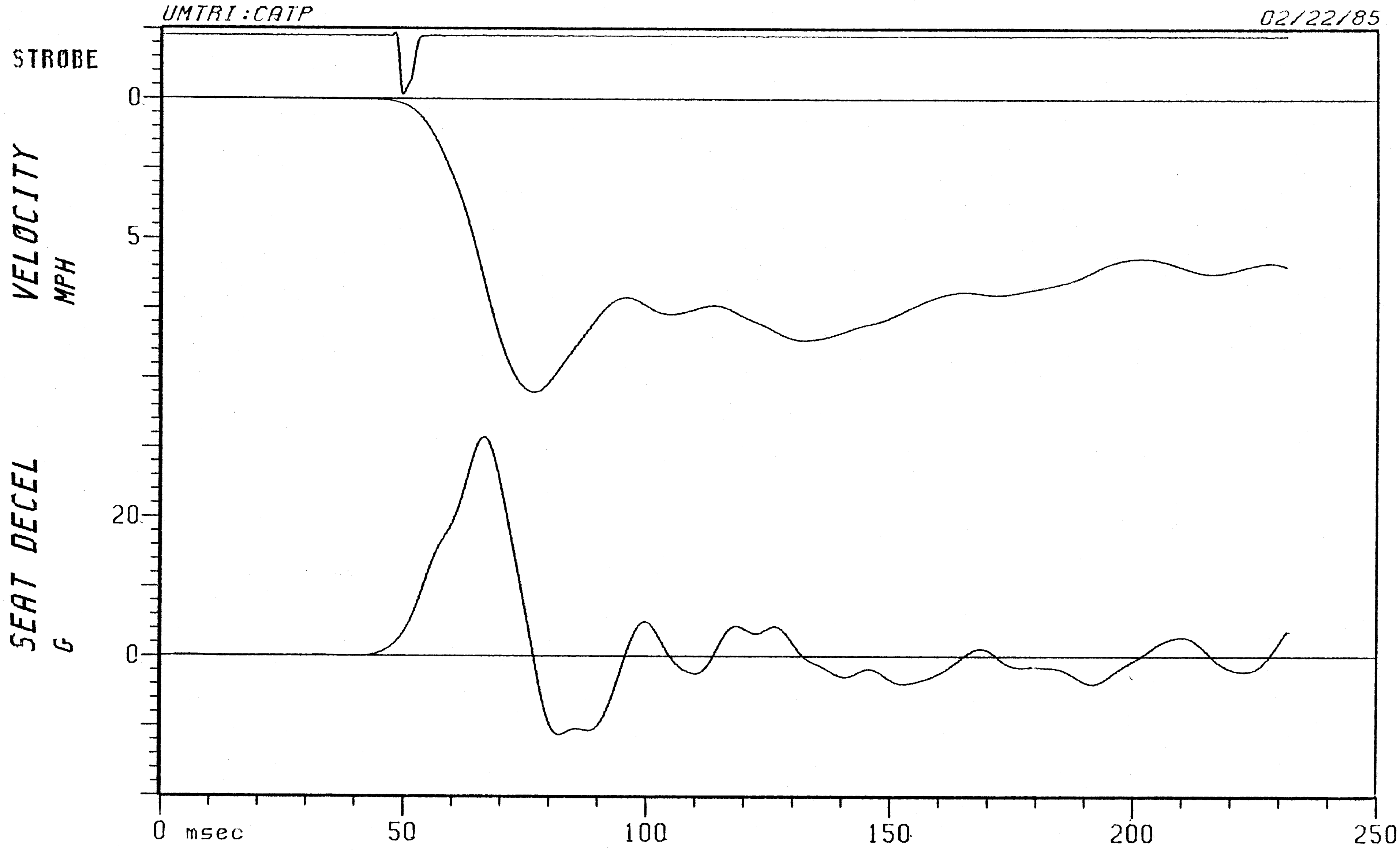
A-2

DECELERATION



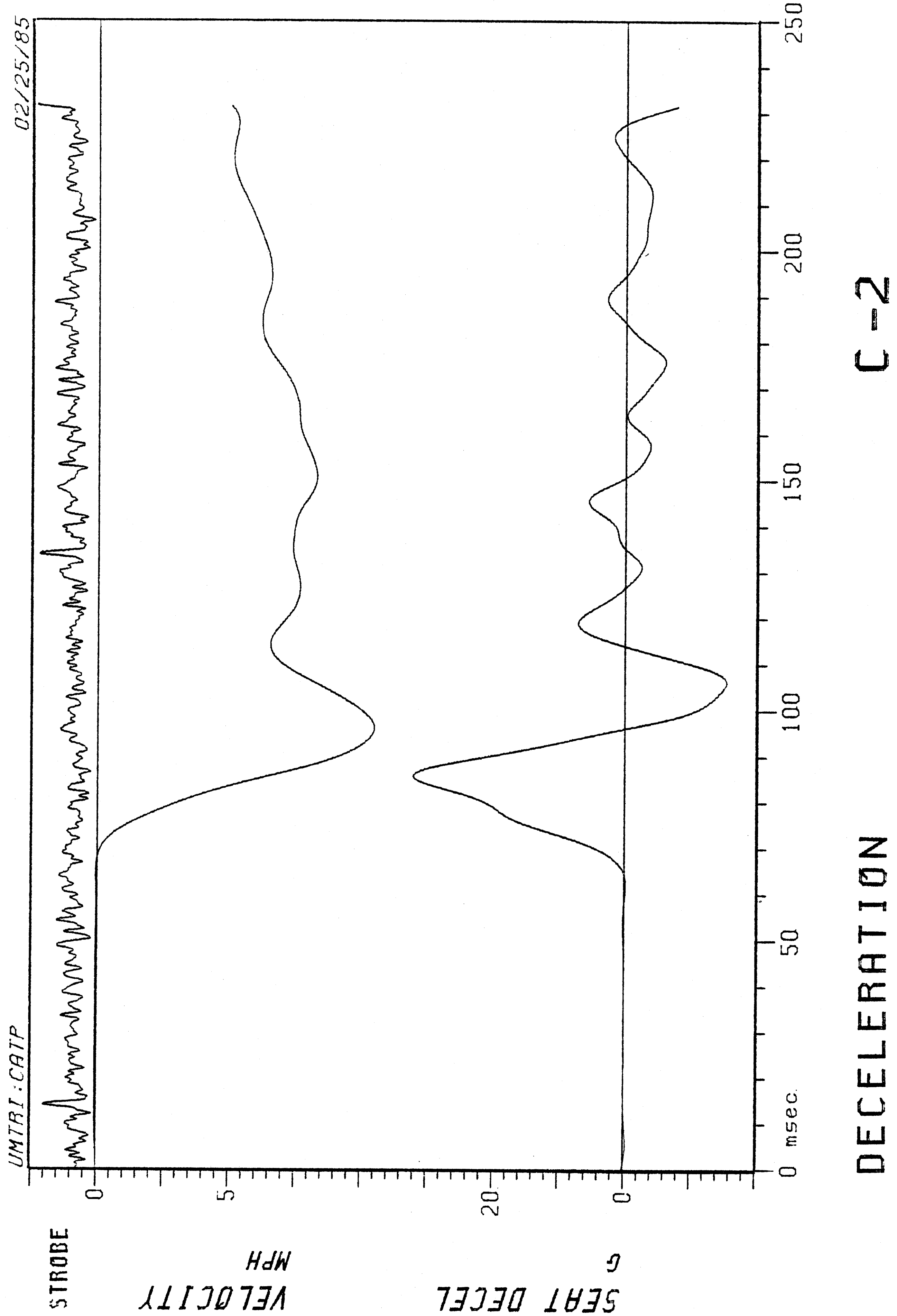
DECELERATION

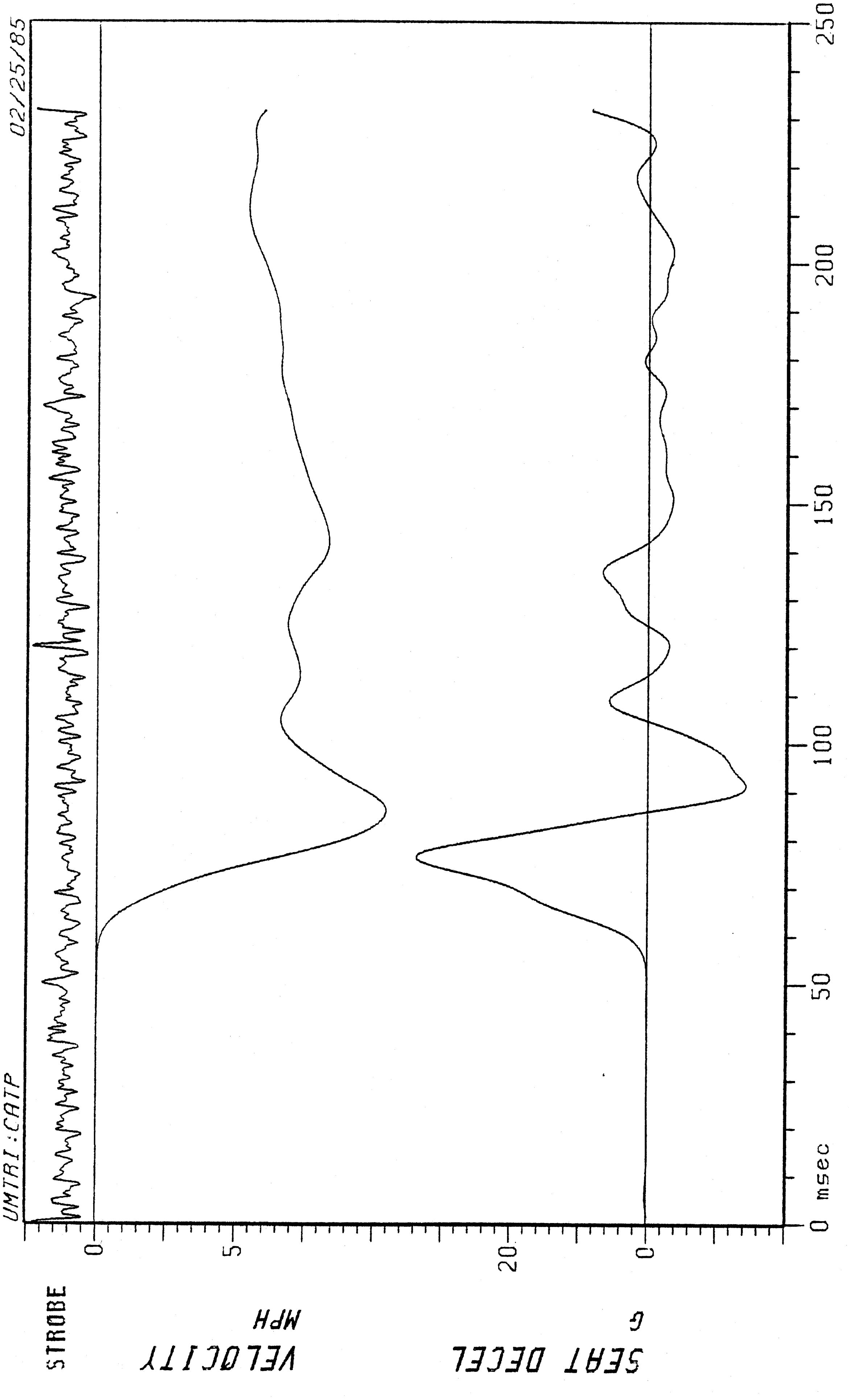
A-3



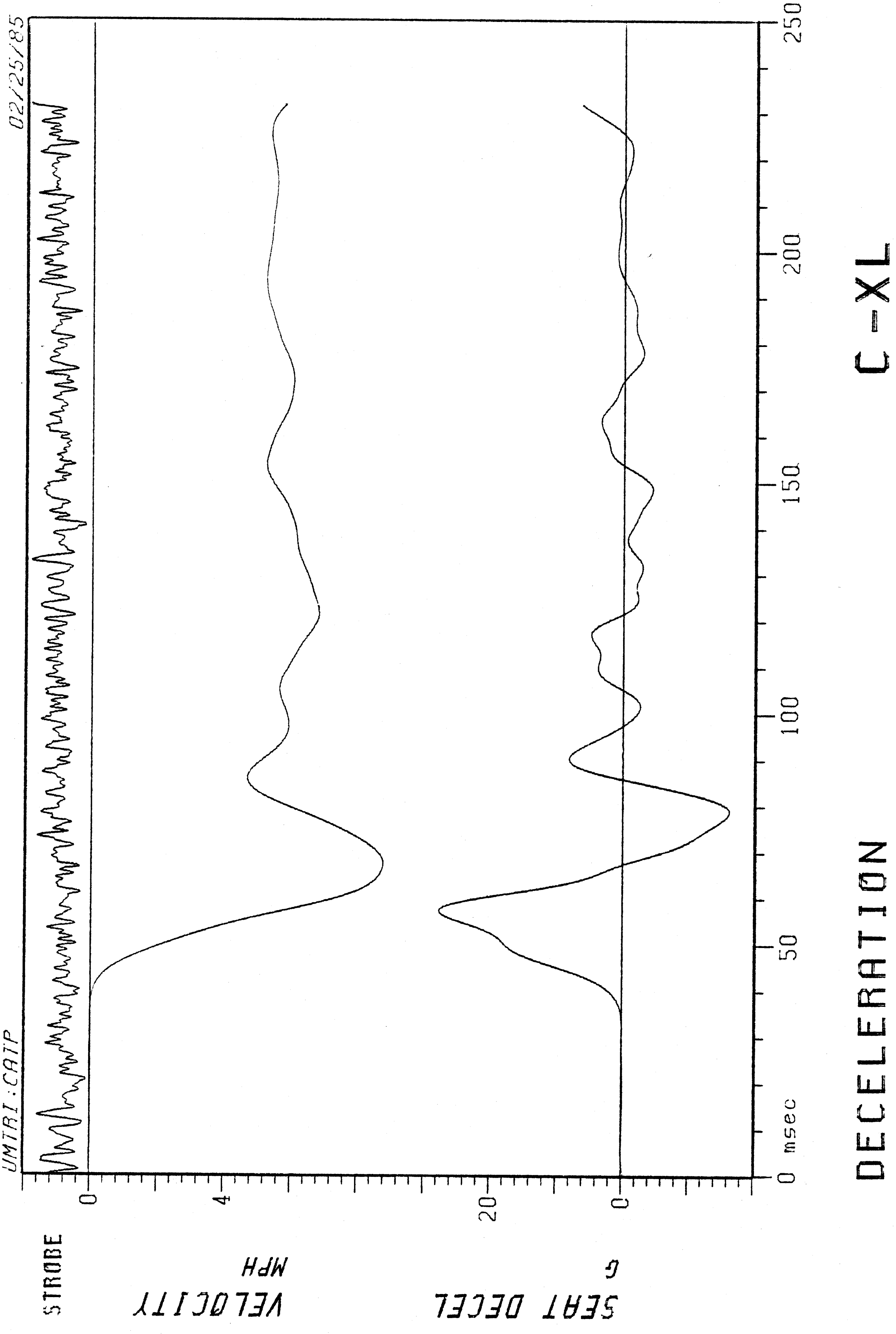
DECELERATION

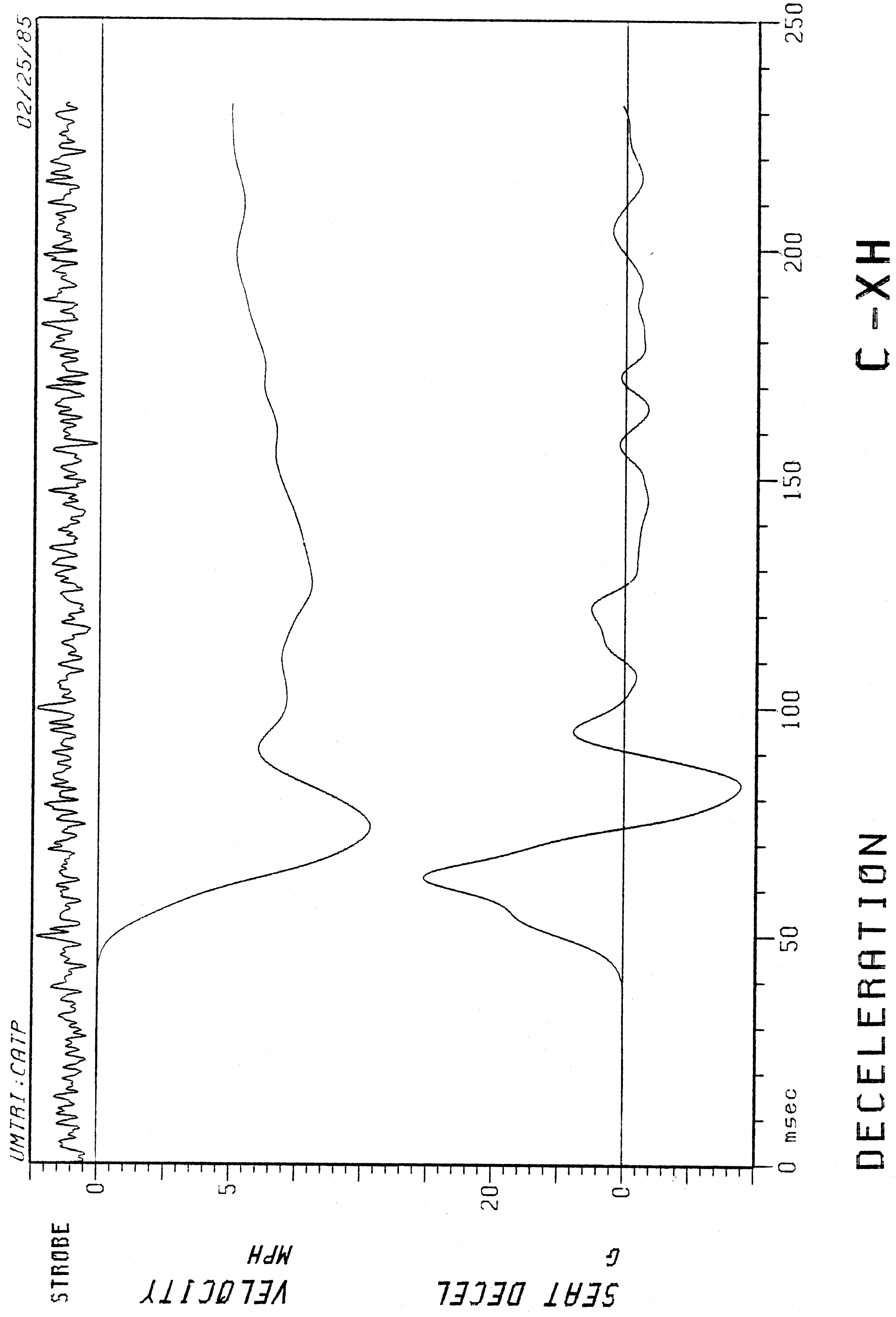
C-1


UMTRI:CATP
02/25/85
STROBE
VELOCITY
MPH
SEAT DECEL
G
0
5
20
0
0 msec.
50
100
150
200
250
DECELERATION
C-2

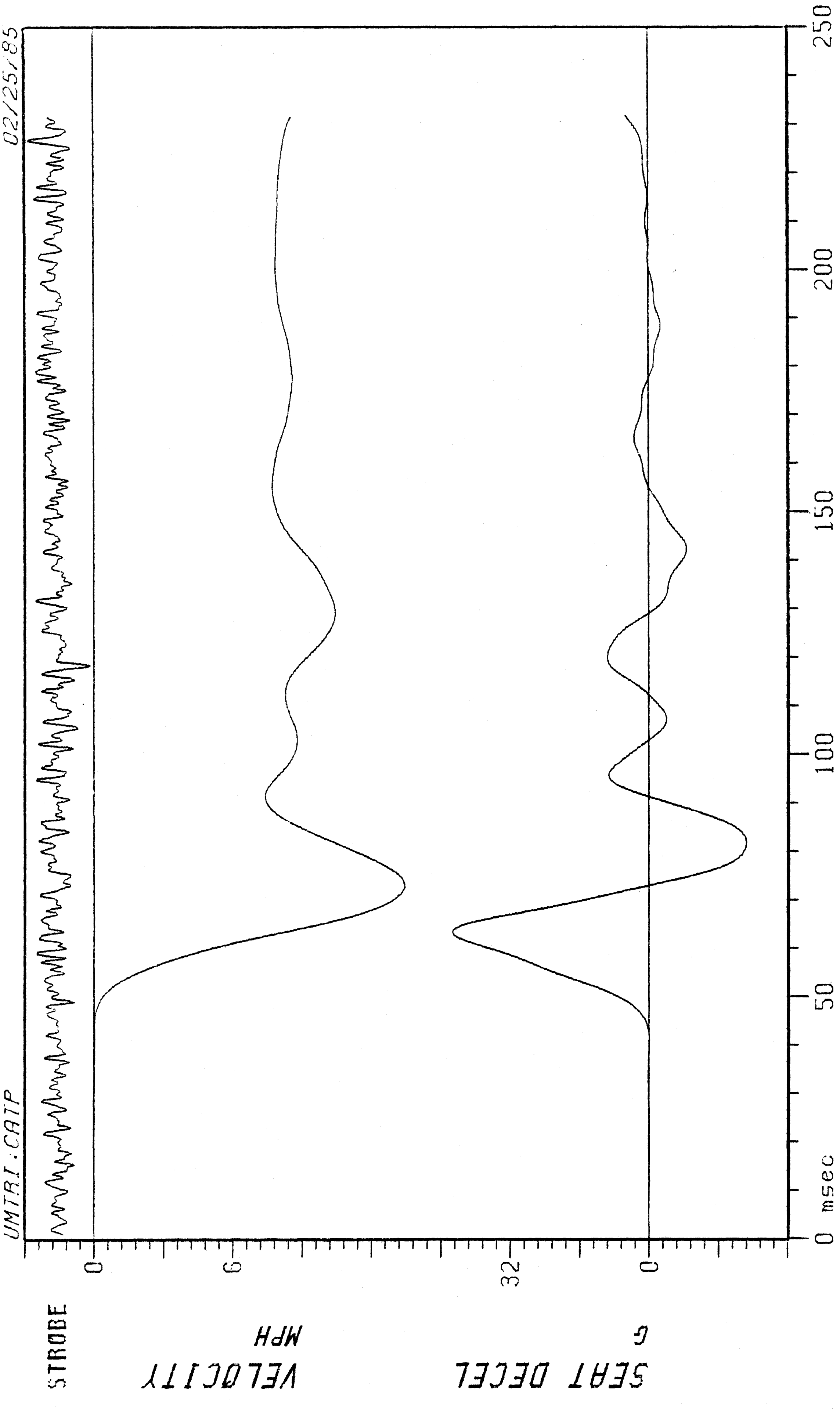


DECELERATION C-3


UMTRI:CATP
02/25/85
STROBE
VELOCITY
MPH
SEAT DECEL
G
0
4
20
0
0 msec
50
100
150
200
250
DECELERATION
C-XL

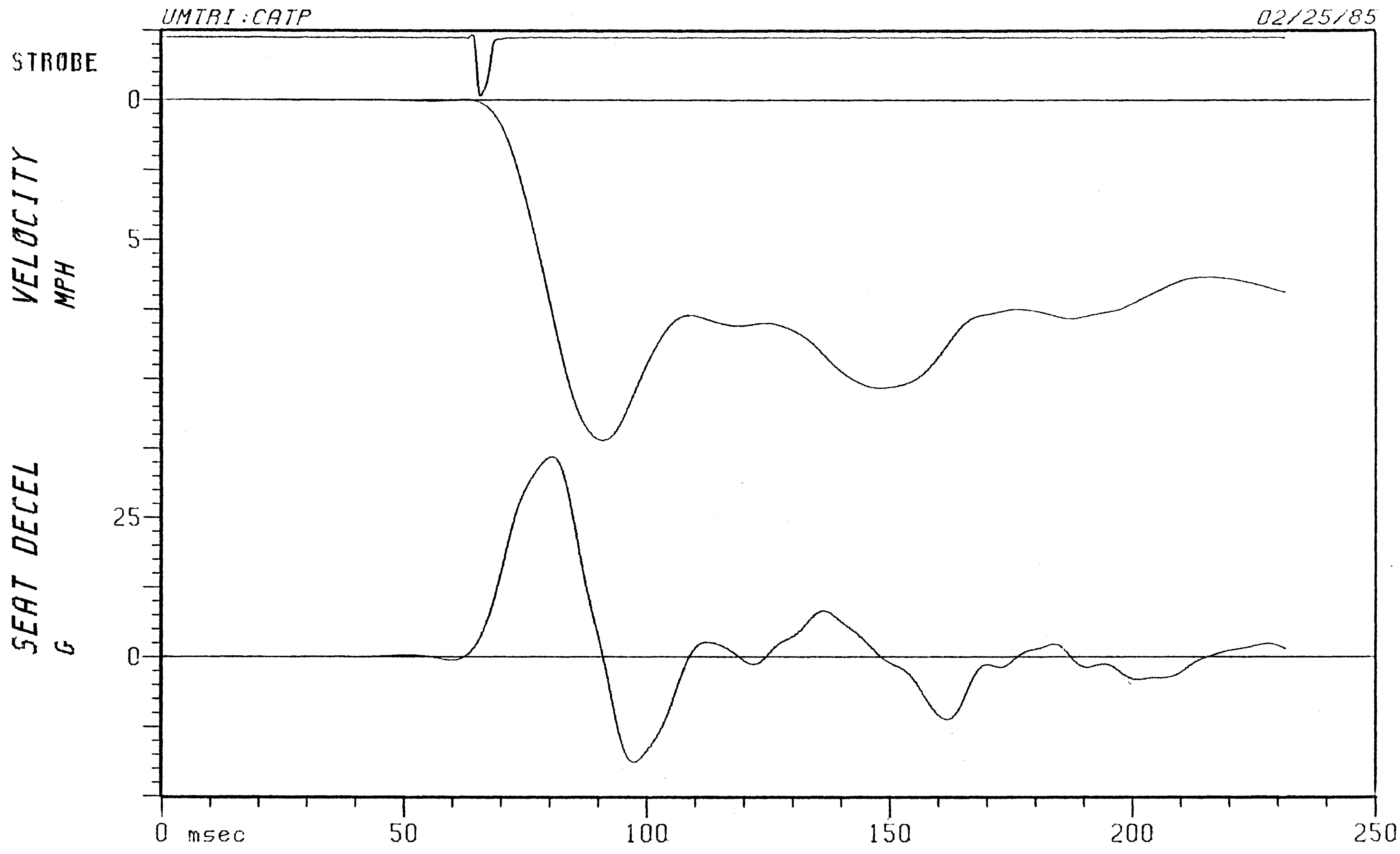


UMTRI:CATP
02/25/85
DECELERATION
C-XH
0 msec
50
100
150
200
250
STROBE
VELOCITY
MPH
0
5
SEAT DECEL
G
20
0



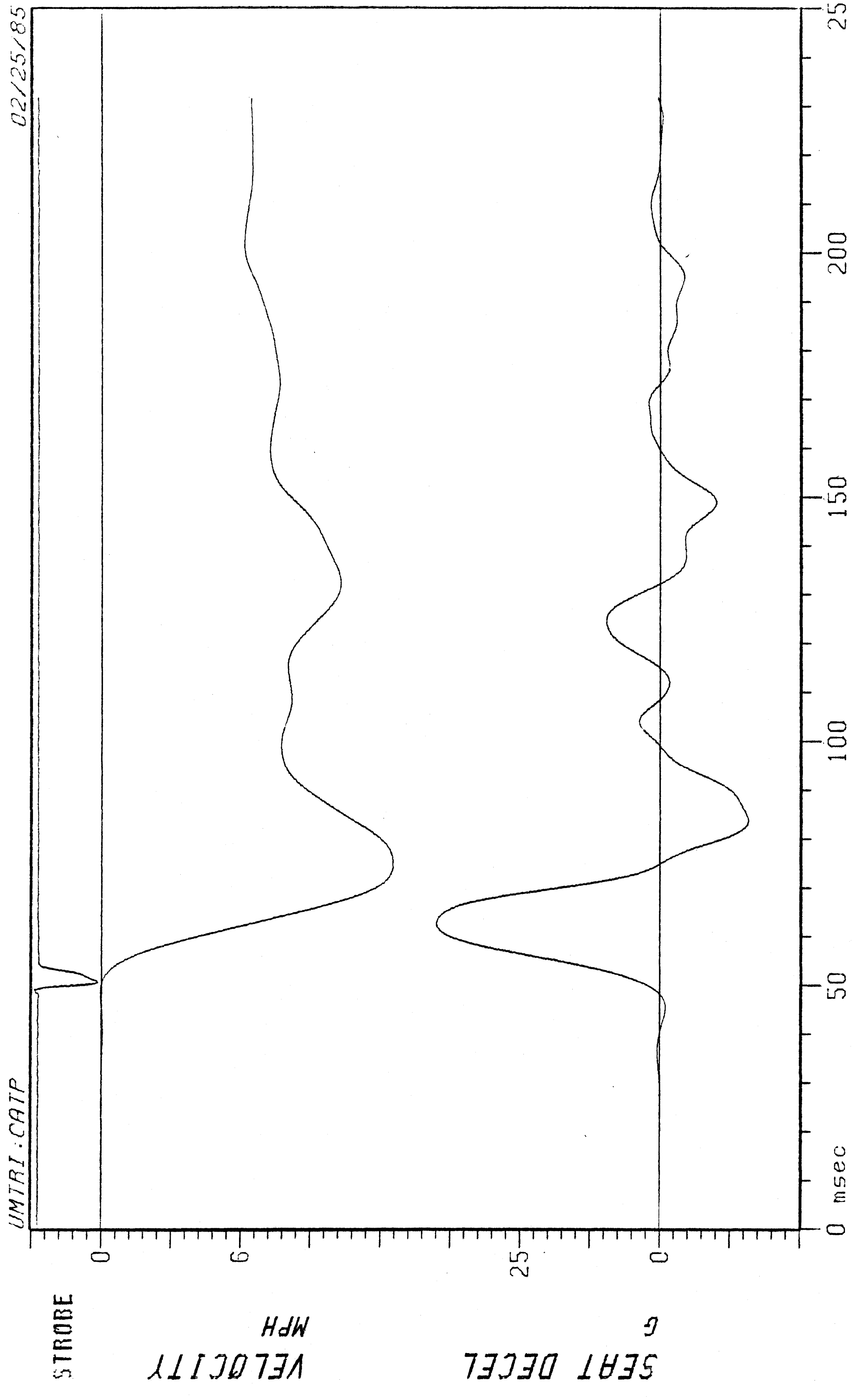
DECELERATION

D-1



DECELERATIØN

D-2

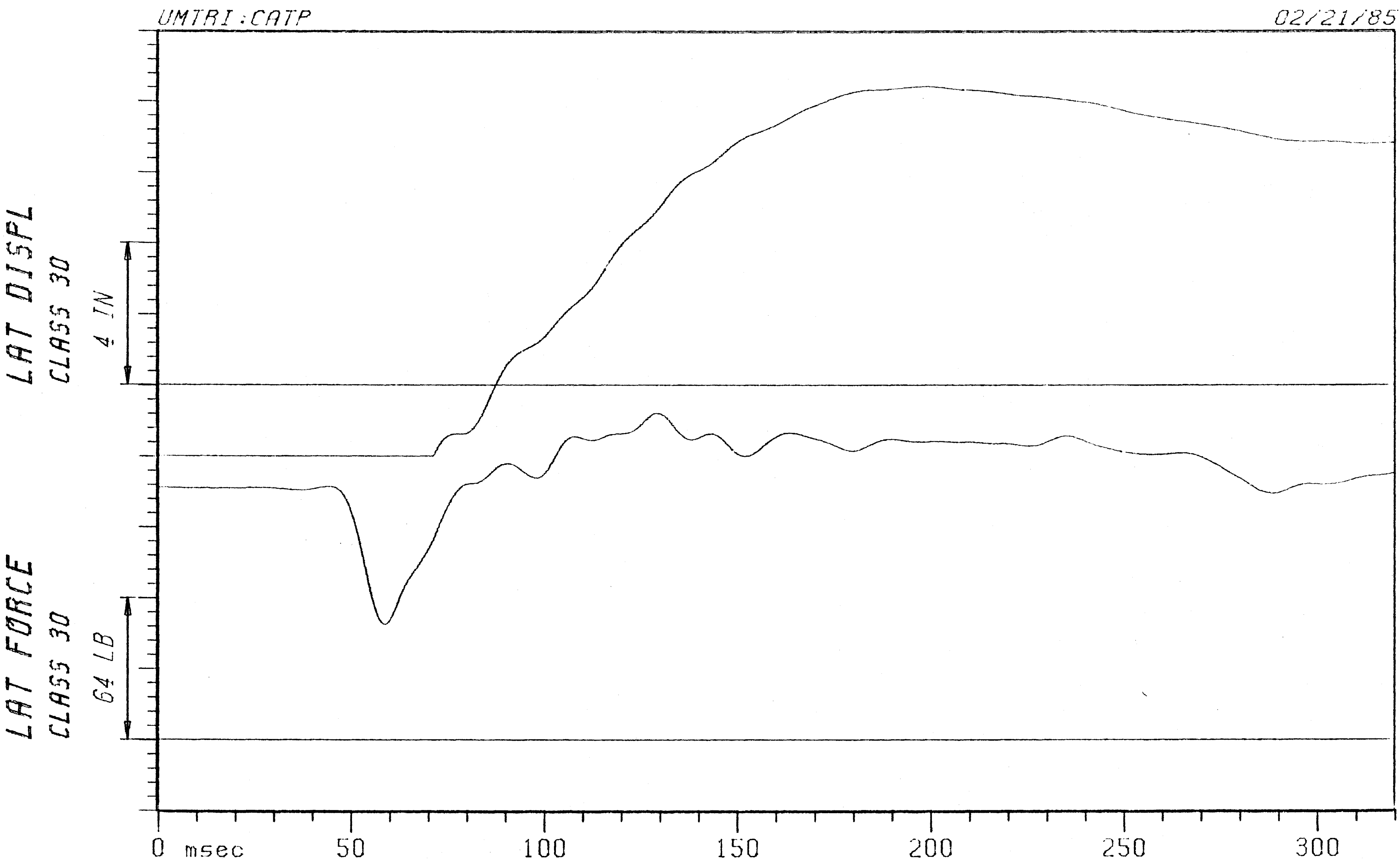


DECELERATION

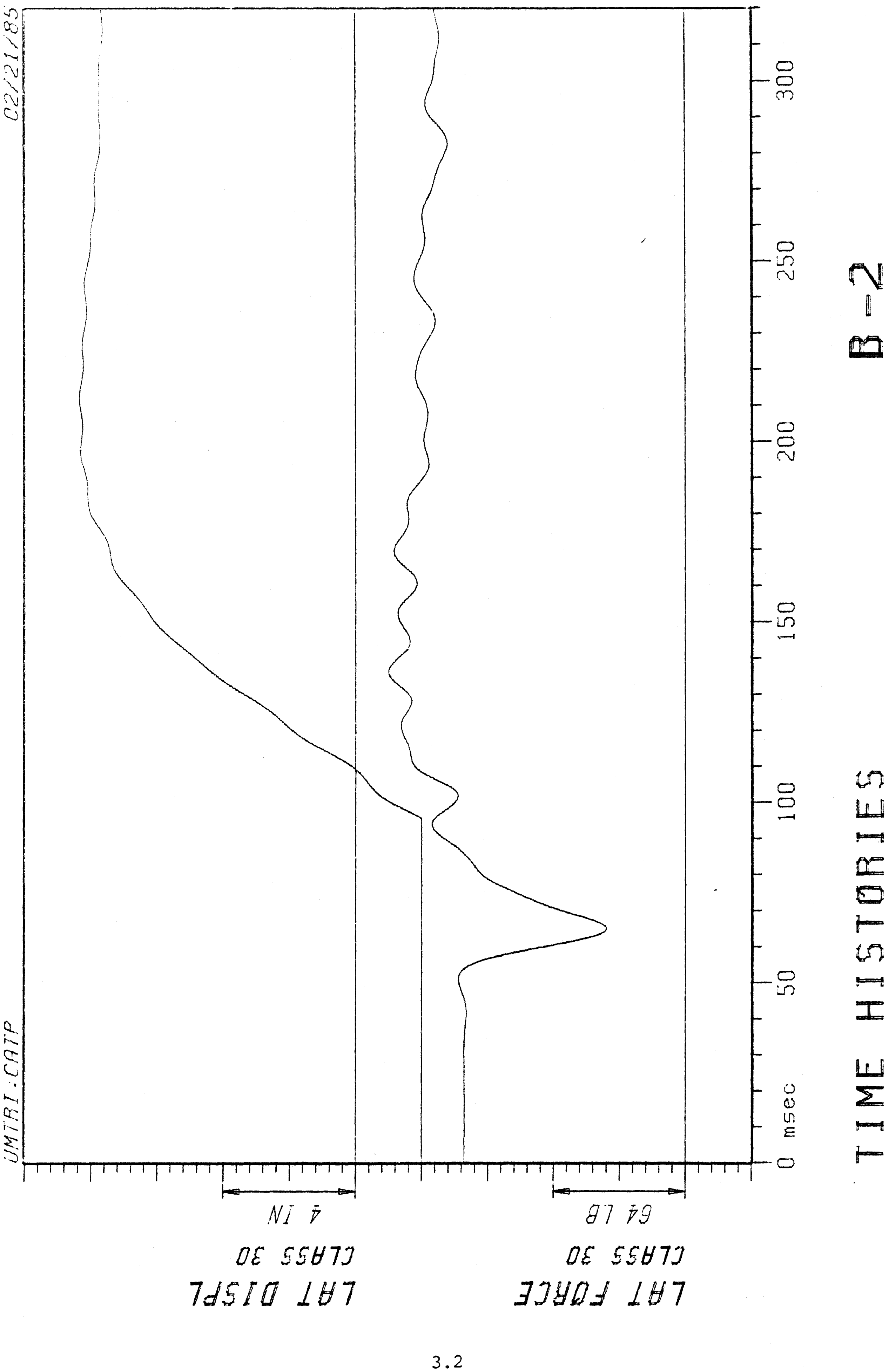
D-3

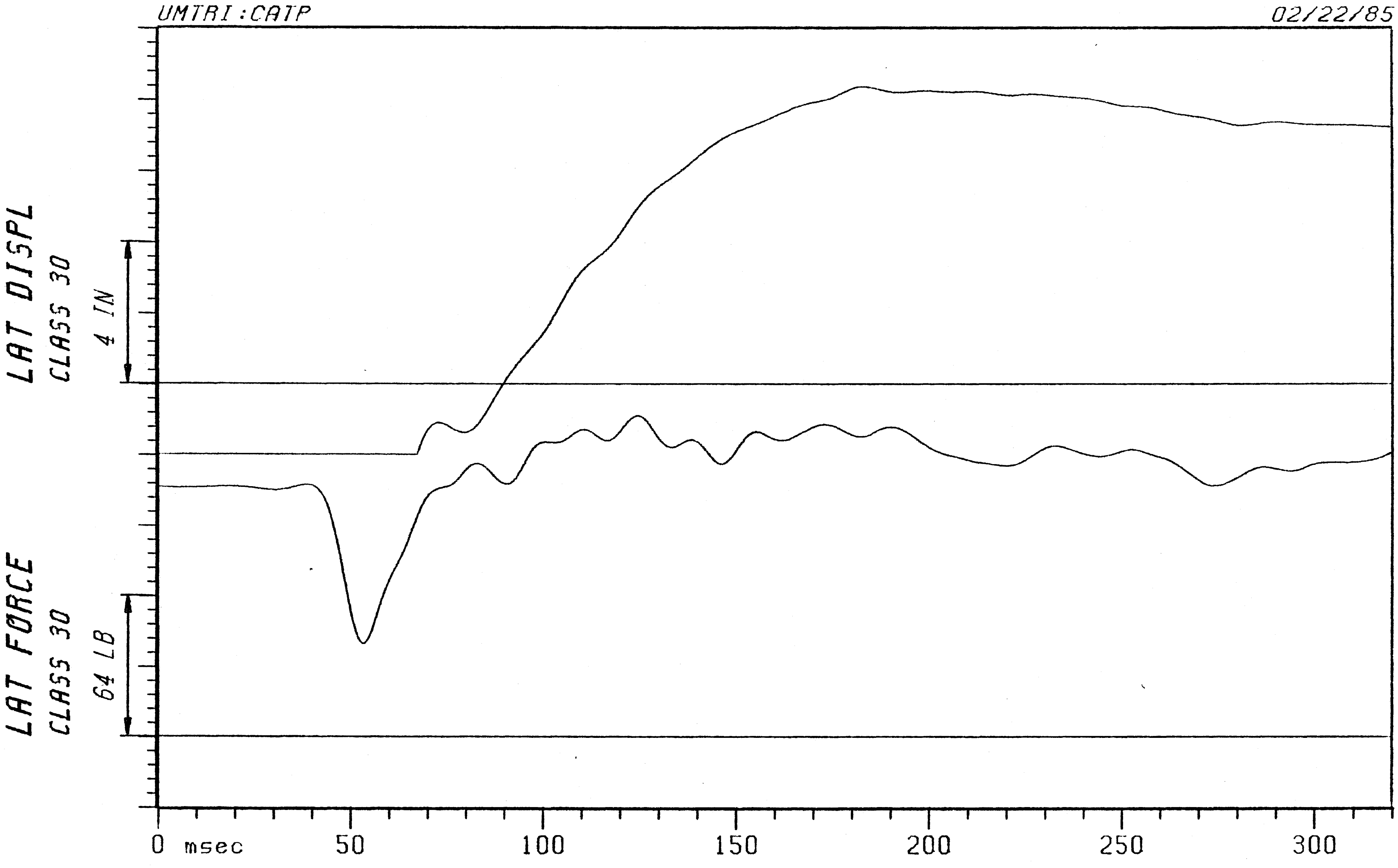
SECTION 3

Lateral Self-Restraint



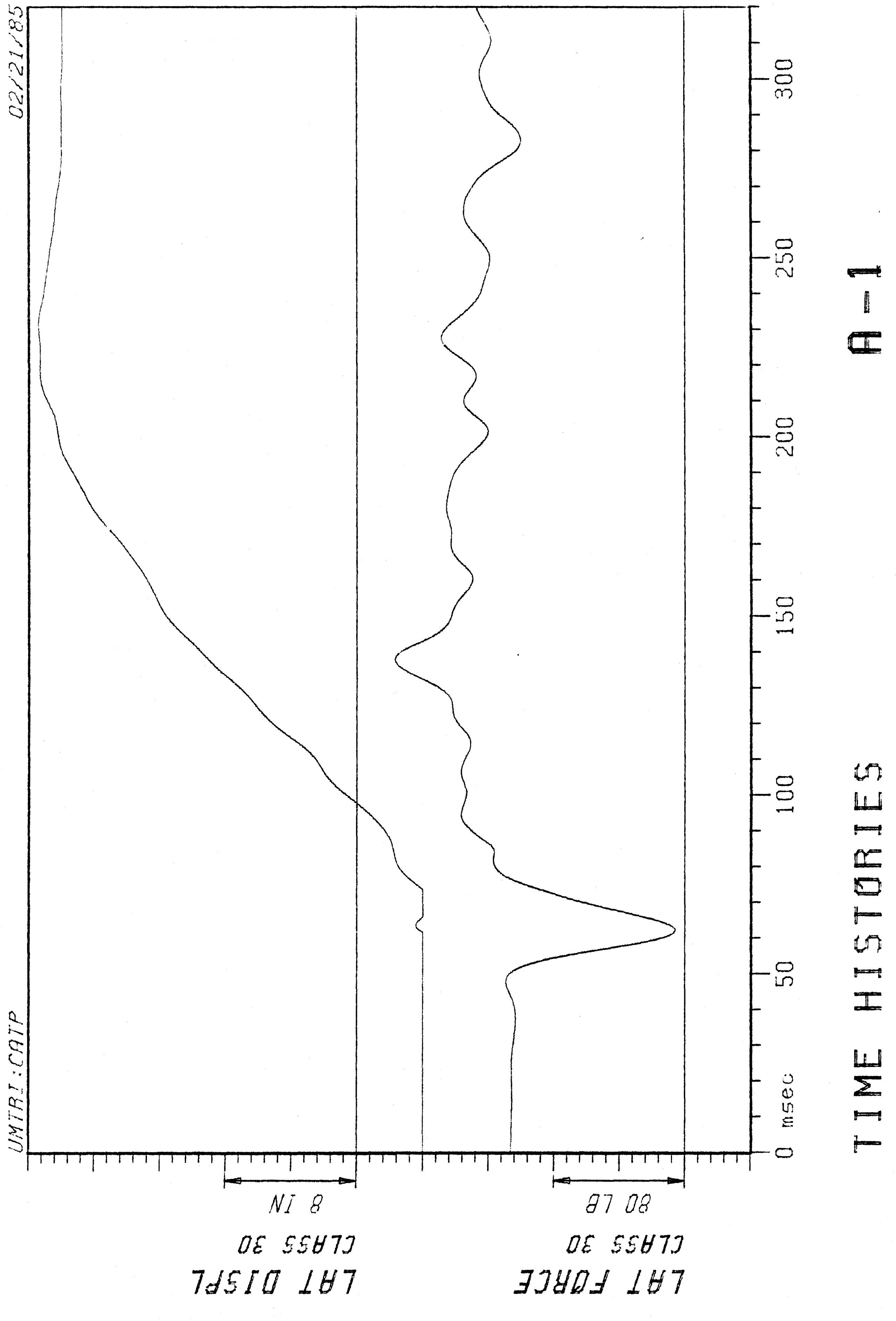
TIME HISTORIES B-1

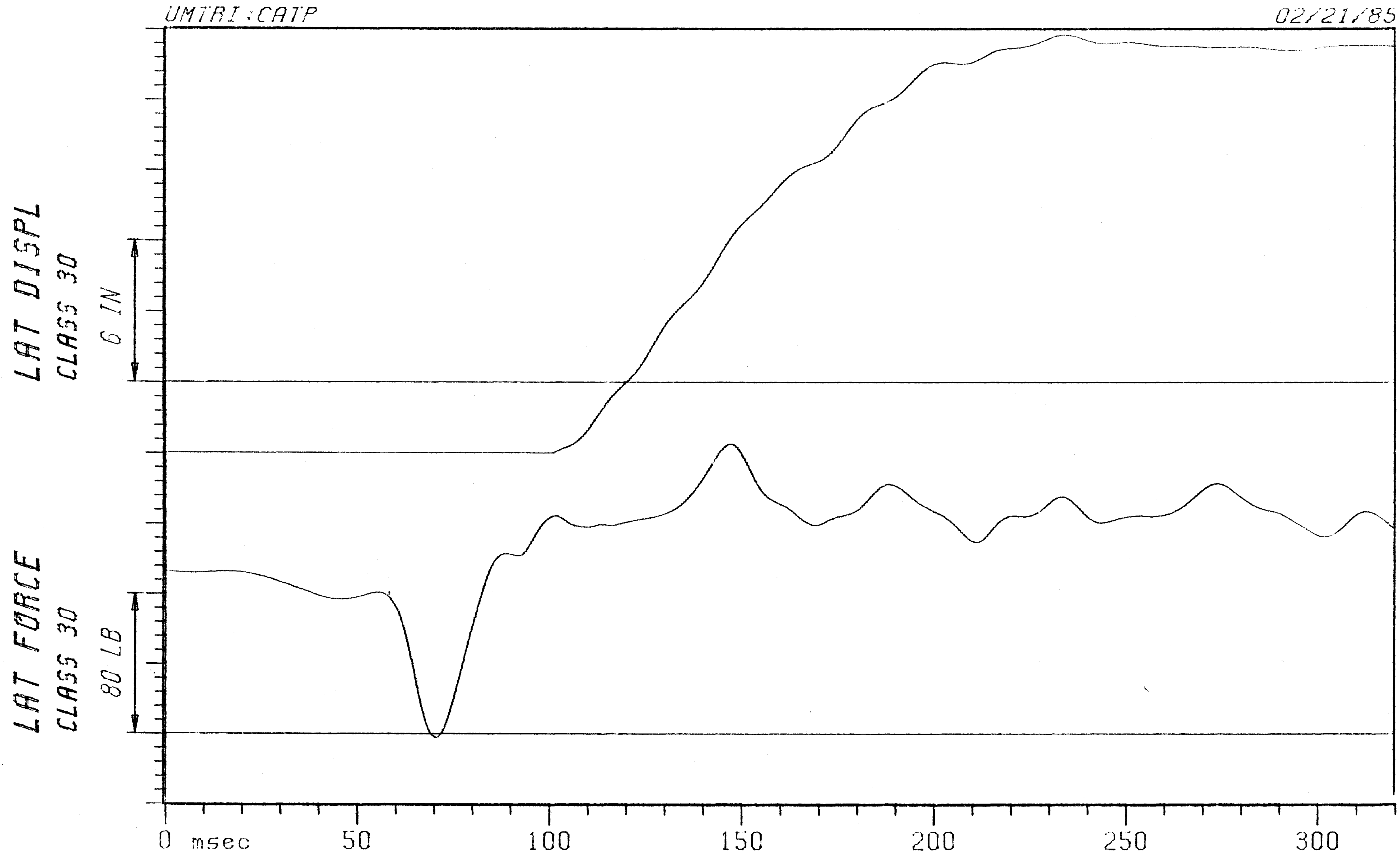

UMTRI:CATP
02/21/85
0 msec
50
100
150
200
250
300
LAT DISPL
CLASS 30
4 IN
LAT FORCE
CLASS 30
64 LB
TIME HISTORIES
B-2



TIME HISTØRIES

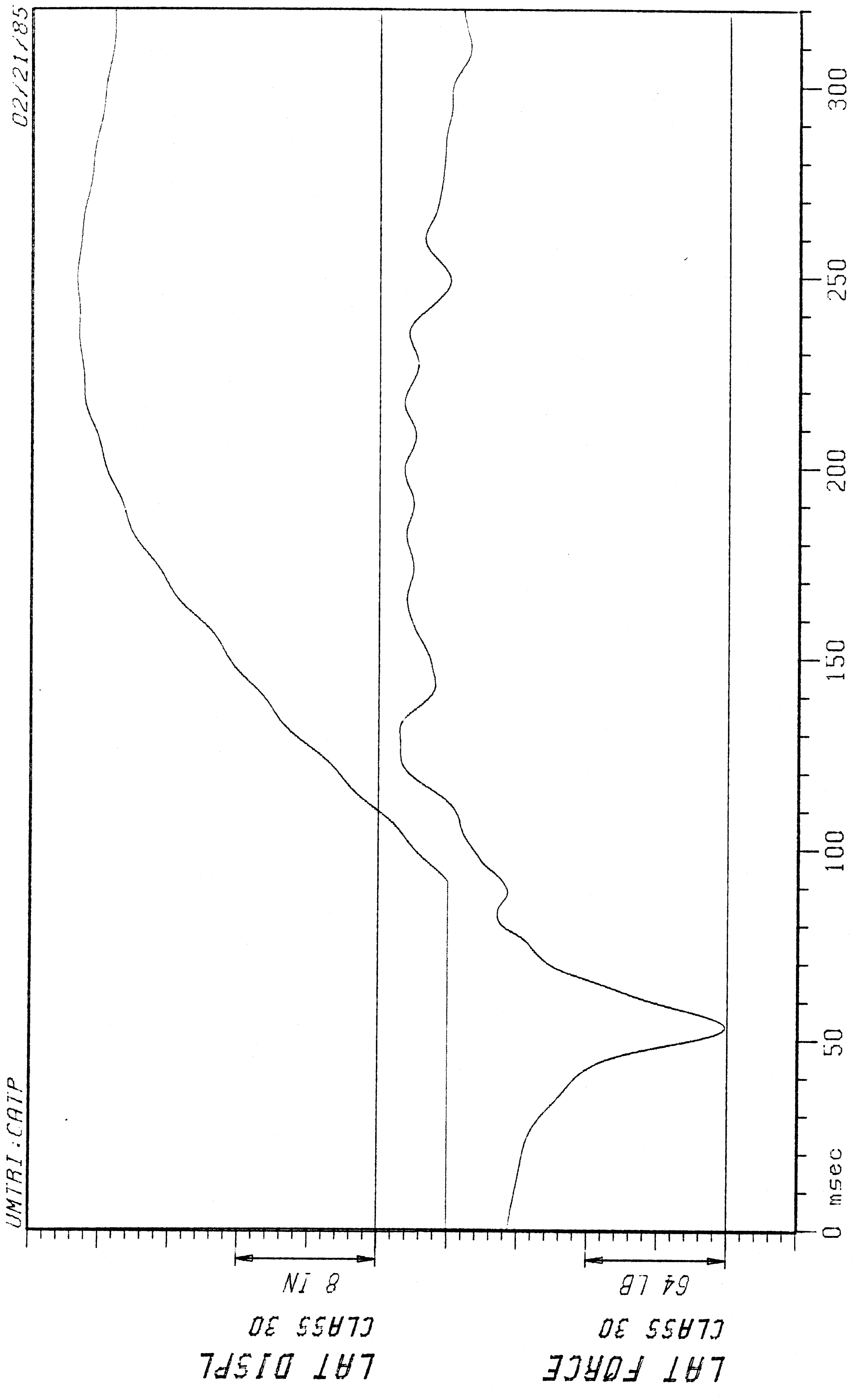
B-3


UMTRI:CATP
02/21/85
LAT DISPL
CLASS 30
8 IN
LAT FORCE
CLASS 30
80 LB
0 msec
50
100
150
200
250
300
TIME HISTORIES
A-1

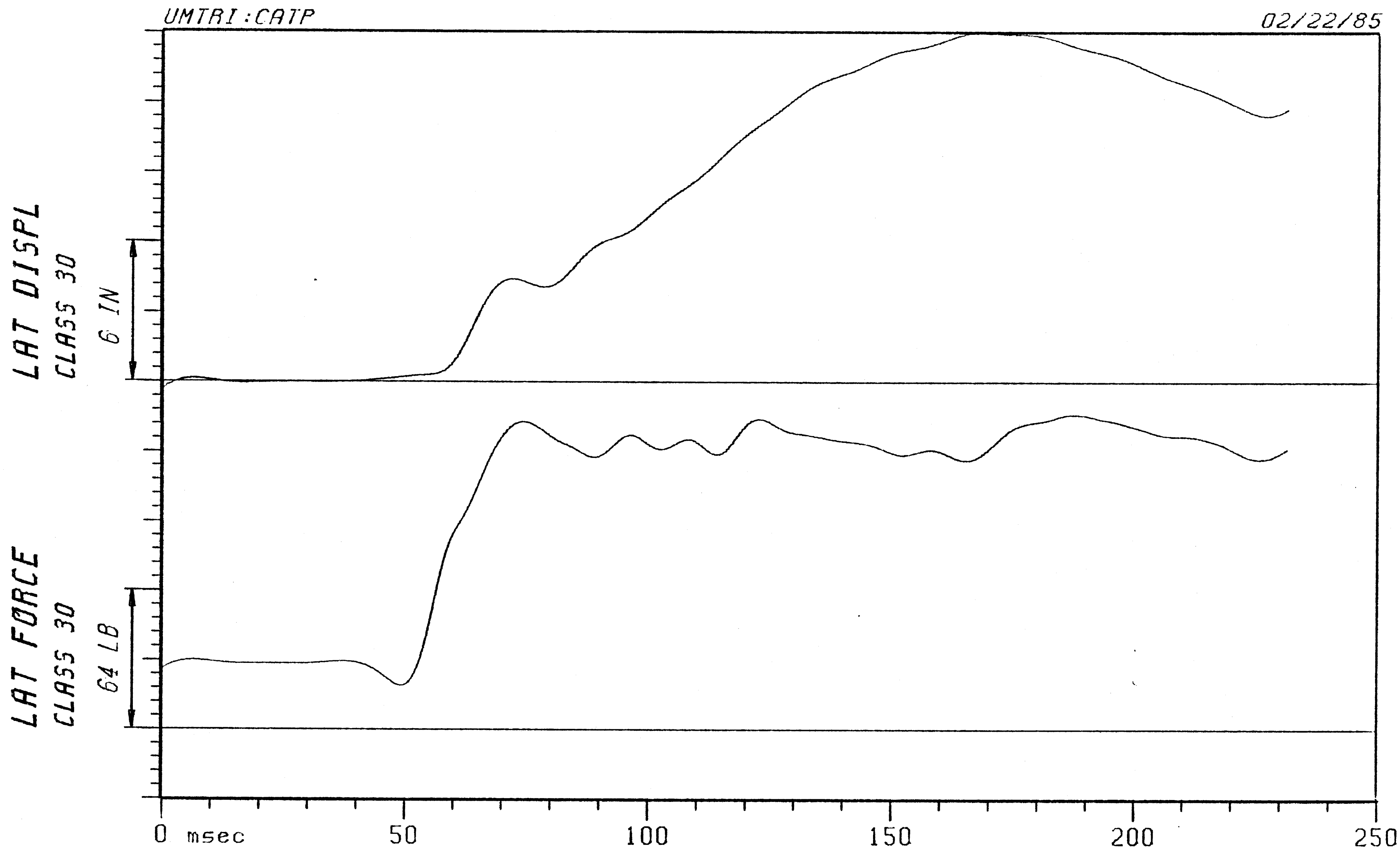


TIME HISTØRIES

A-2

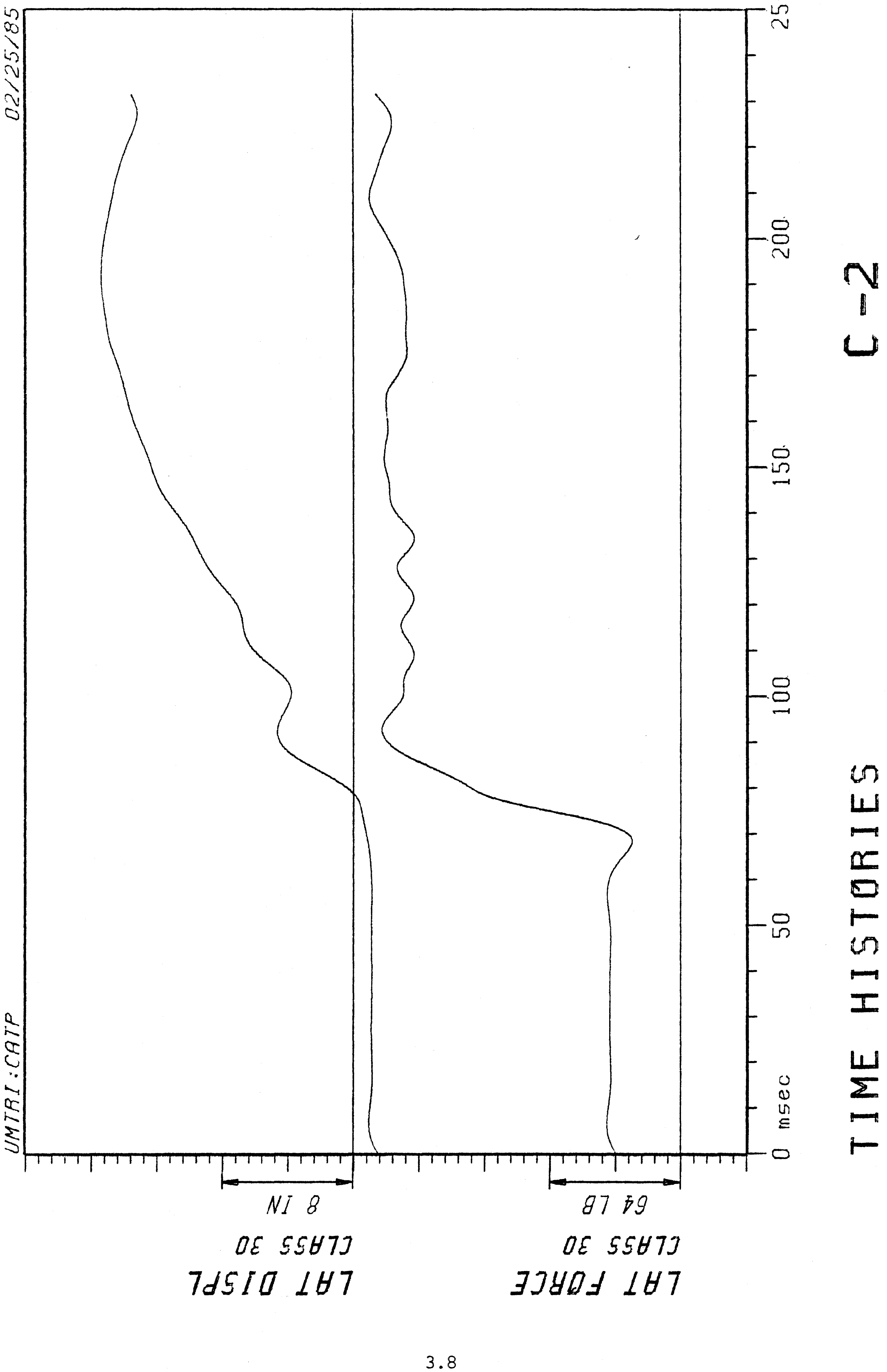


TIME HISTORIES A-3

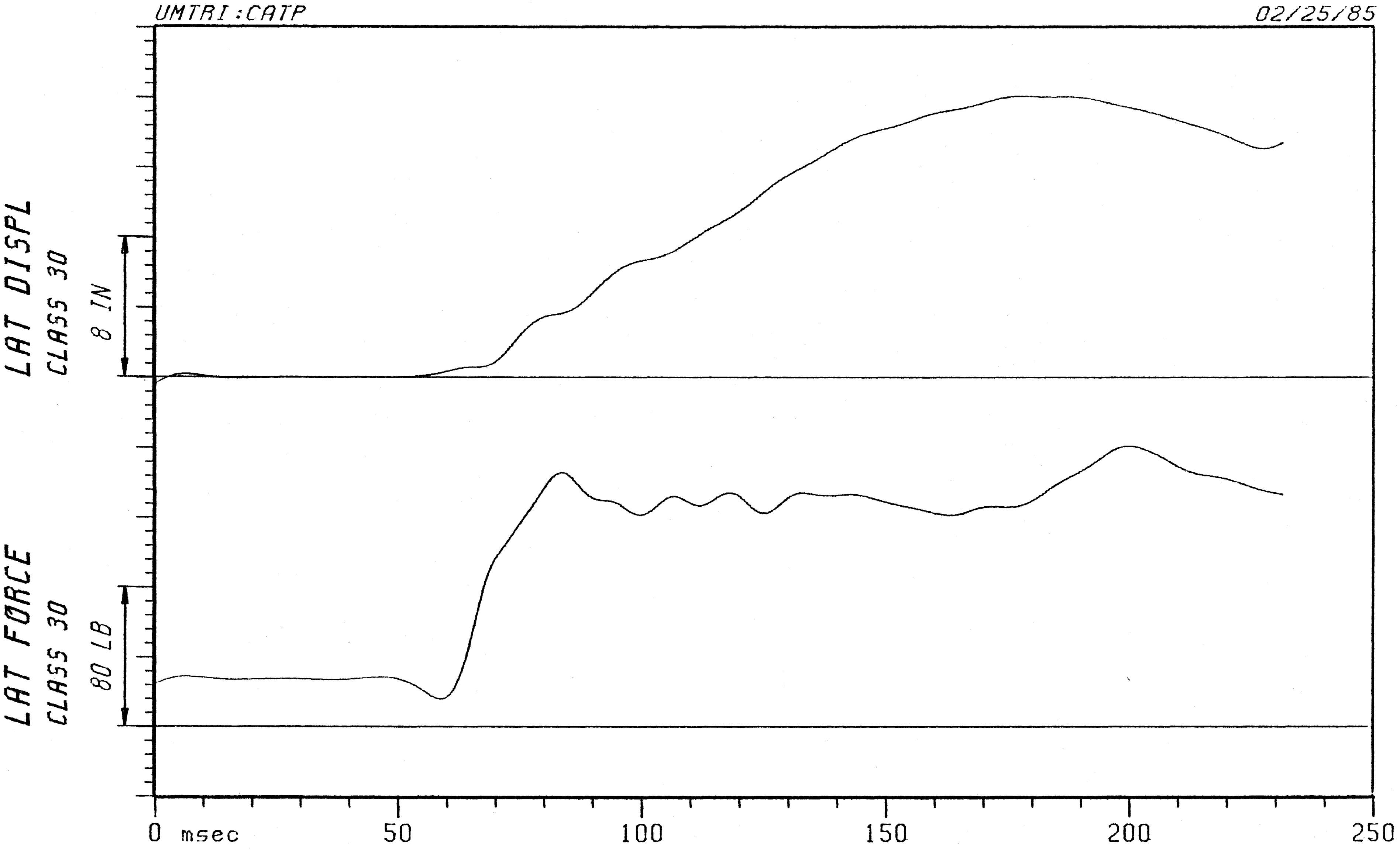


TIME HISTORIES

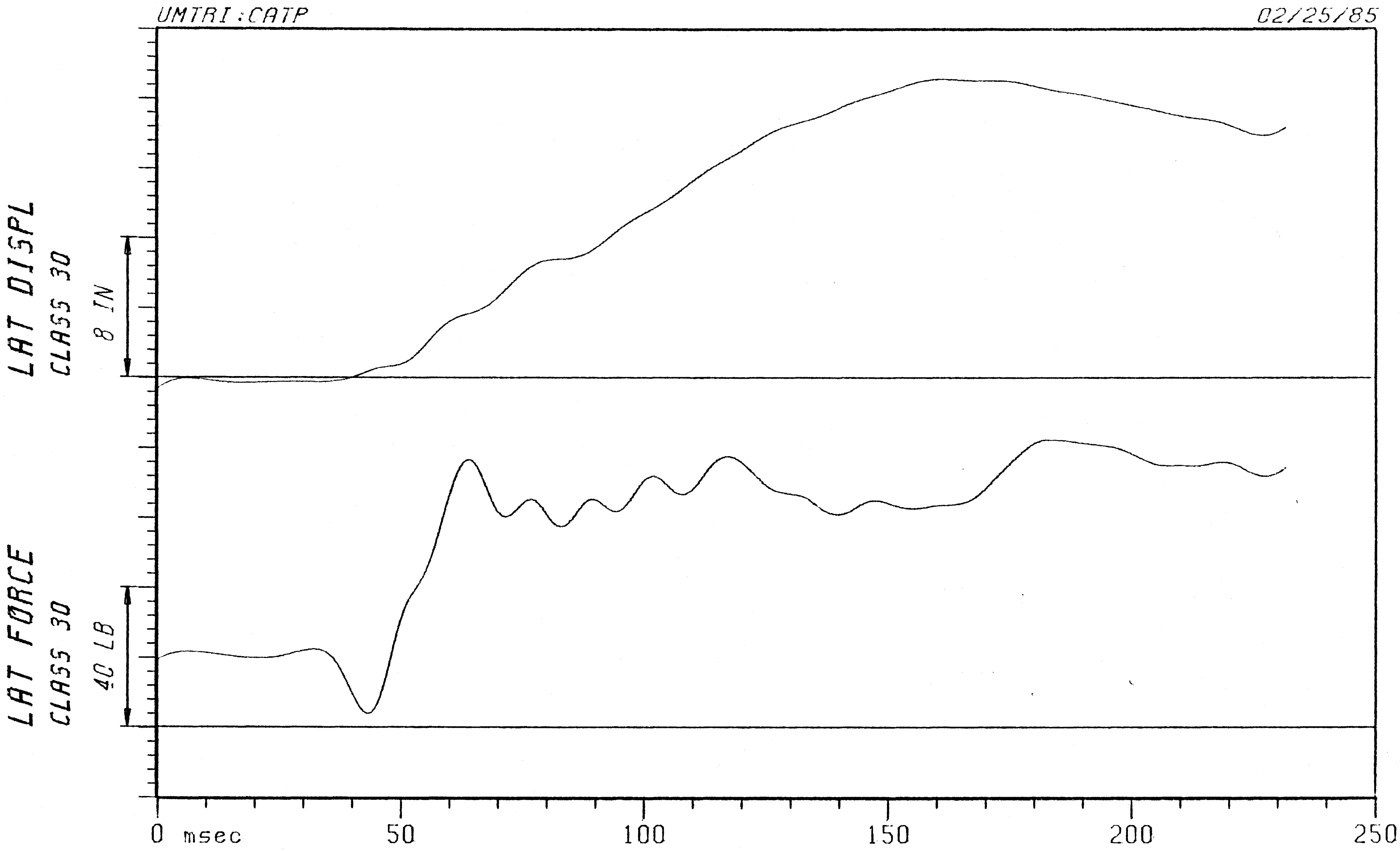
C-1



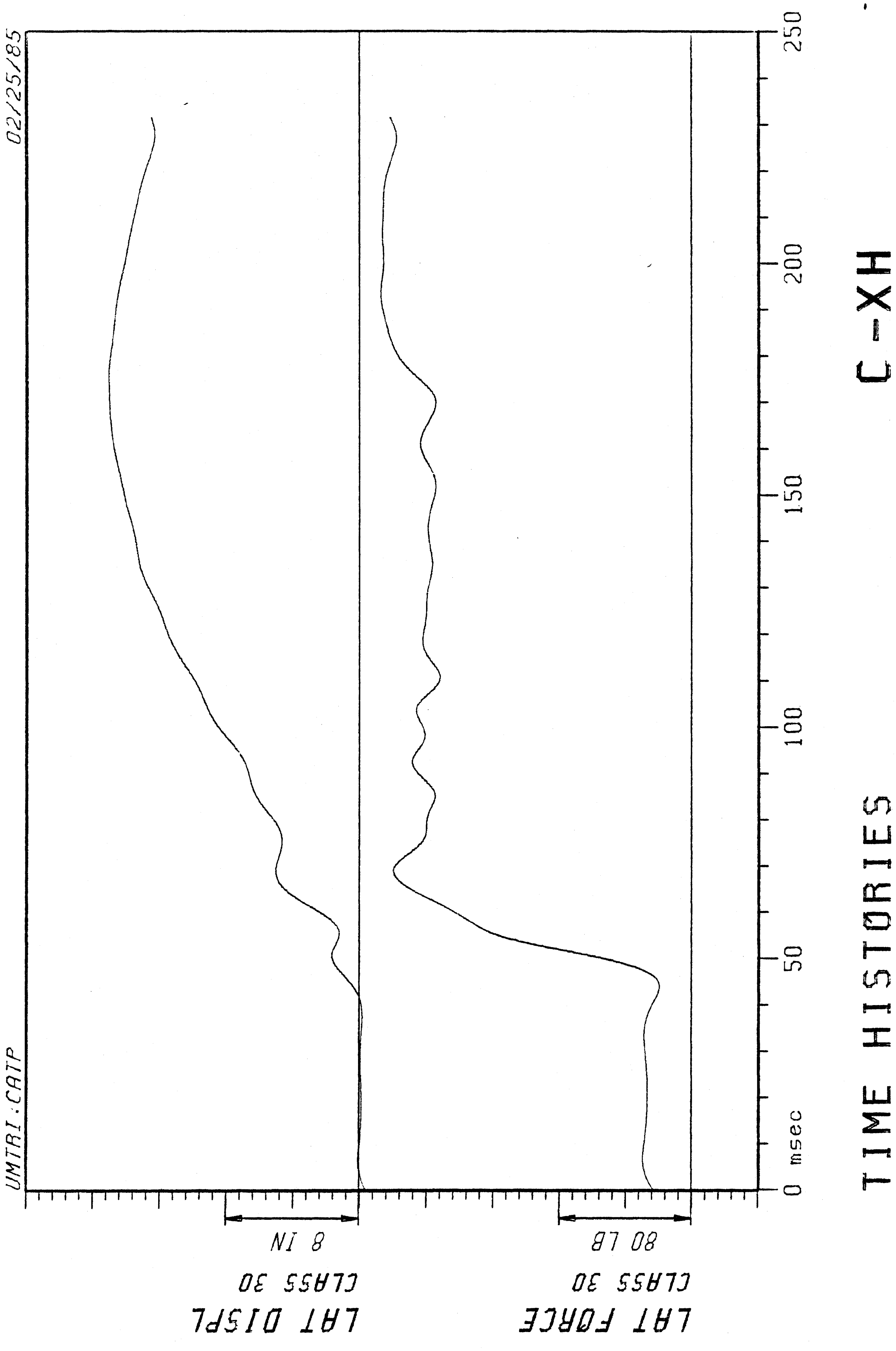
UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
8 IN
CLASS 30
LAT DISPL
64 LB
CLASS 30
LAT FORCE
TIME HISTORIES
C-2

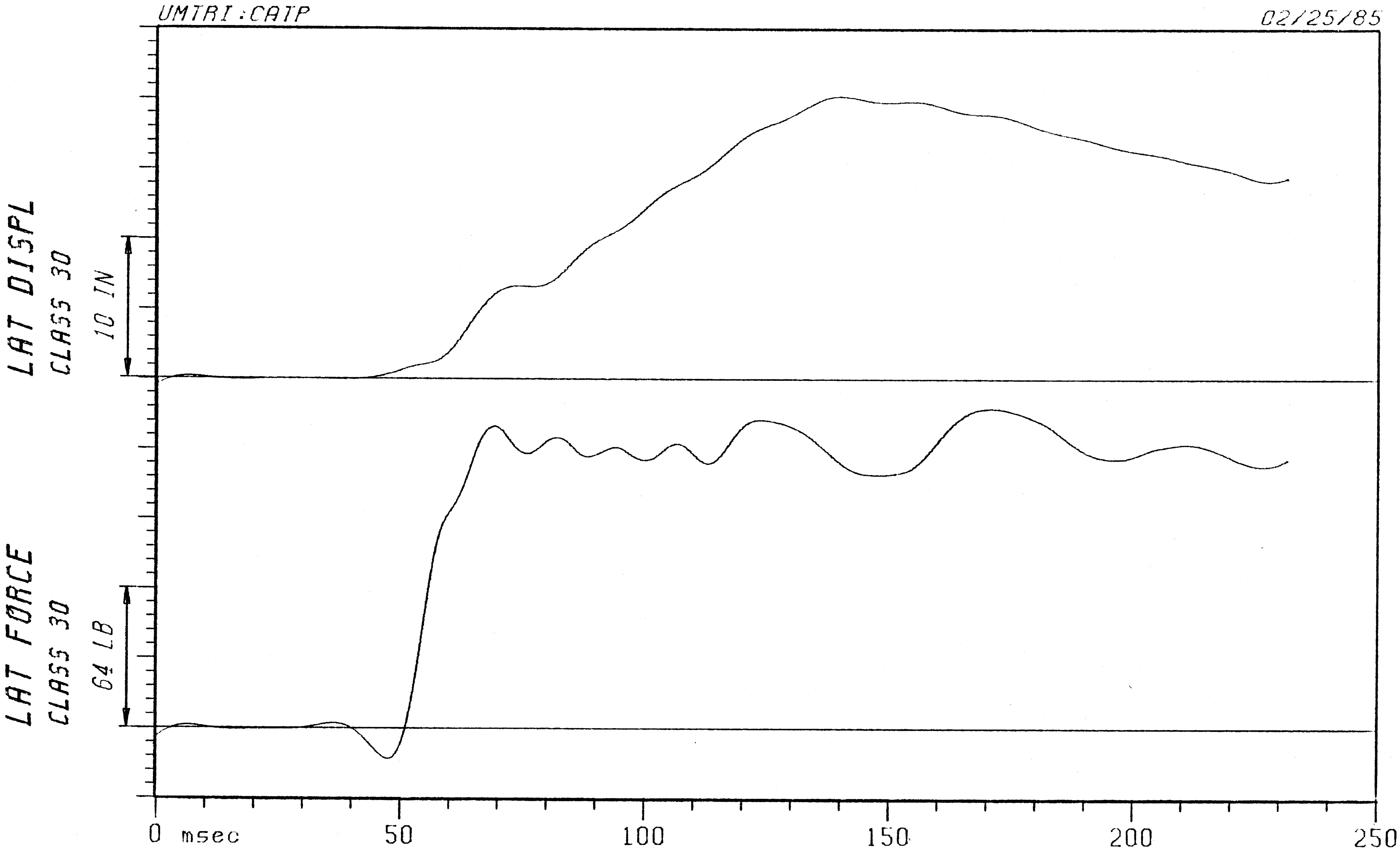


TIME HISTØRIES C-3

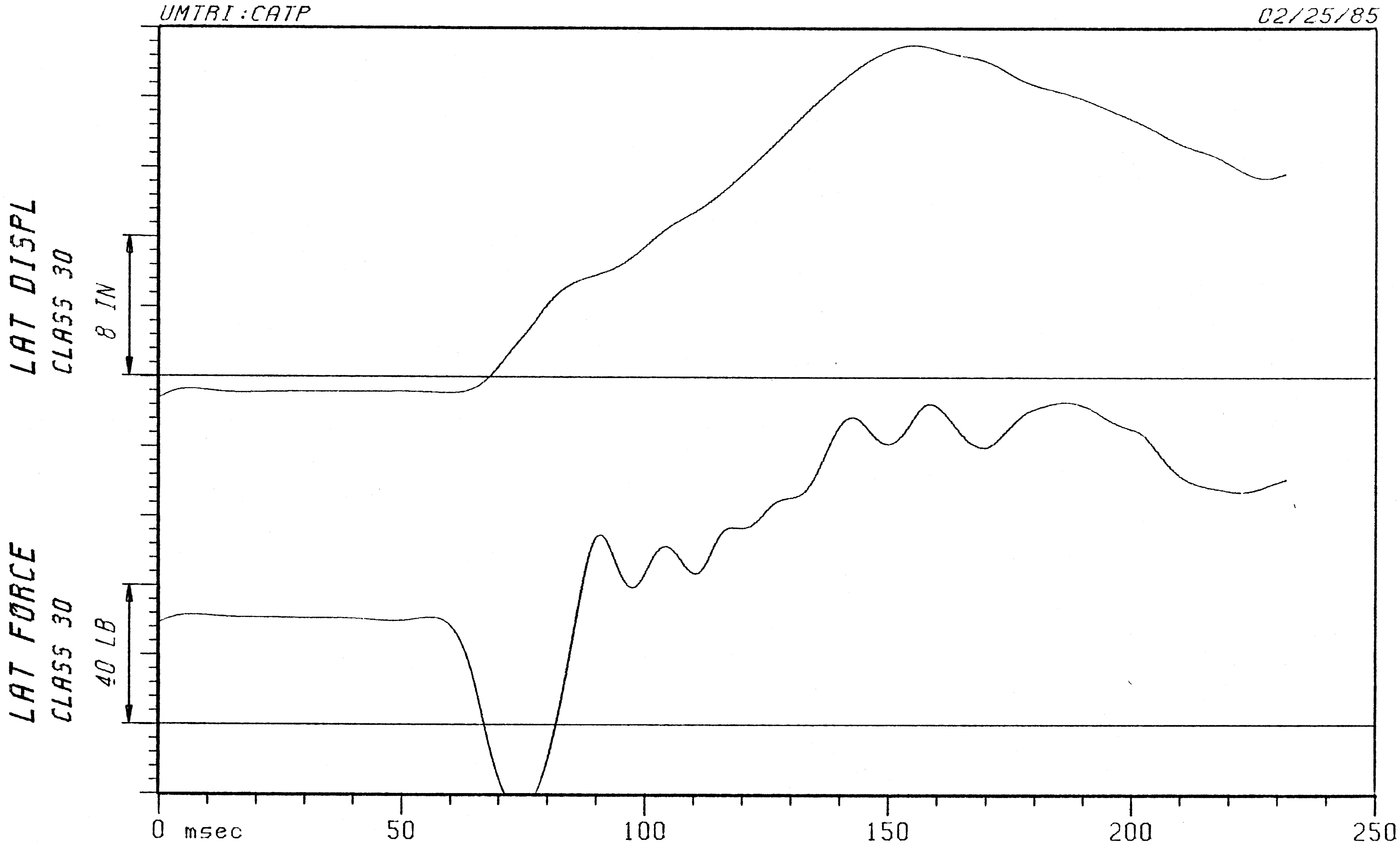


TIME HISTØRIES C-XL

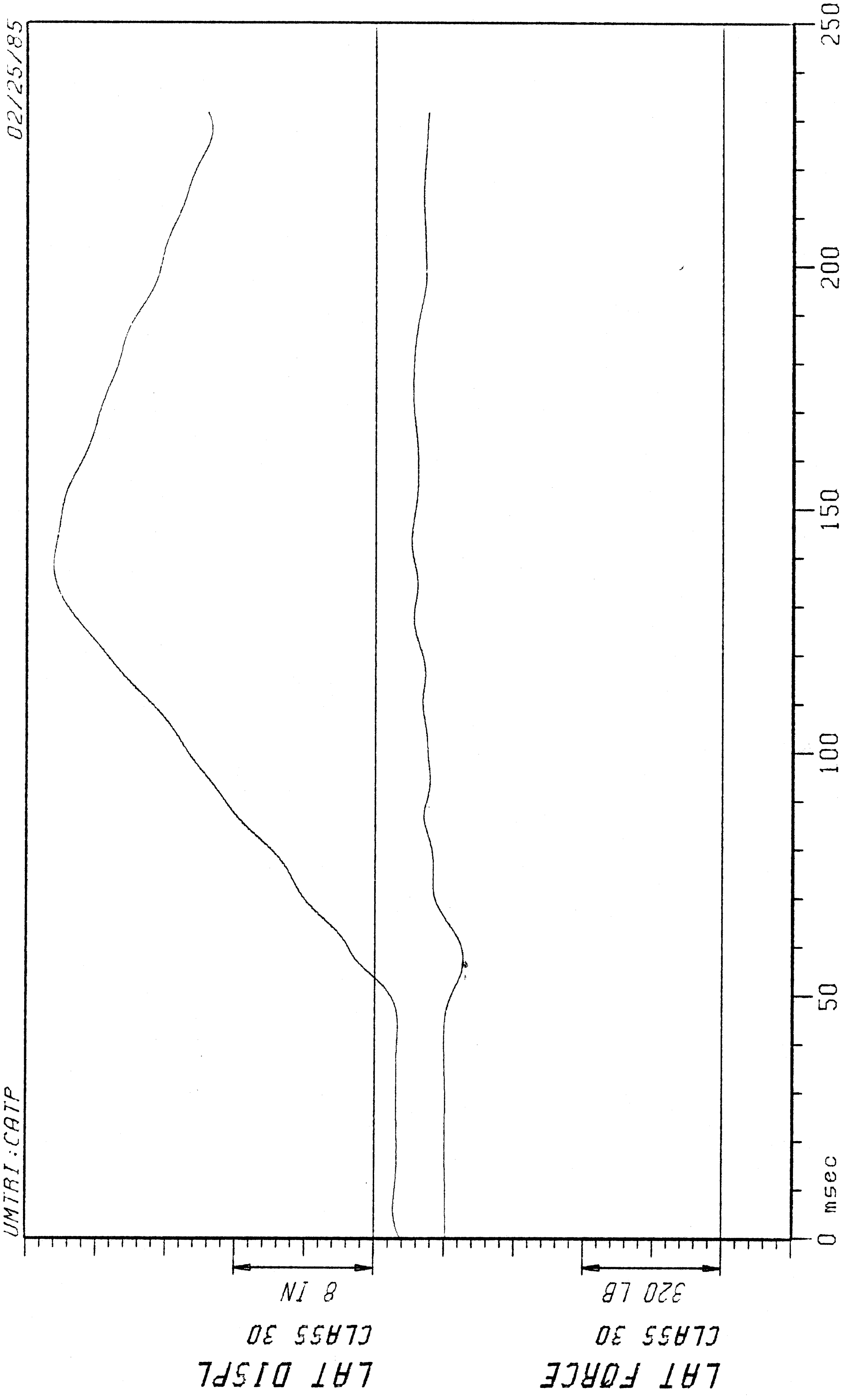

UMTRI:CATP
02/25/85
LAT DISPL
CLASS 30
8 IN
LAT FØRCE
CLASS 30
80 LB
0 msec
50
100
150
200
250
TIME HISTØRIES
C-XH



TIME HISTØRIES D-1



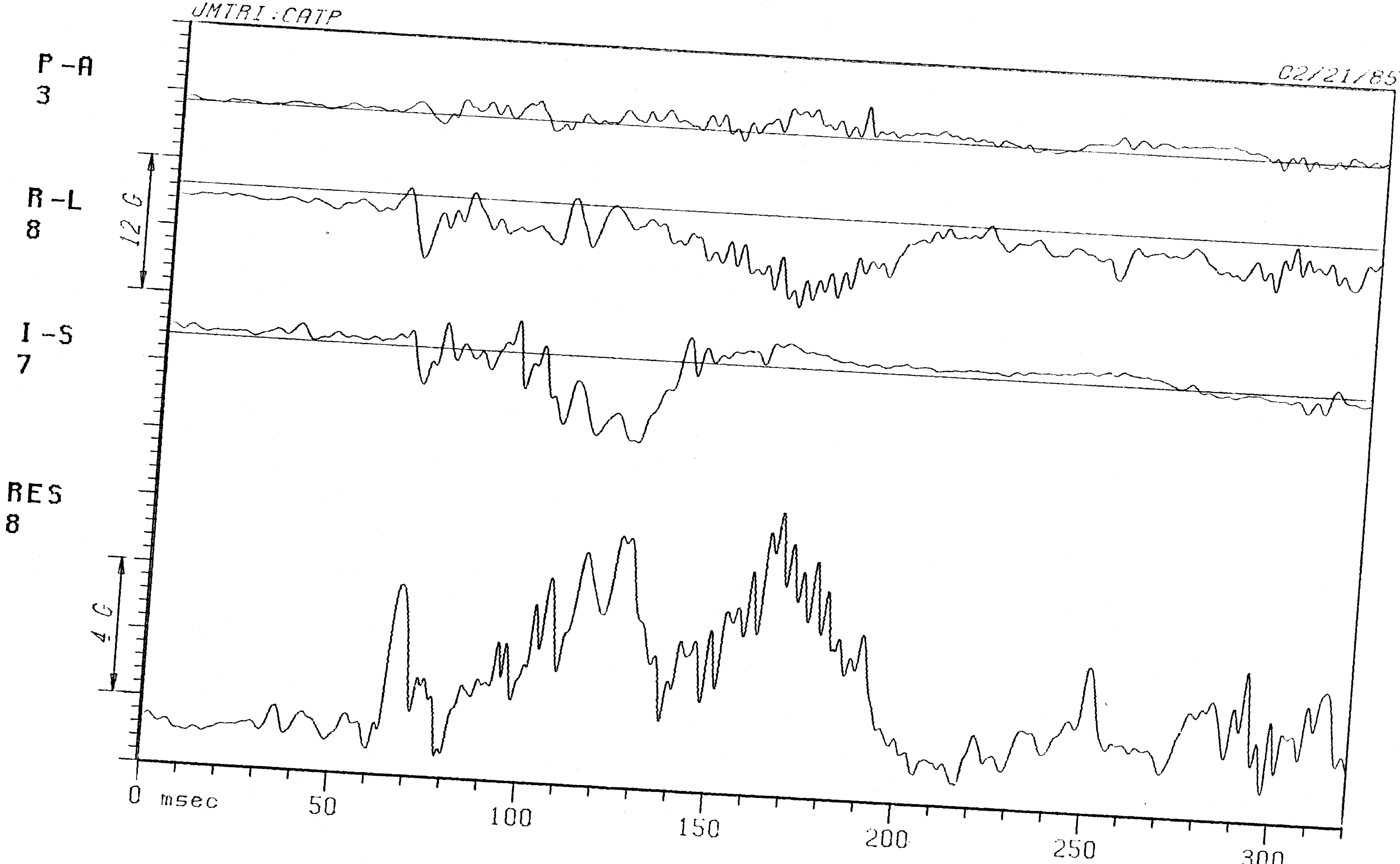
TIME HISTØRIES D-2



TIME HISTORIES D-3

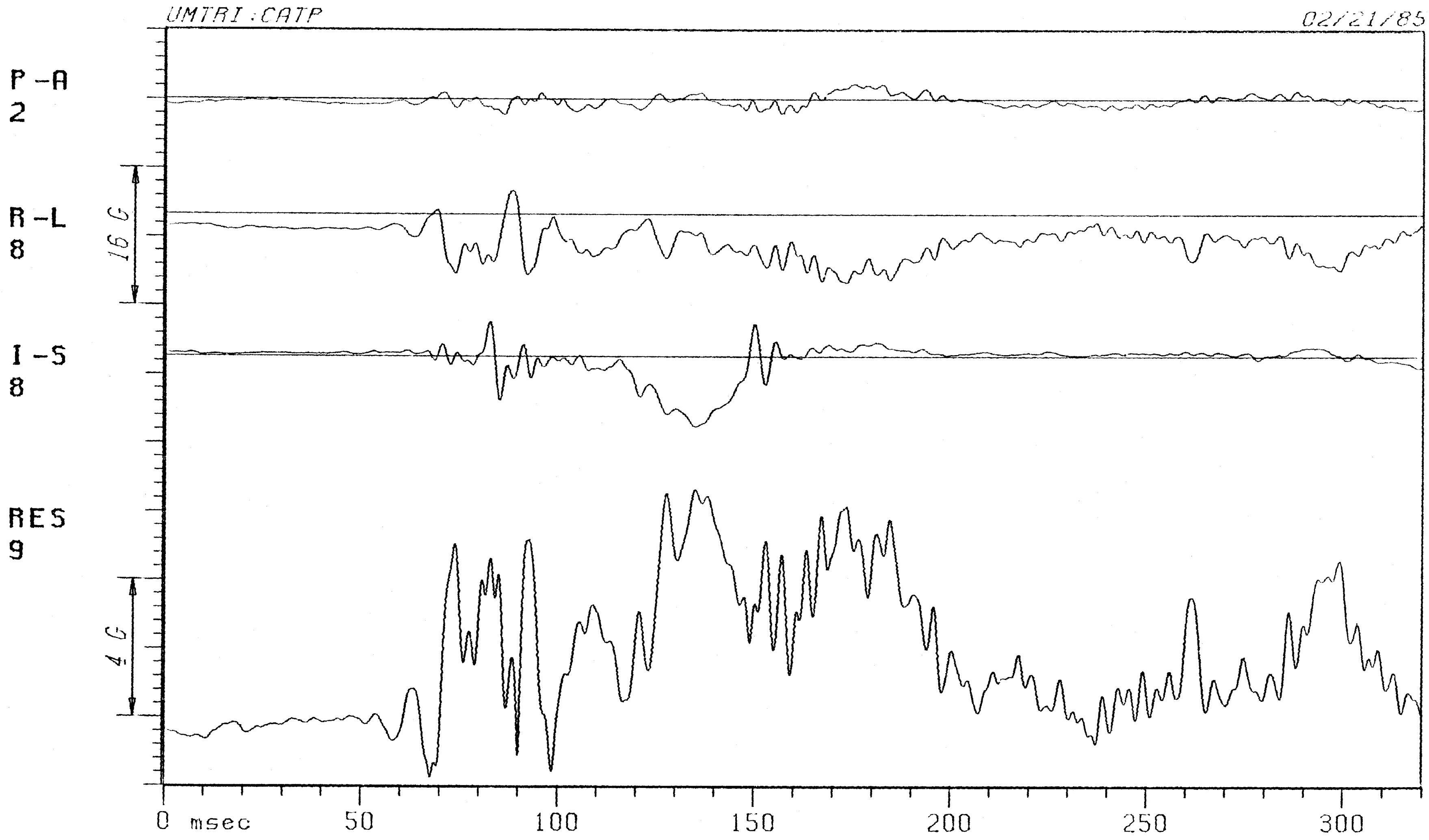
SECTION 4

Chest Accelerations

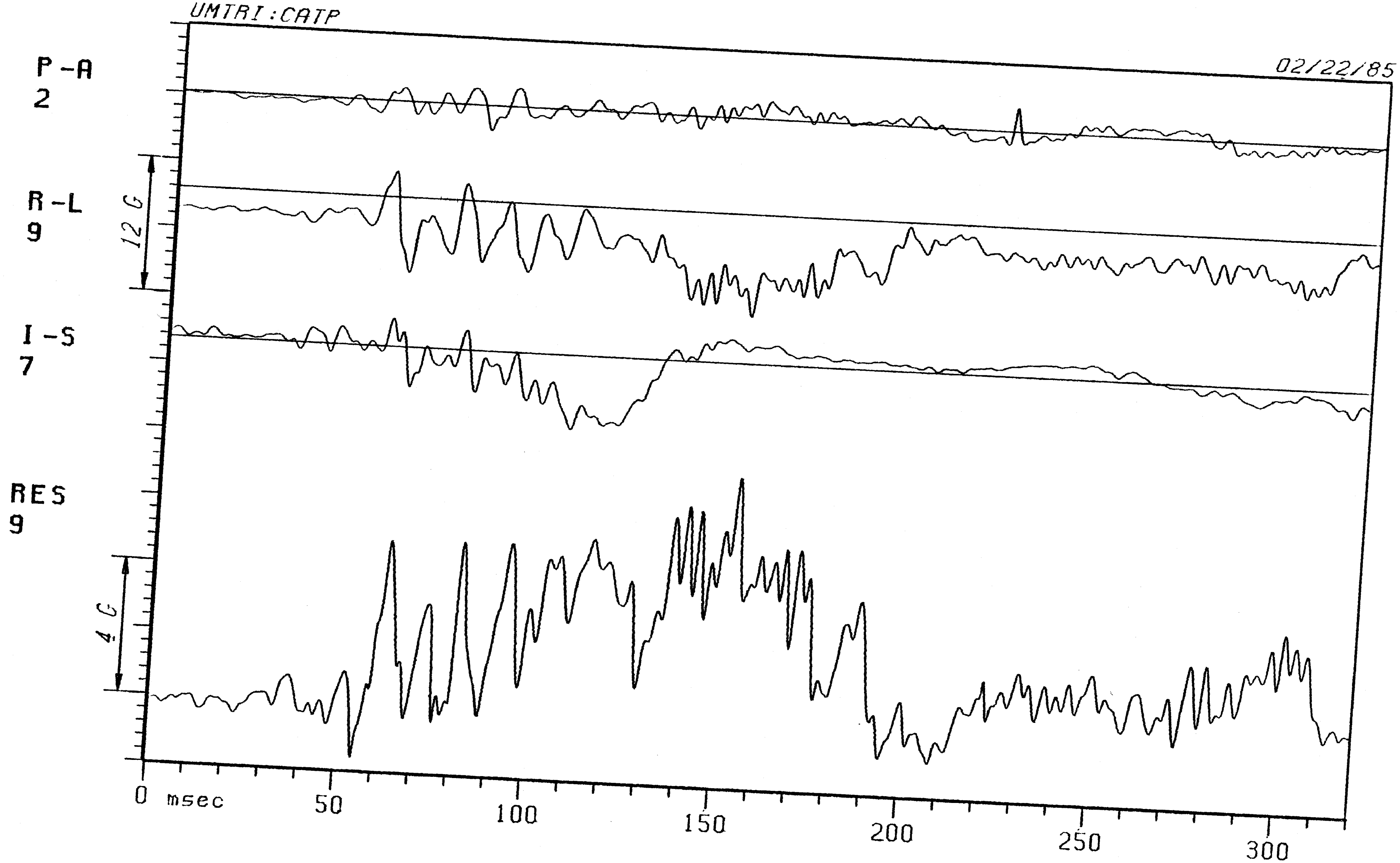


CHEST ACCEL.

B-1

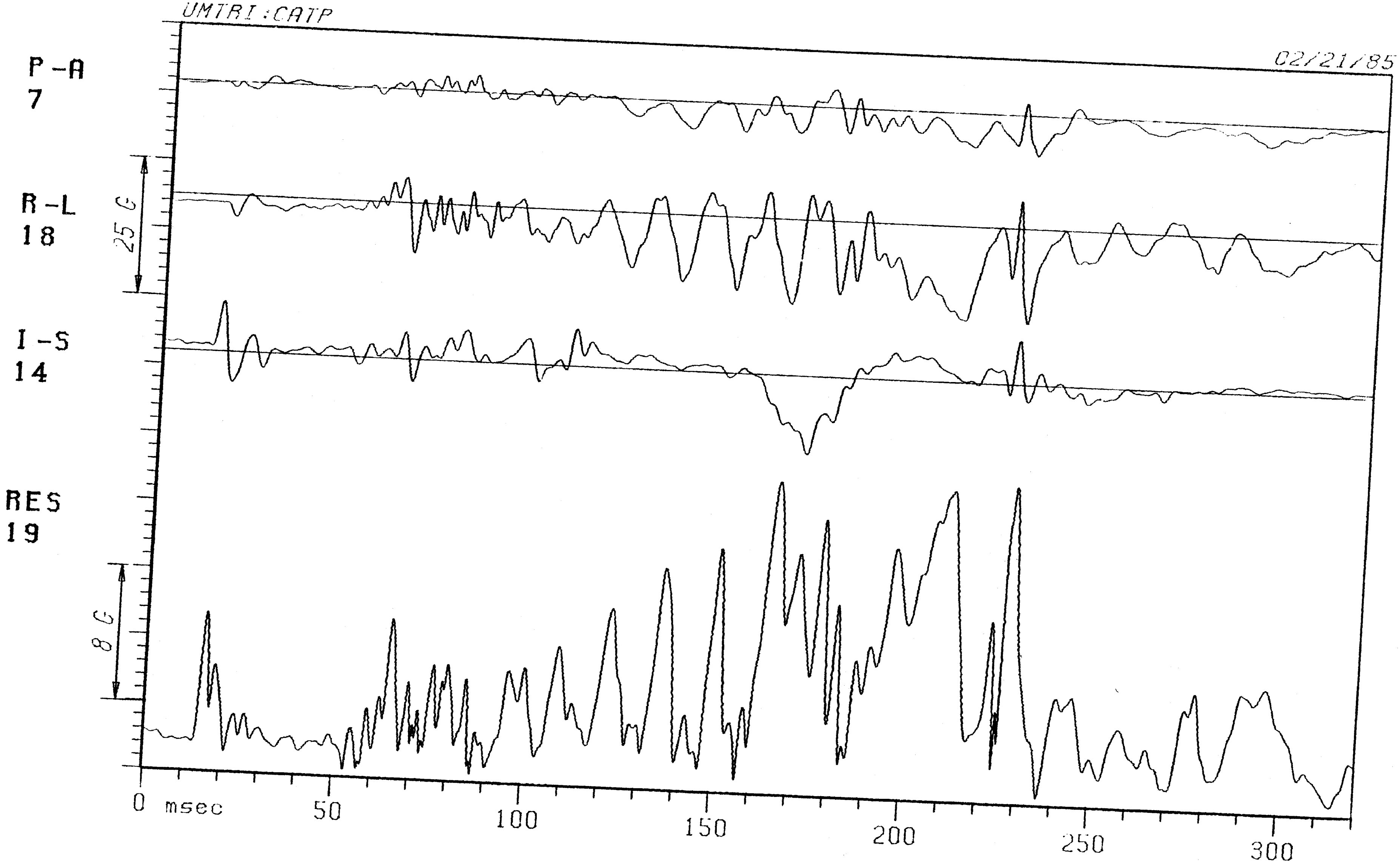


CHEST ACCEL. B-2



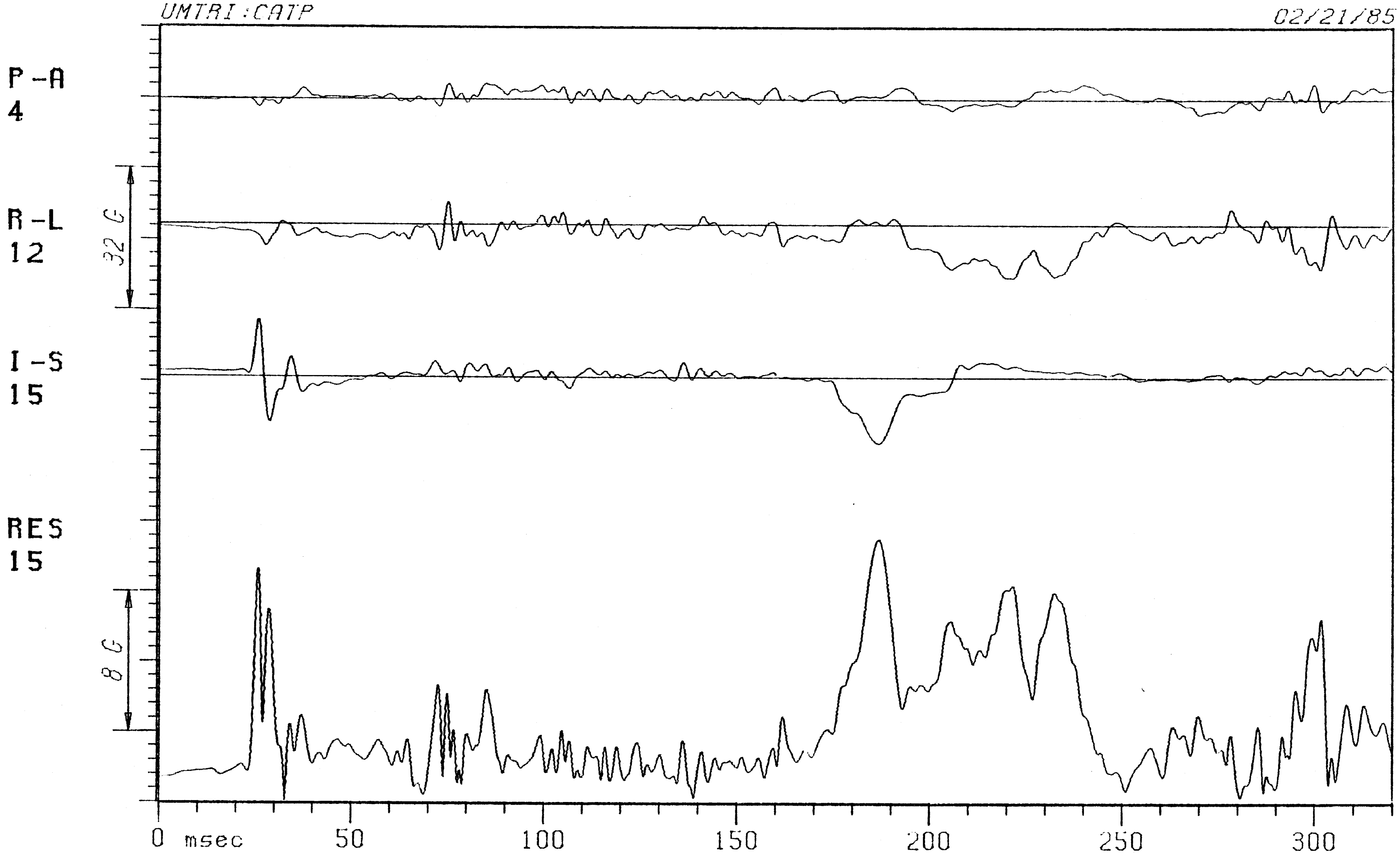
CHEST ACCEL.

B-3

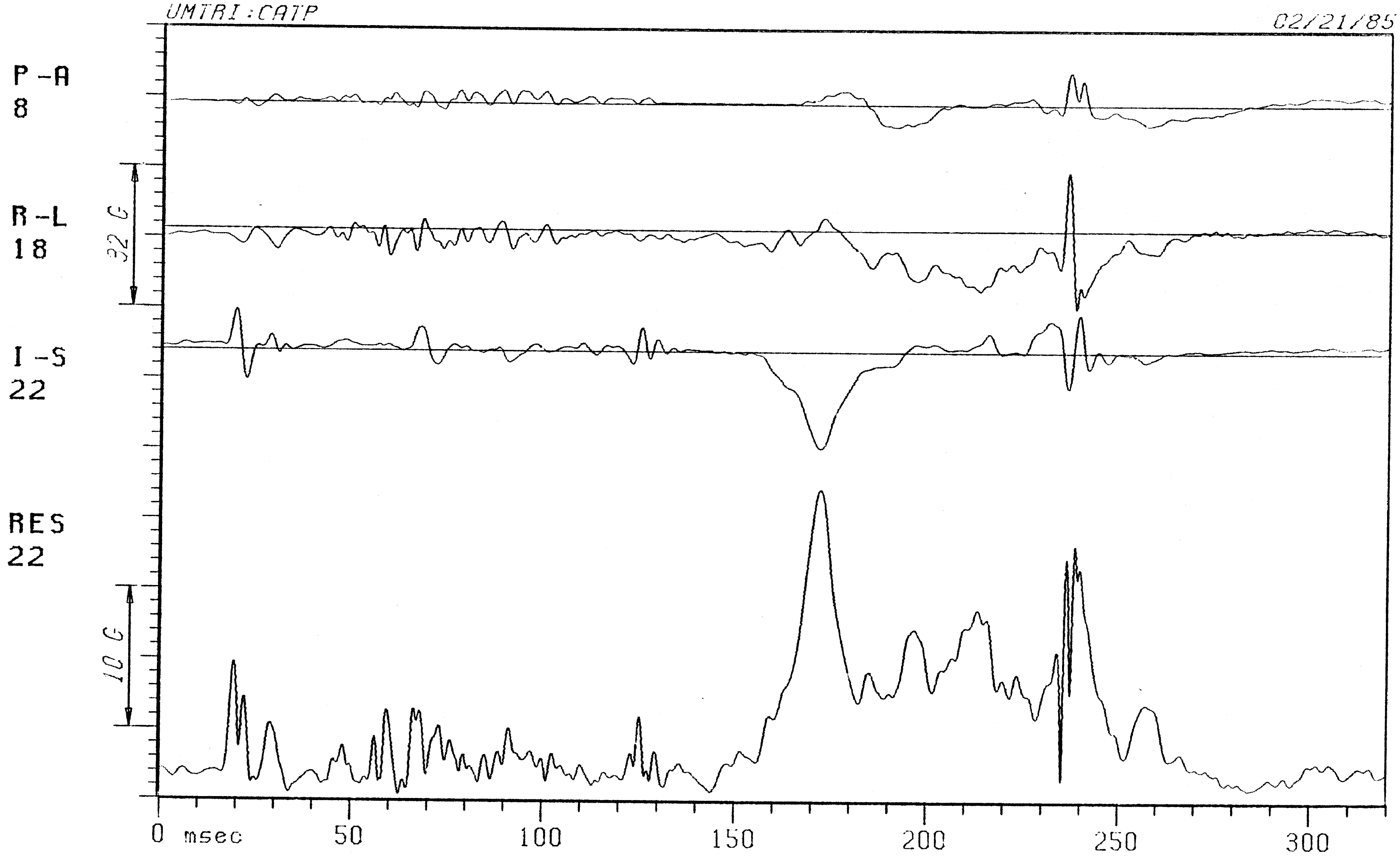


CHEST ACCEL.

A-1

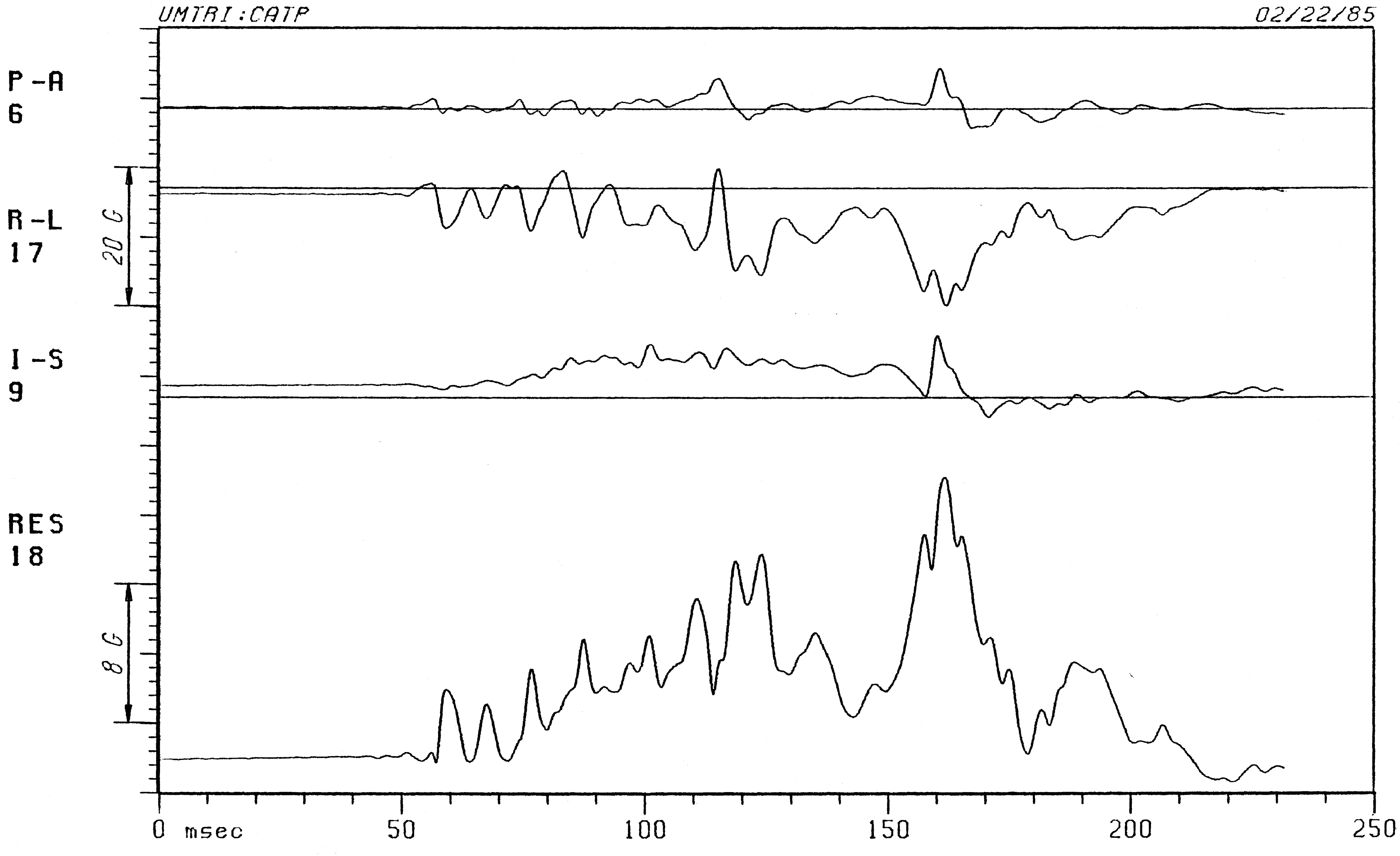


CHEST ACCEL. A-2



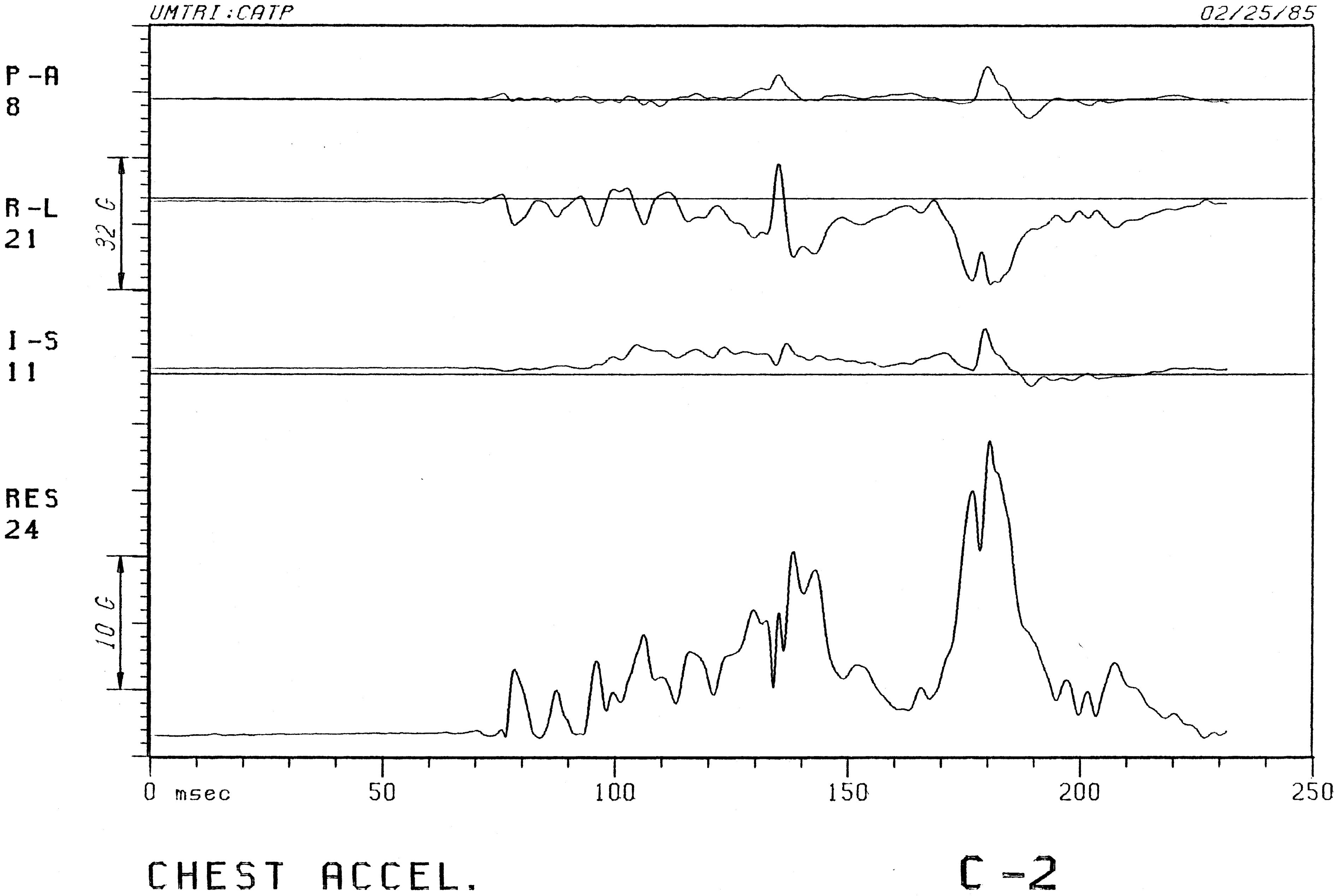
CHEST ACCEL.

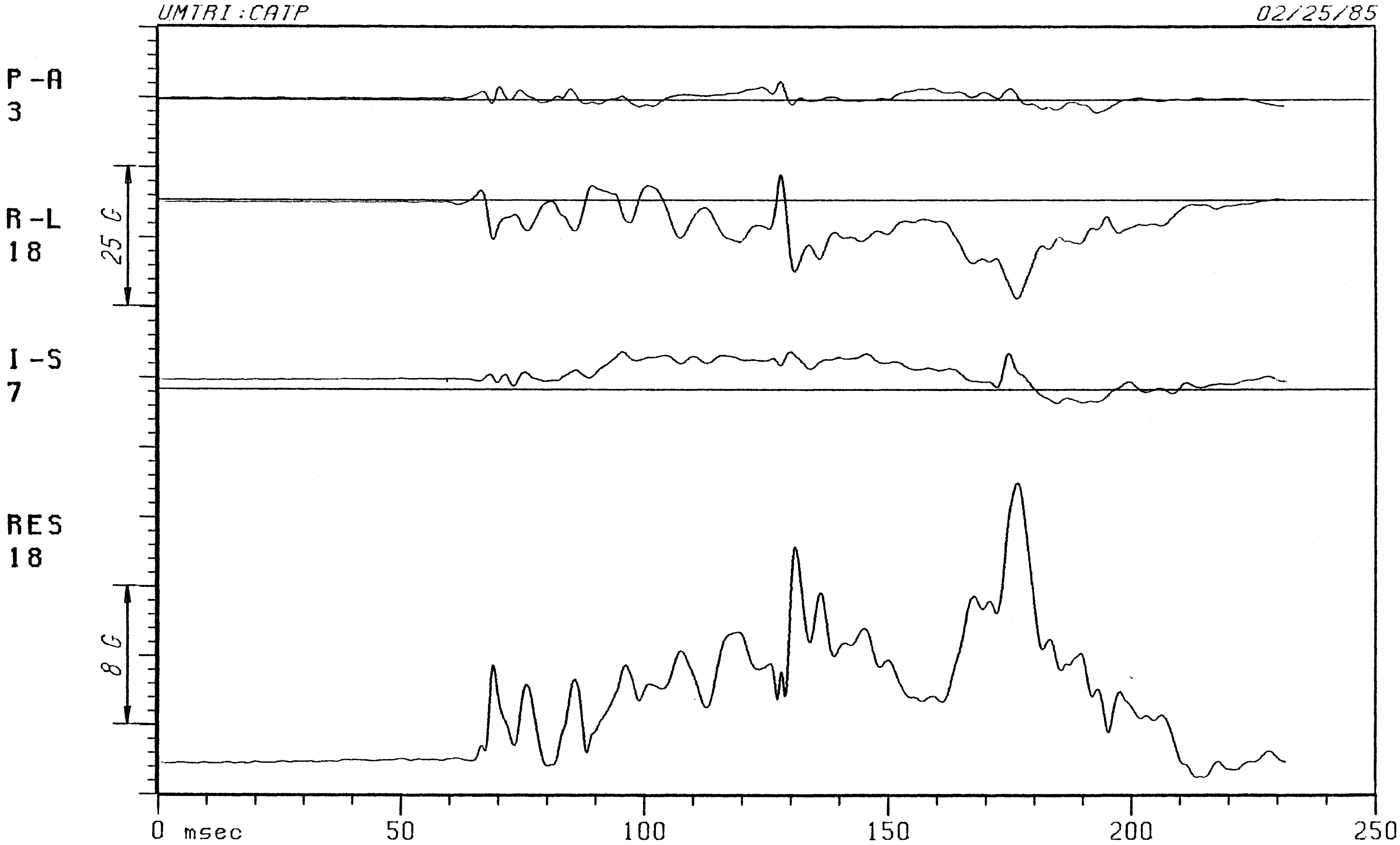
A-3



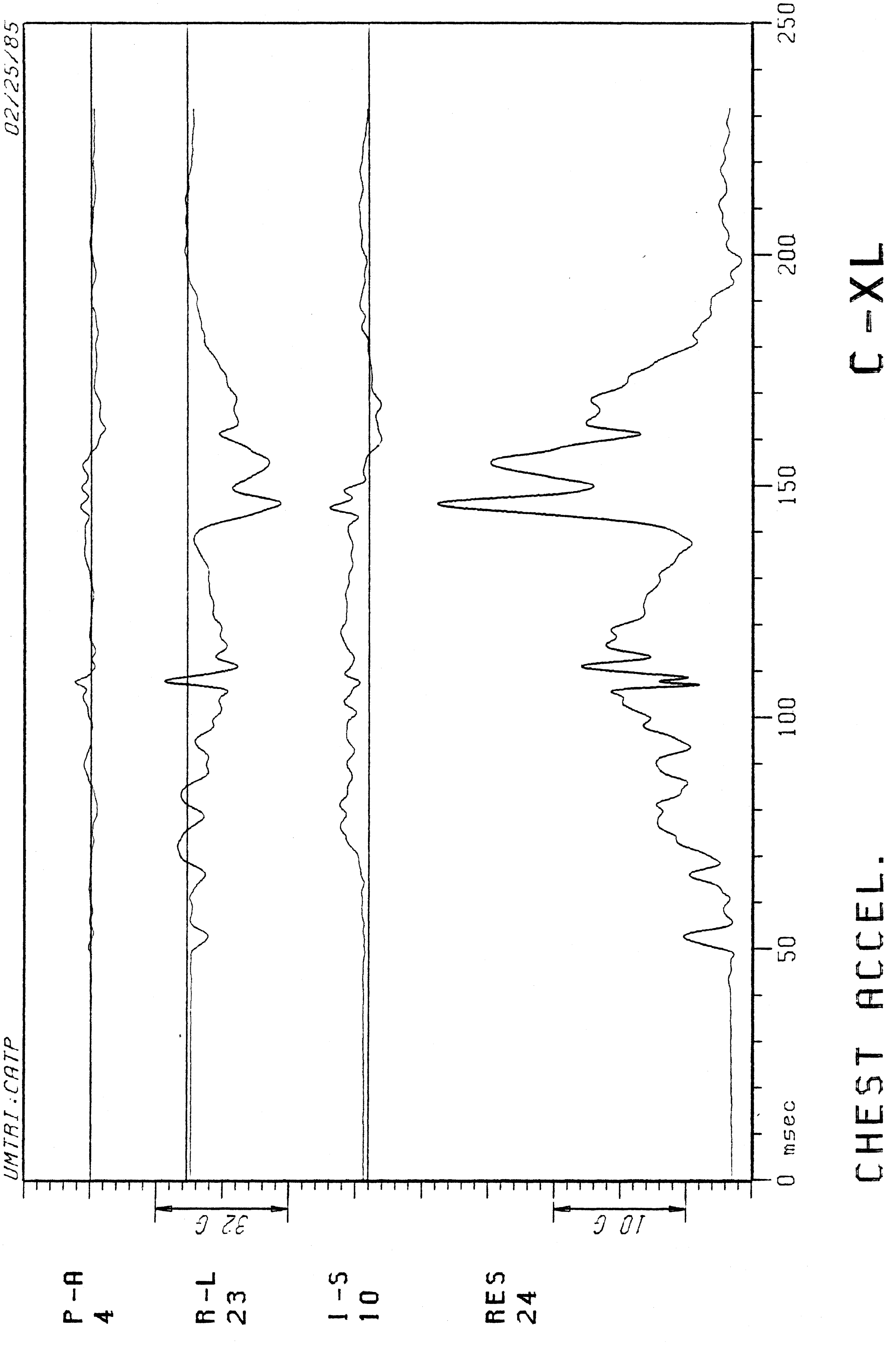
CHEST ACCEL.

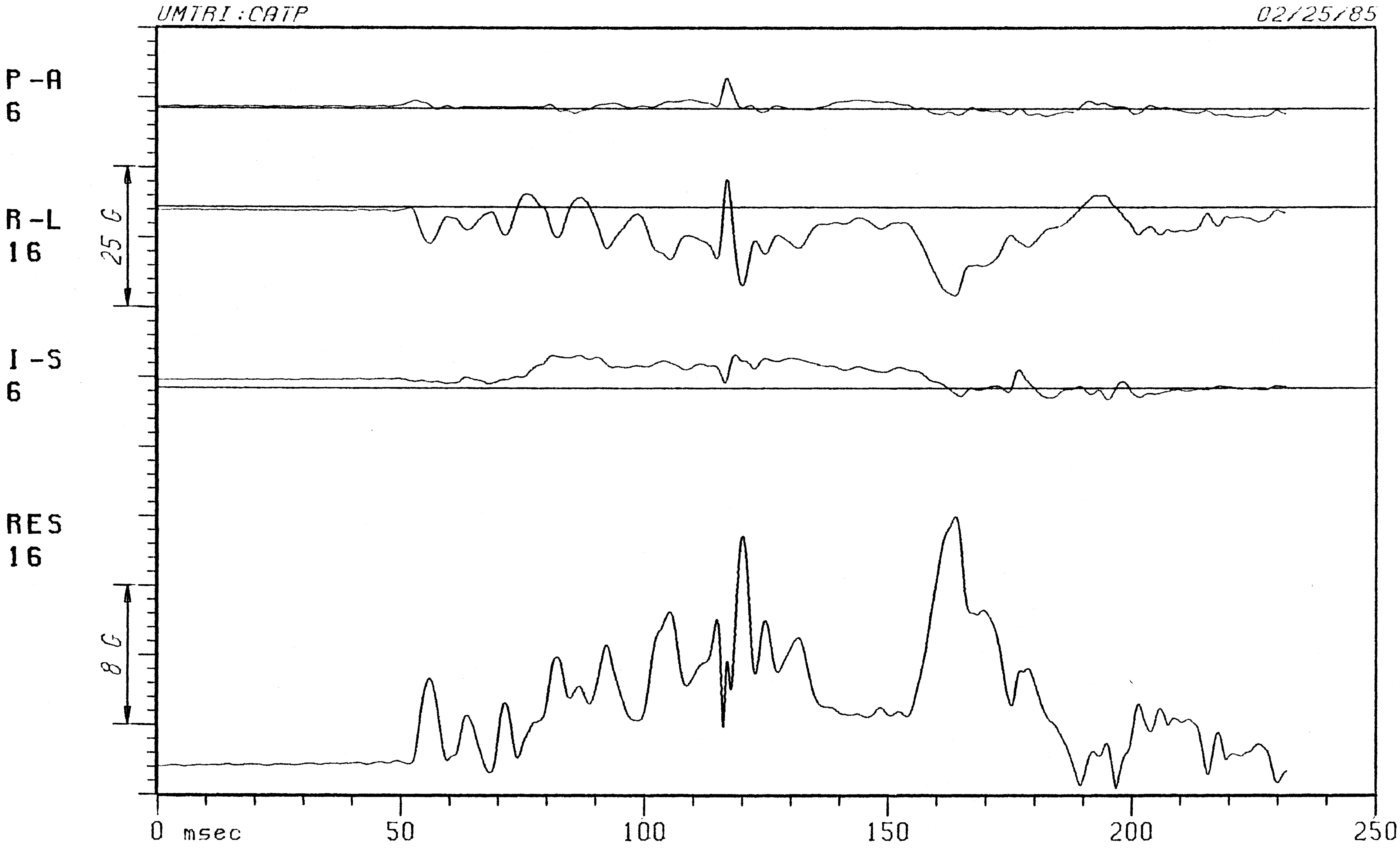
C-1


UMTRI:CATP
02/25/85
P-A
8
R-L
21
I-S
11
RES
24
32 G
10 G
0 msec
50
100
150
200
250
CHEST ACCEL.
C-2



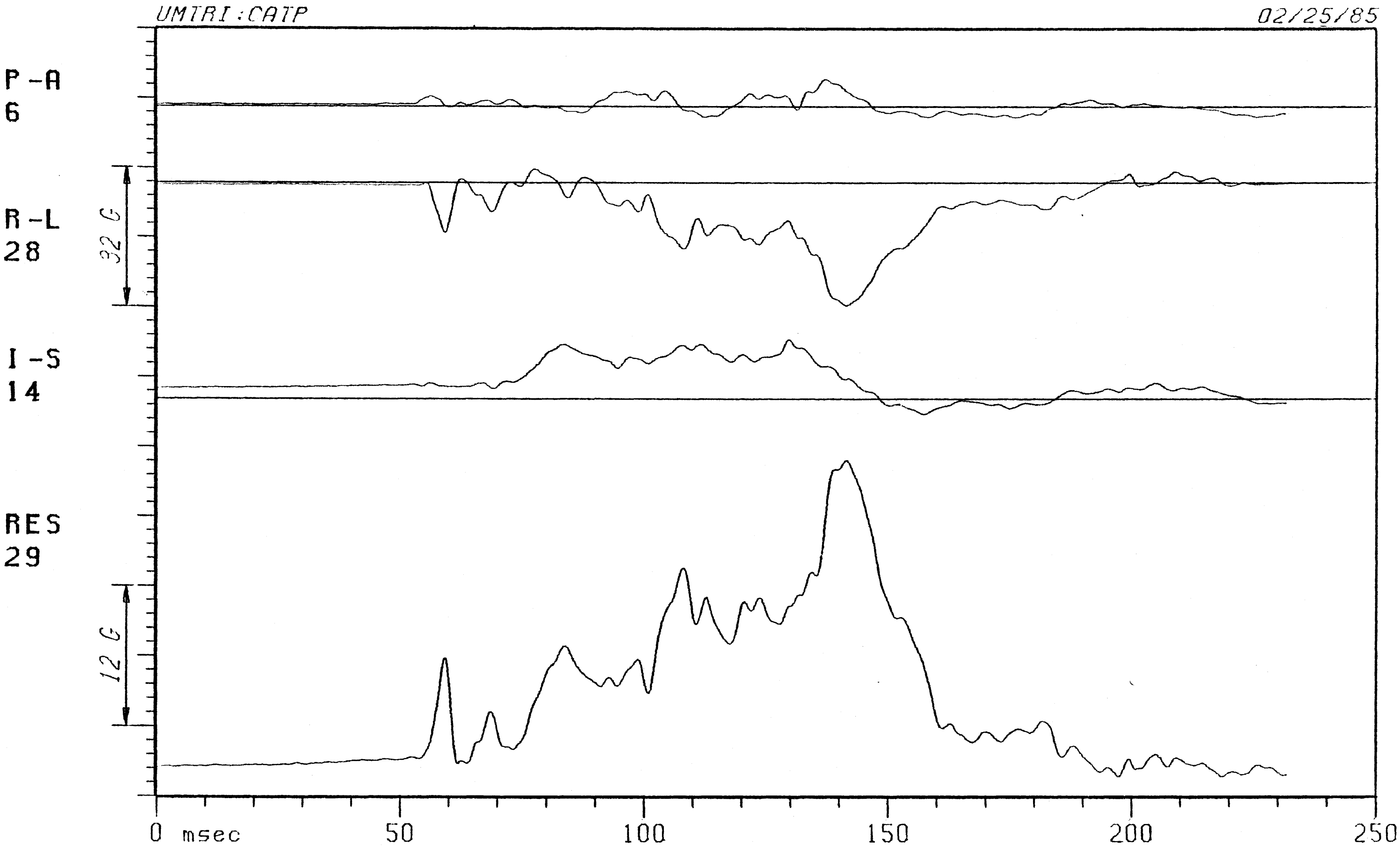
CHEST ACCEL. C-3


UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
32 G
10 G
P-A 4
R-L 23
I-S 10
RES 24
CHEST ACCEL.
C-XL



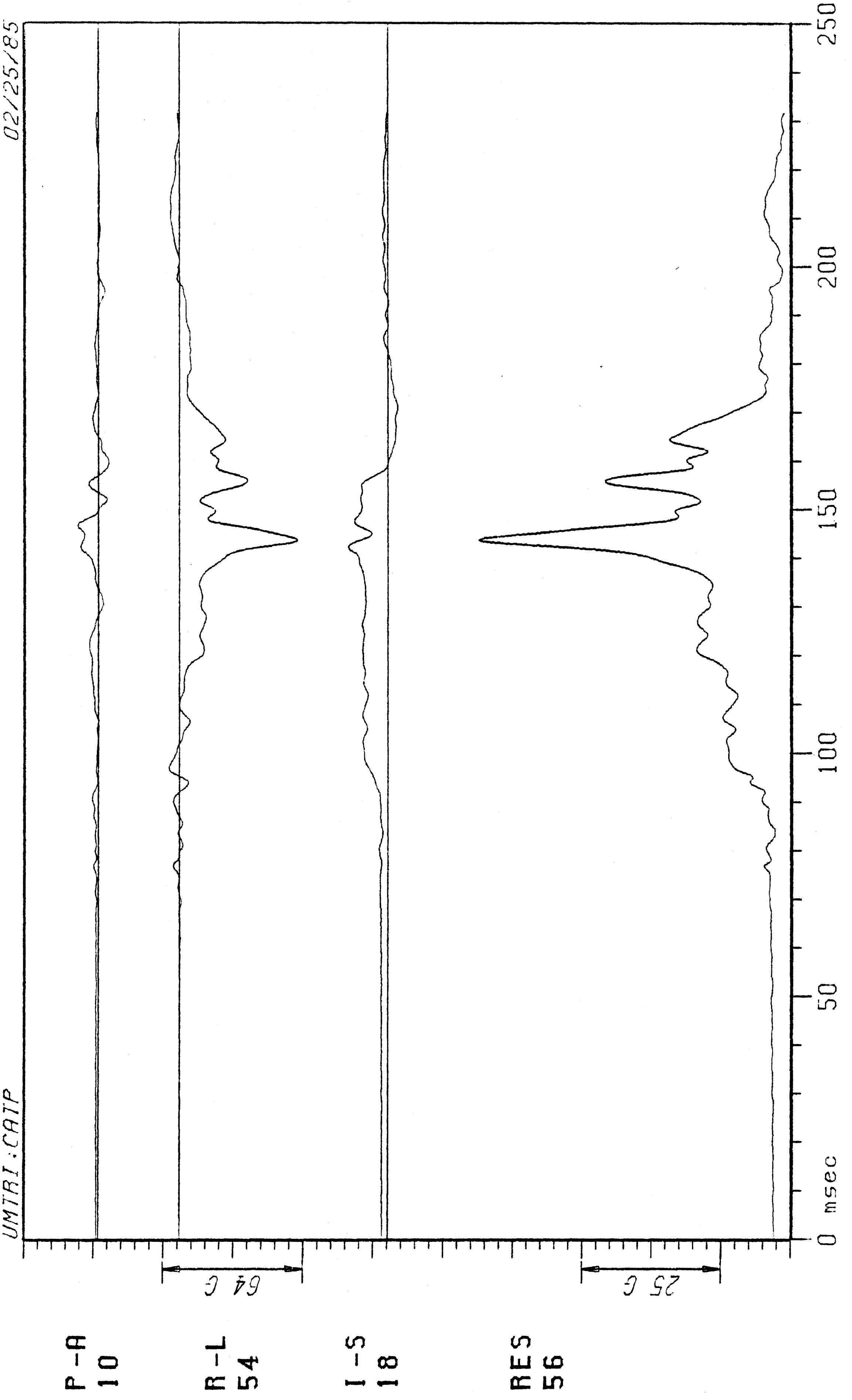
CHEST ACCEL.

C-XH



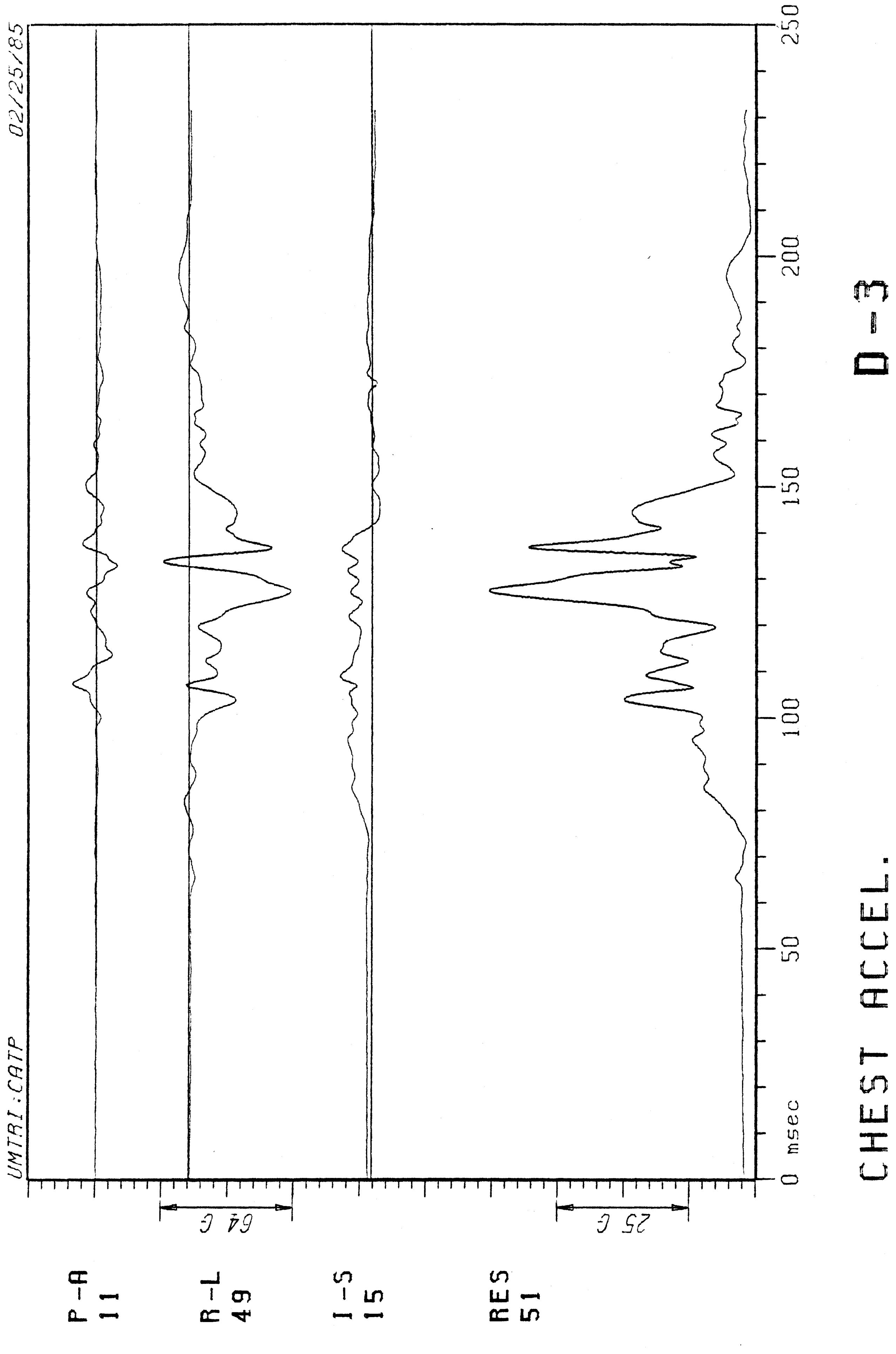
CHEST ACCEL.

D-1



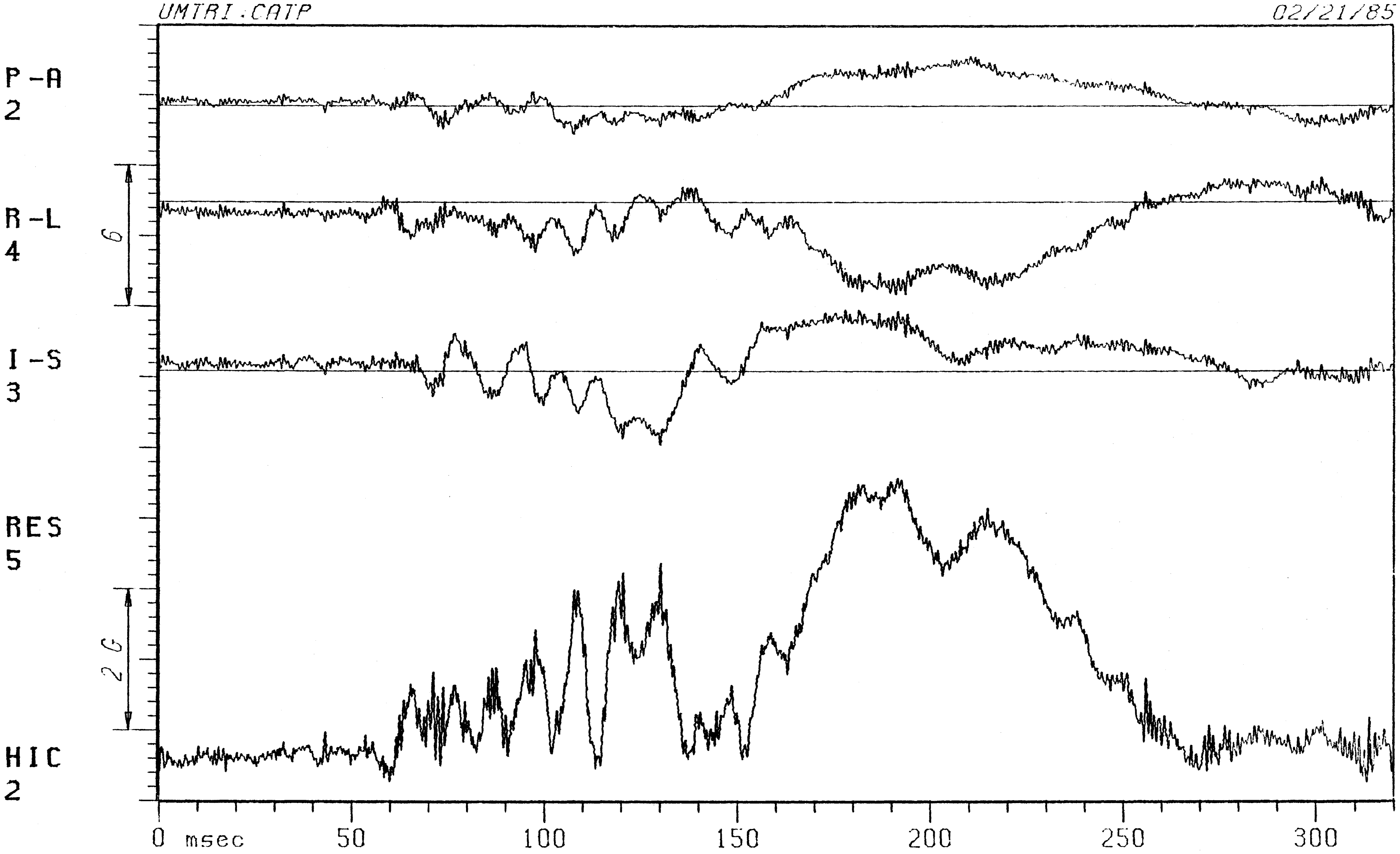
CHEST ACCEL.

D-2

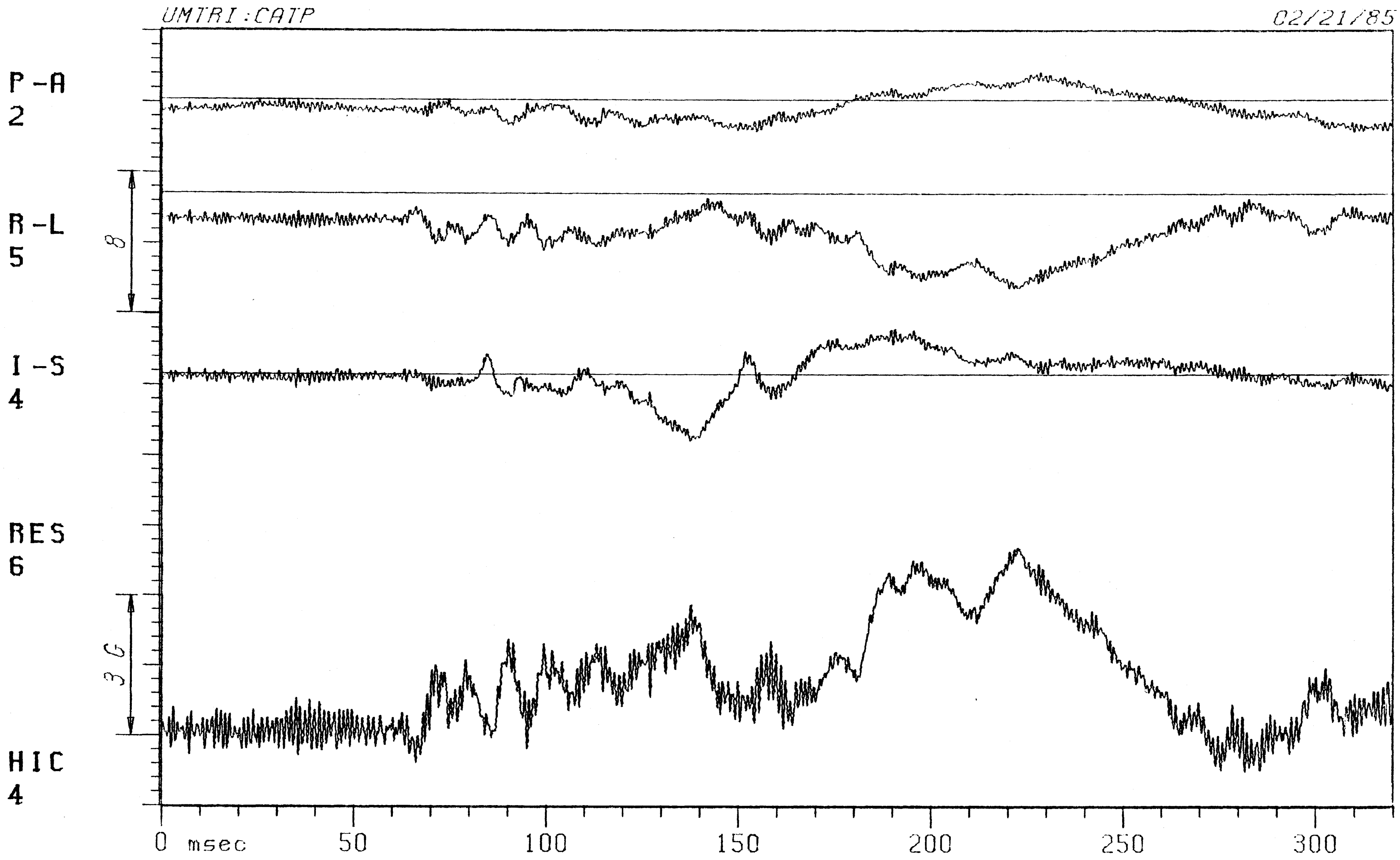

UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
64 G
25 G
P-A 11
R-L 49
I-S 15
RES 51
CHEST ACCEL.
D-3

SECTION 5

Head Accelerations

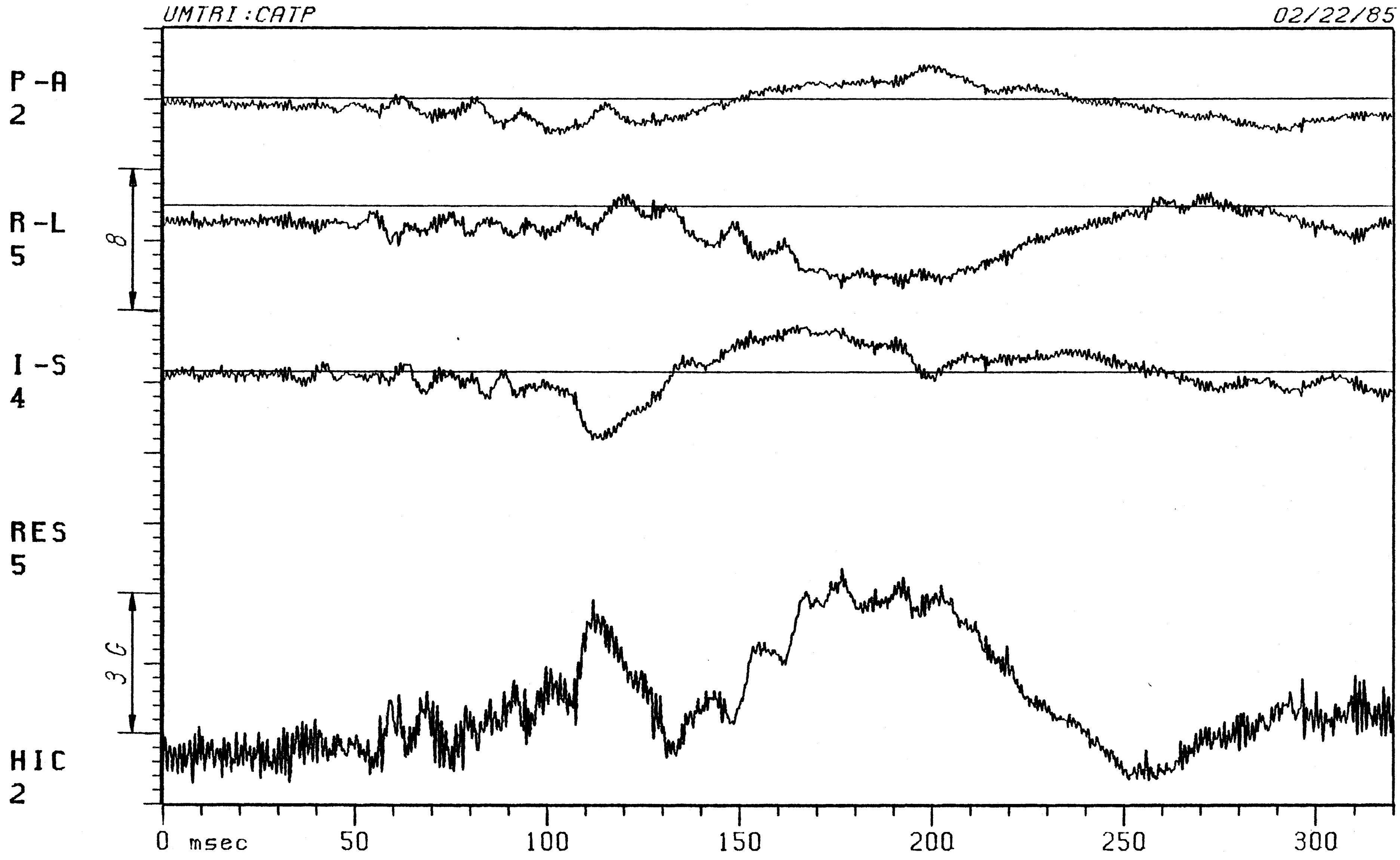


HEAD ACCEL. B-1



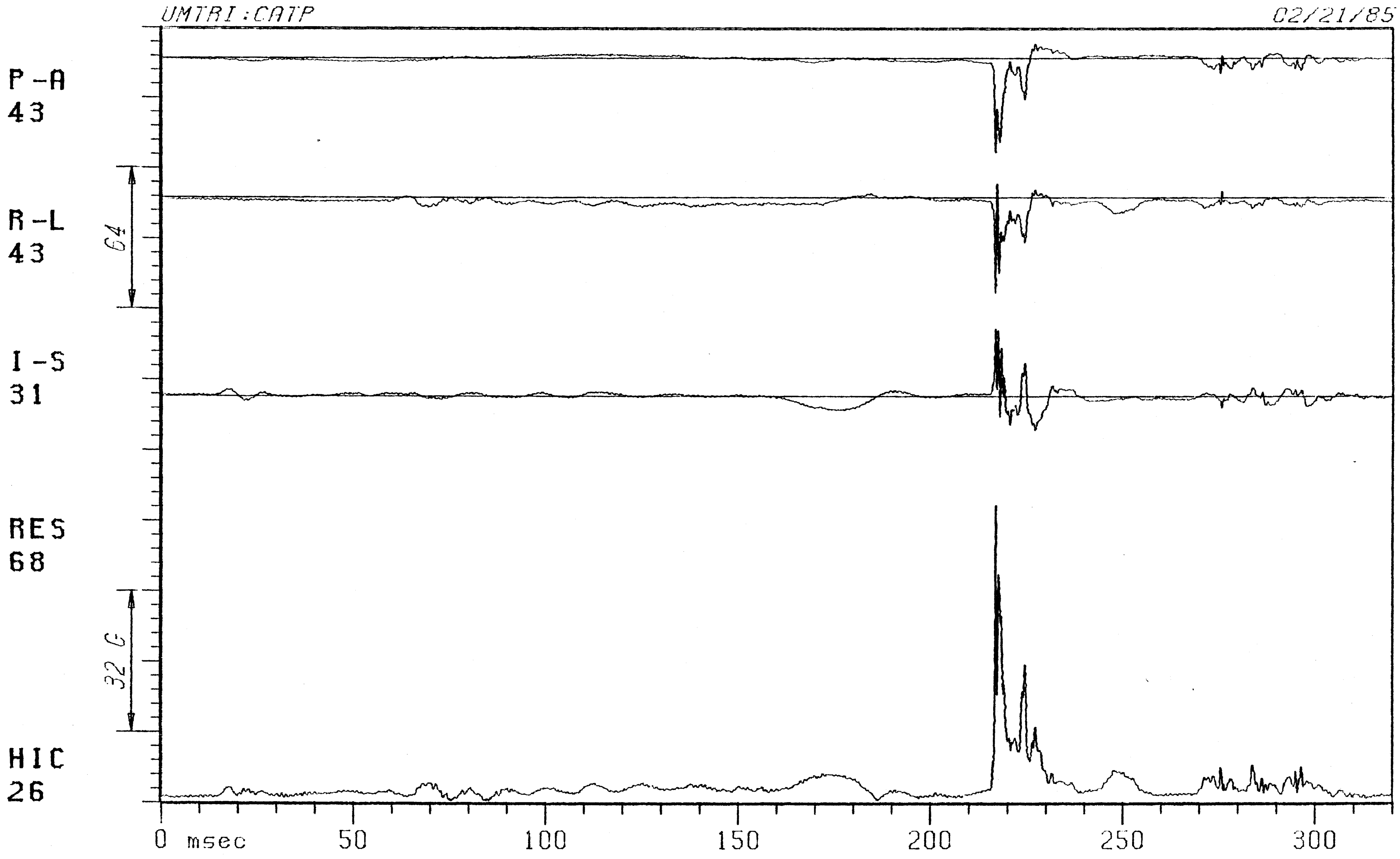
HEAD ACCEL.

B-2

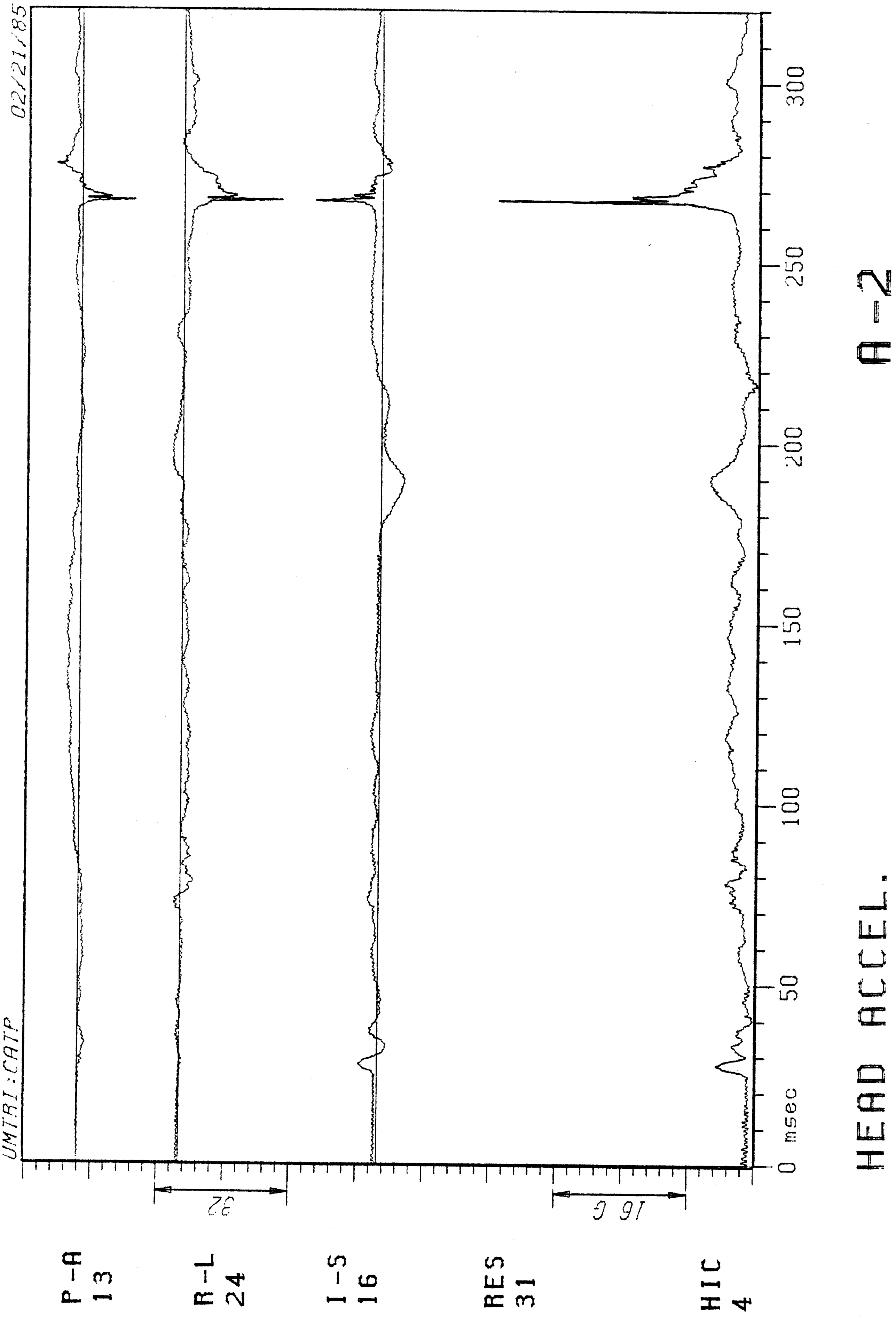


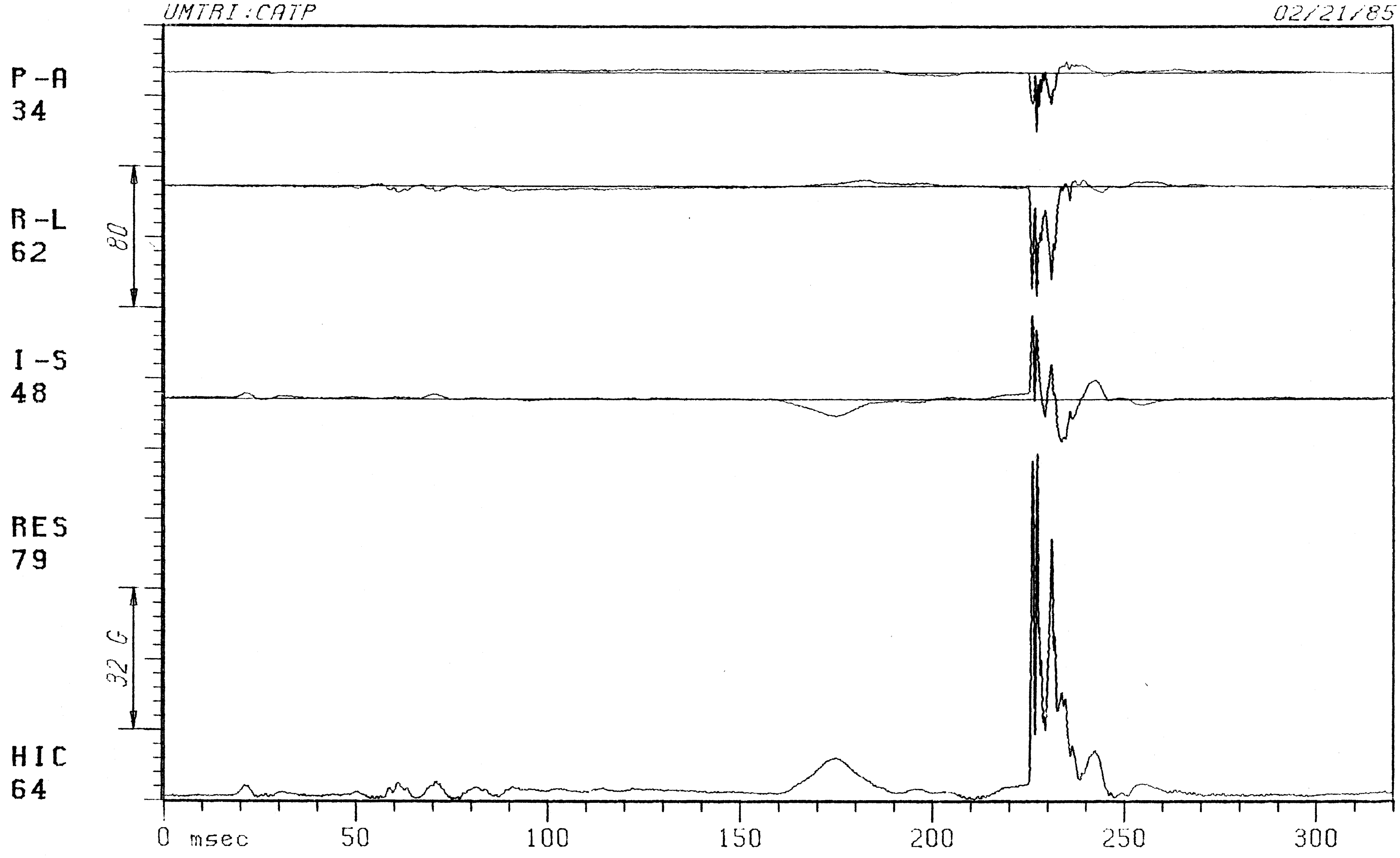
HEAD ACCEL.

B-3



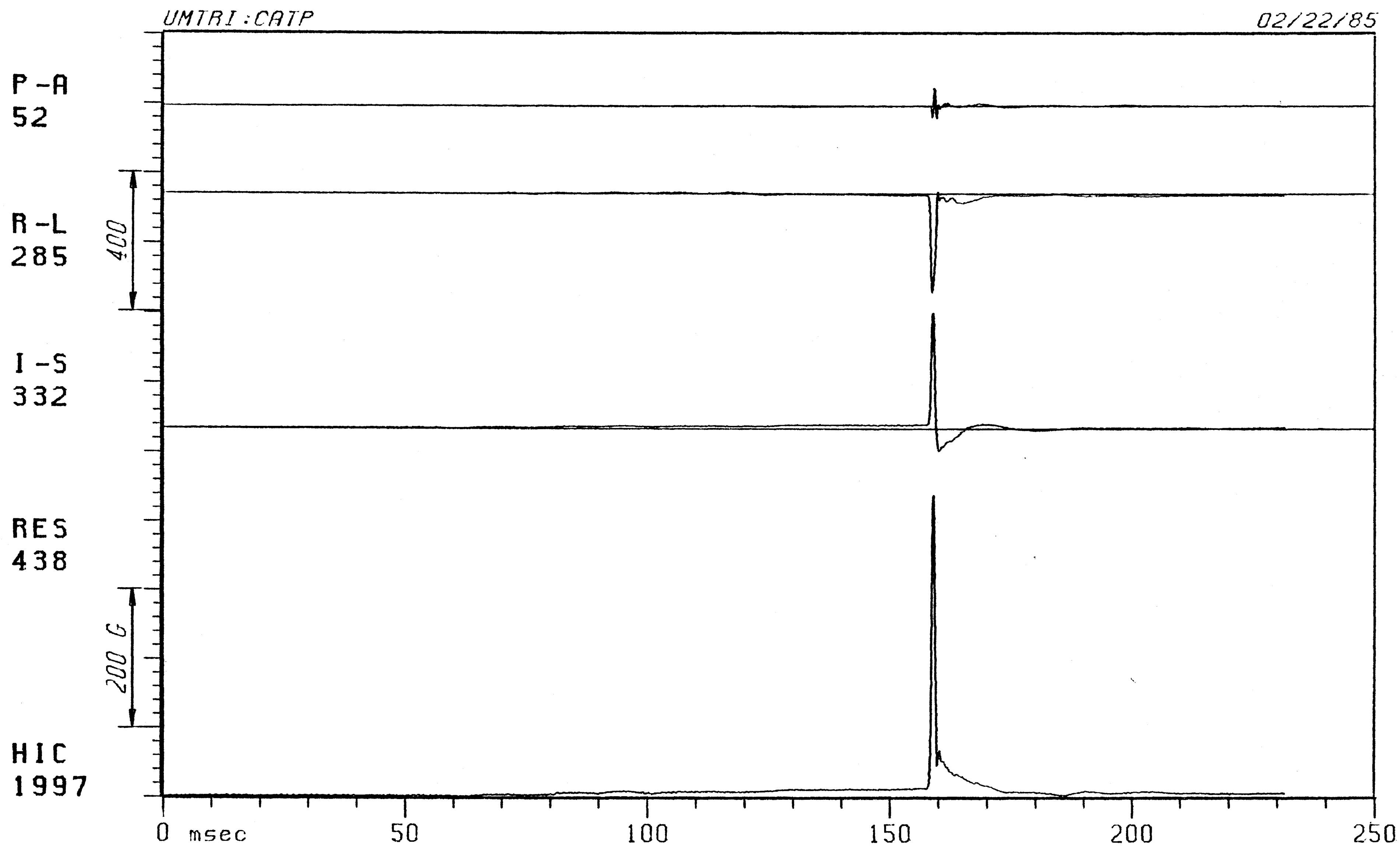
HEAD ACCEL. A-1


UMTRI:CATP
02/21/85
P-A
13
R-L
24
I-S
16
RES
31
HIC
4
32
16 G
0 msec
50
100
150
200
250
300
HEAD ACCEL.
A-2



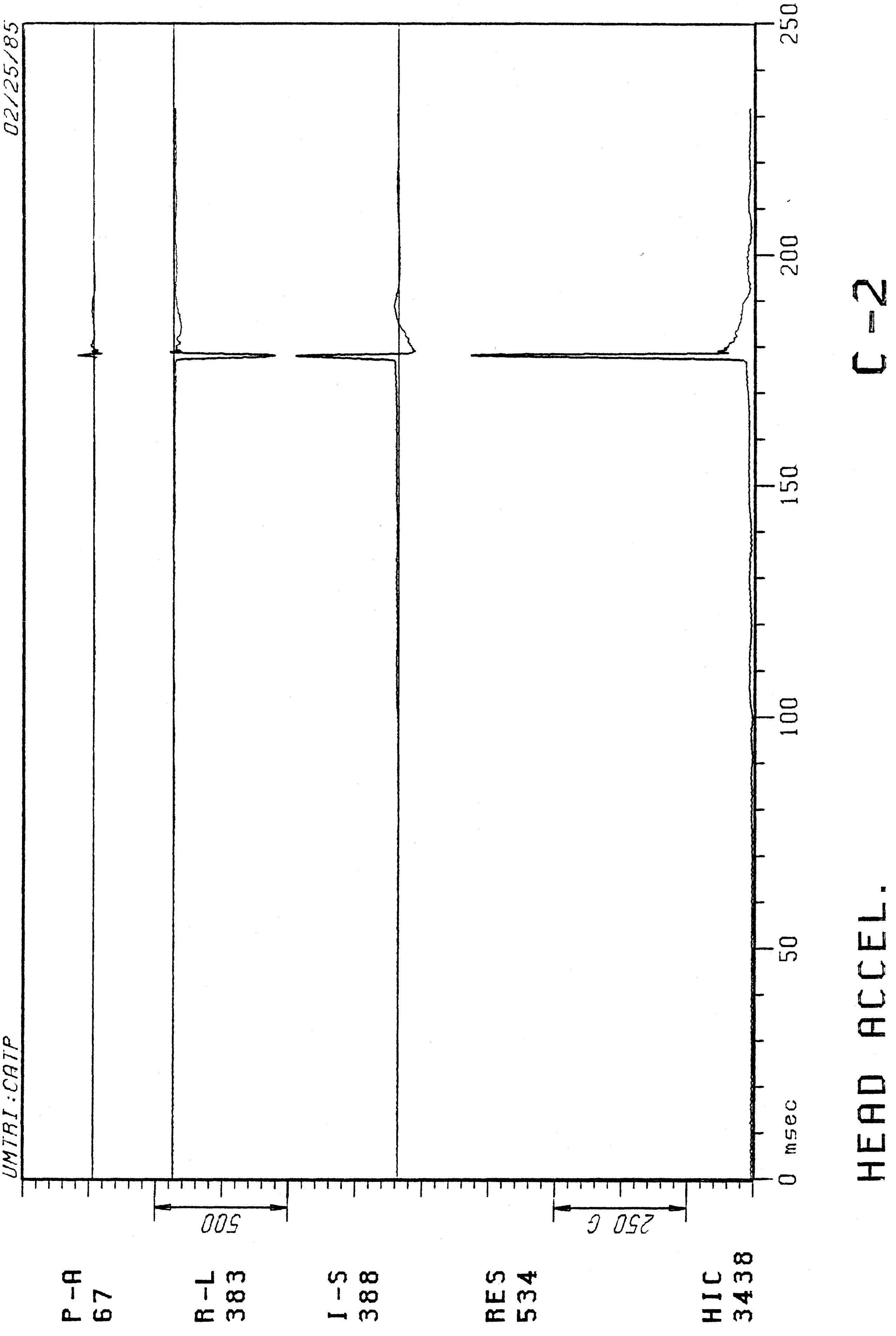
HEAD ACCEL.

A-3

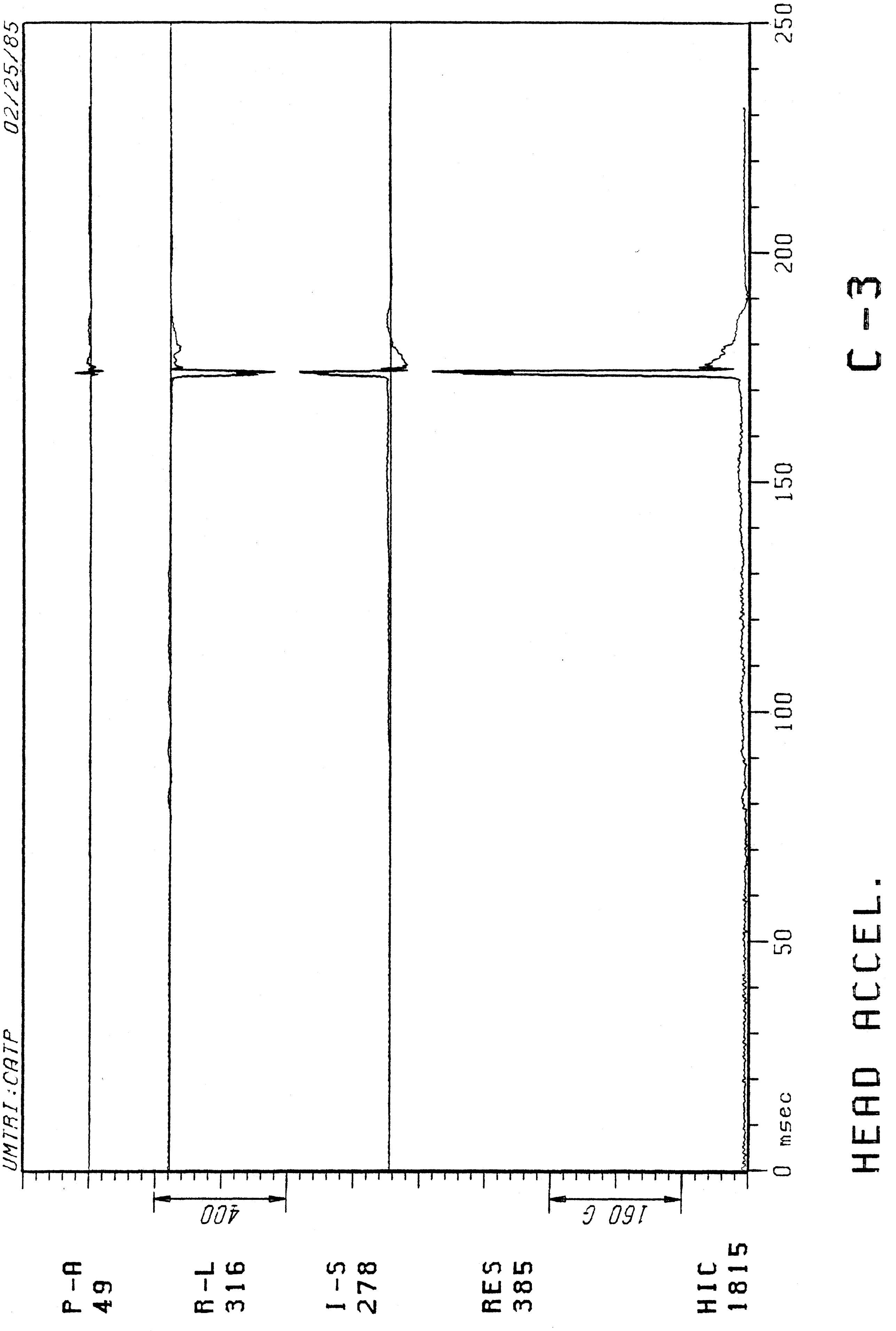


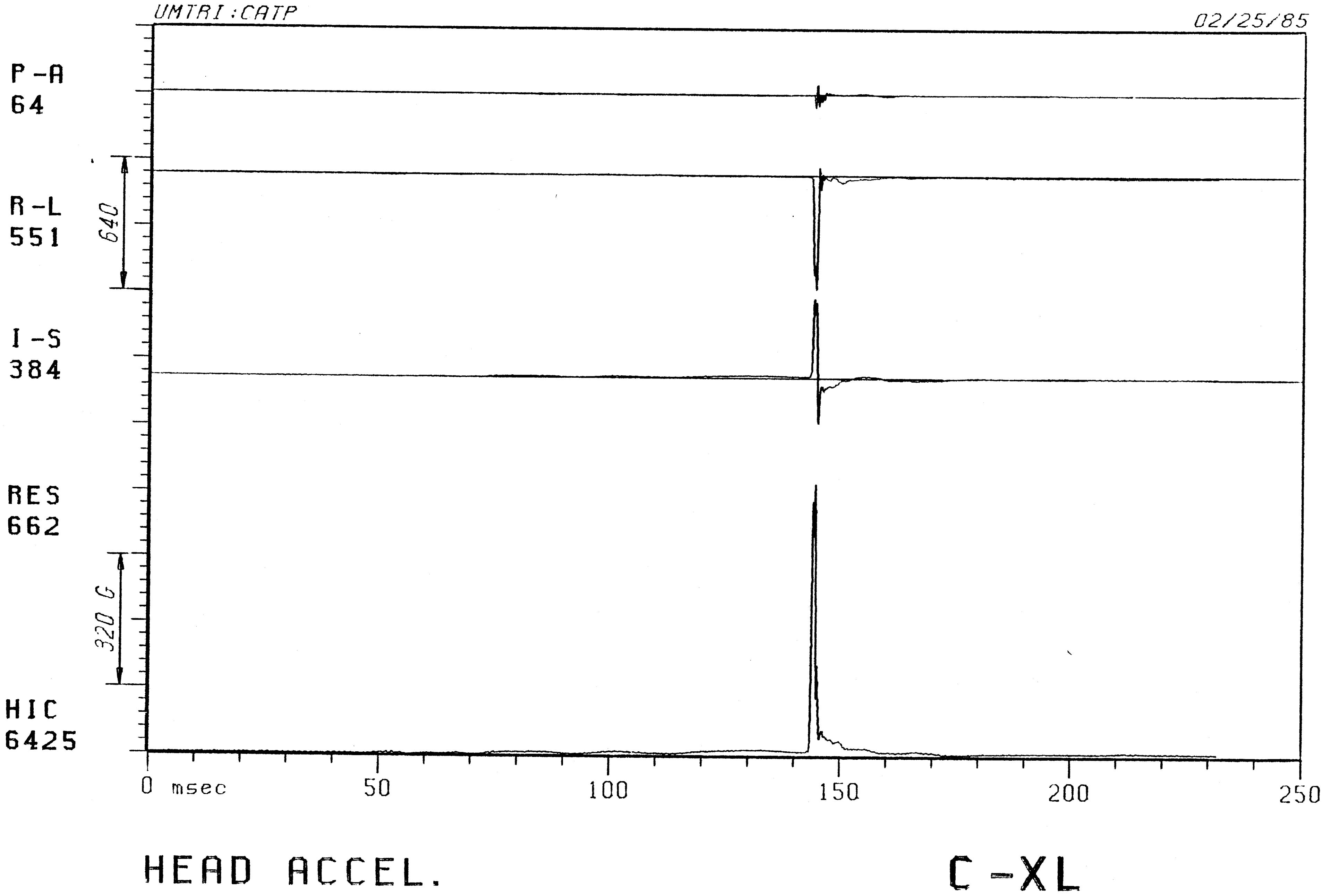
HEAD ACCEL.

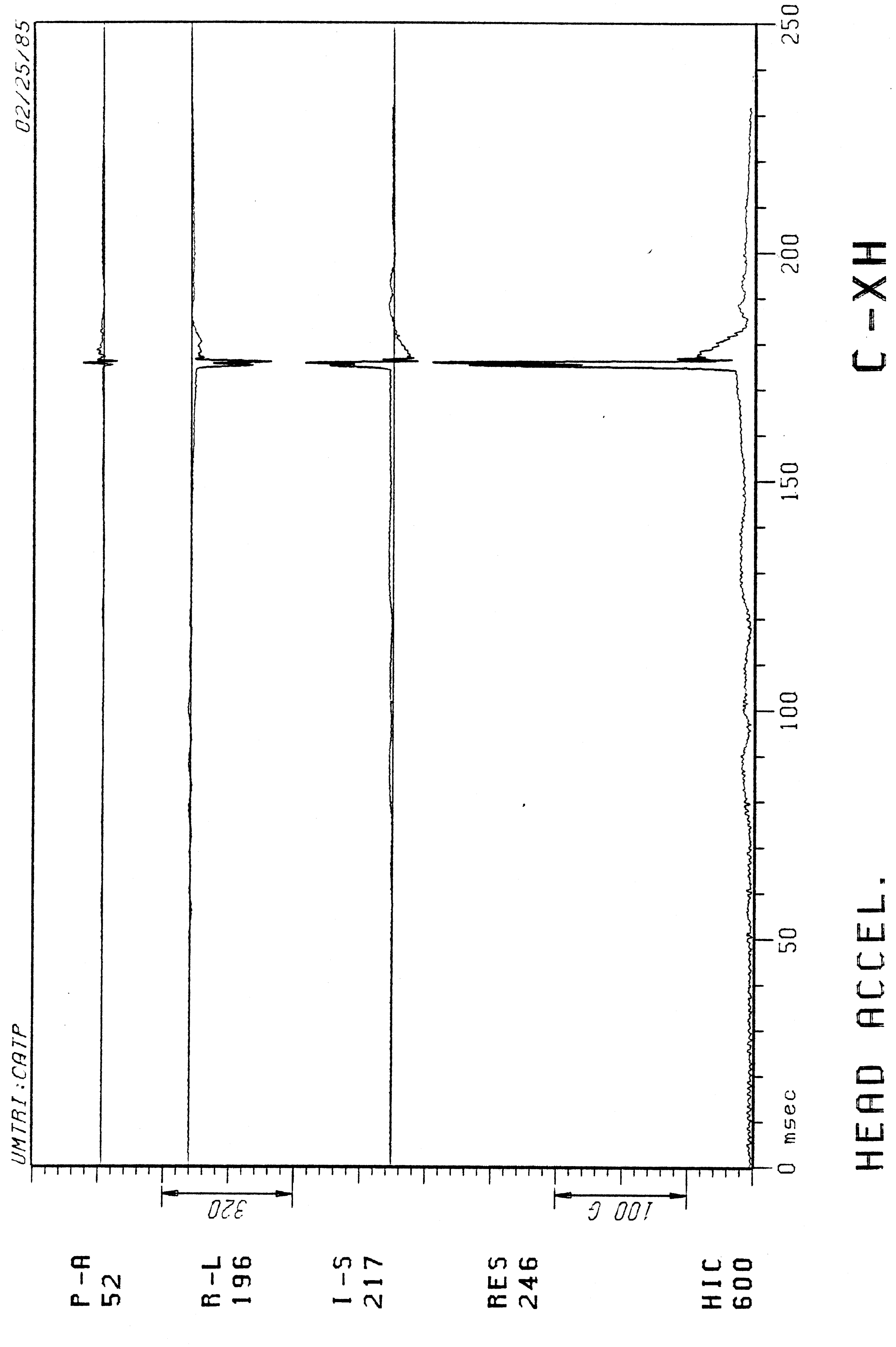
C-1



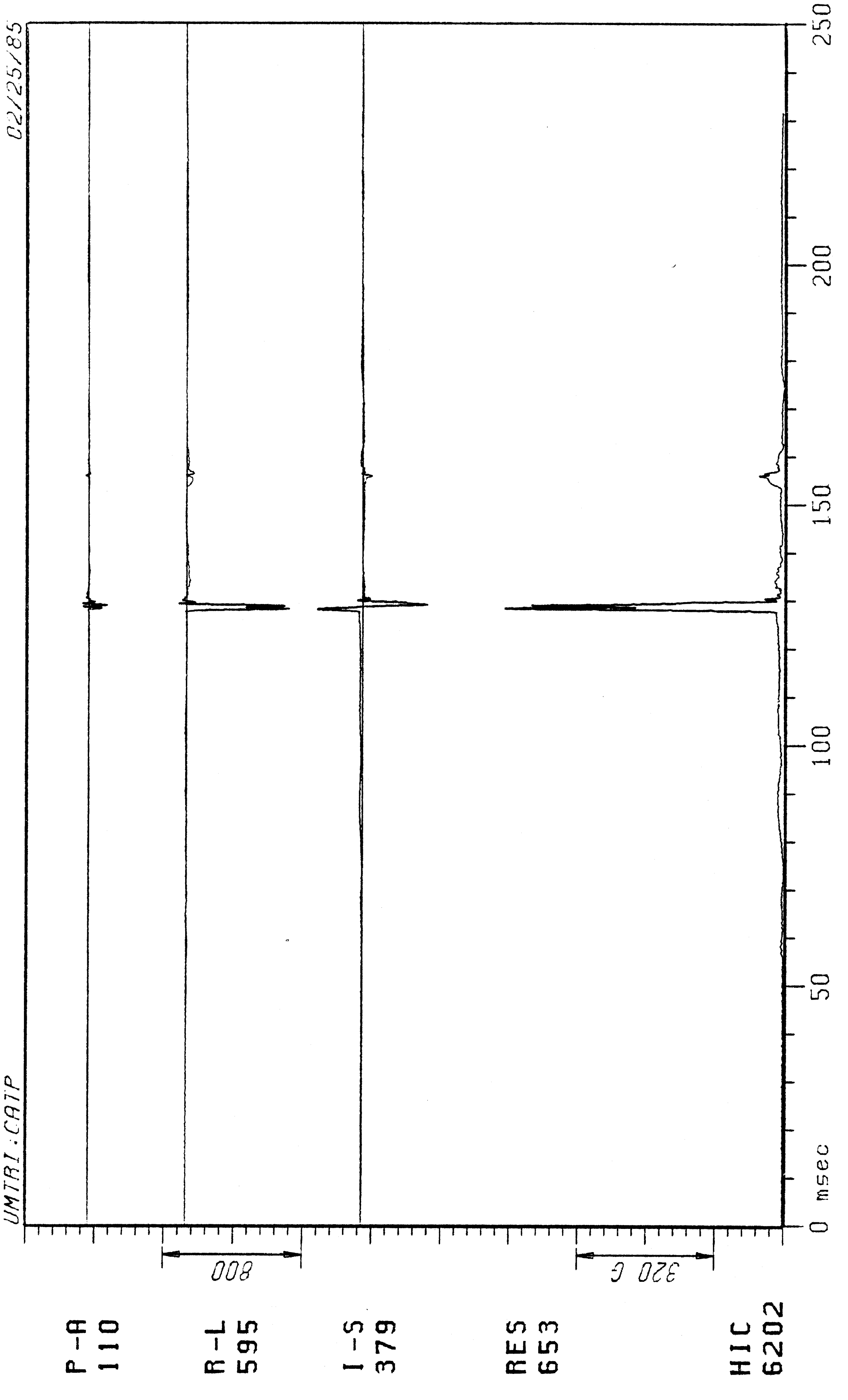
UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
500
250 G
P-A 67
R-L 383
I-S 388
RES 534
HIC 3438
HEAD ACCEL.
C-2


UMTRI:CATP
02/25/85
P-A 49
R-L 316
I-S 278
RES 385
HIC 1815
400
160 G
0 msec
50
100
150
200
250
HEAD ACCEL.
C-3

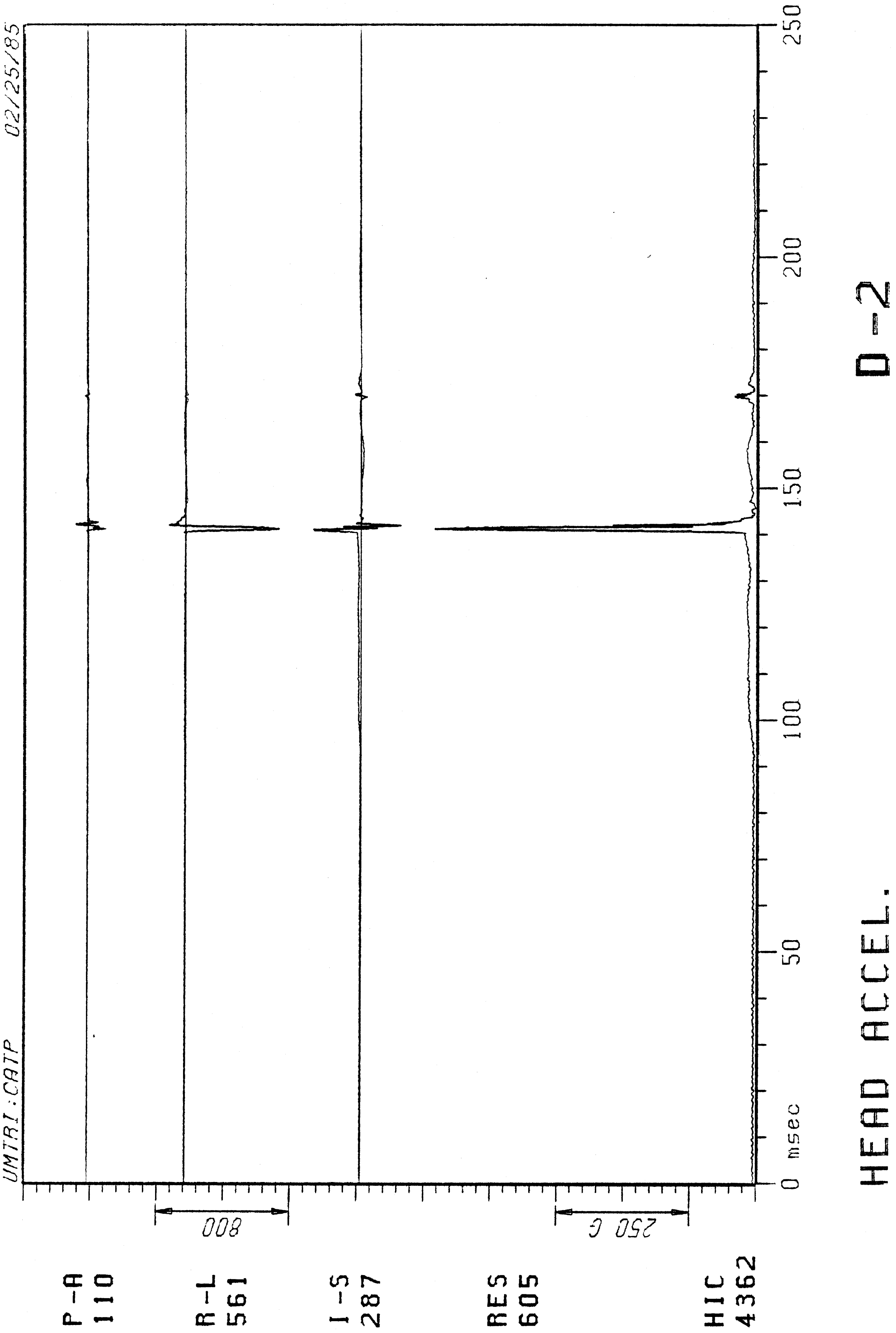

UMTRI:CATP
02/25/85
P-A
64
R-L
551
I-S
384
RES
662
HIC
6425
640
320 G
0 msec
50
100
150
200
250
HEAD ACCEL.
C-XL



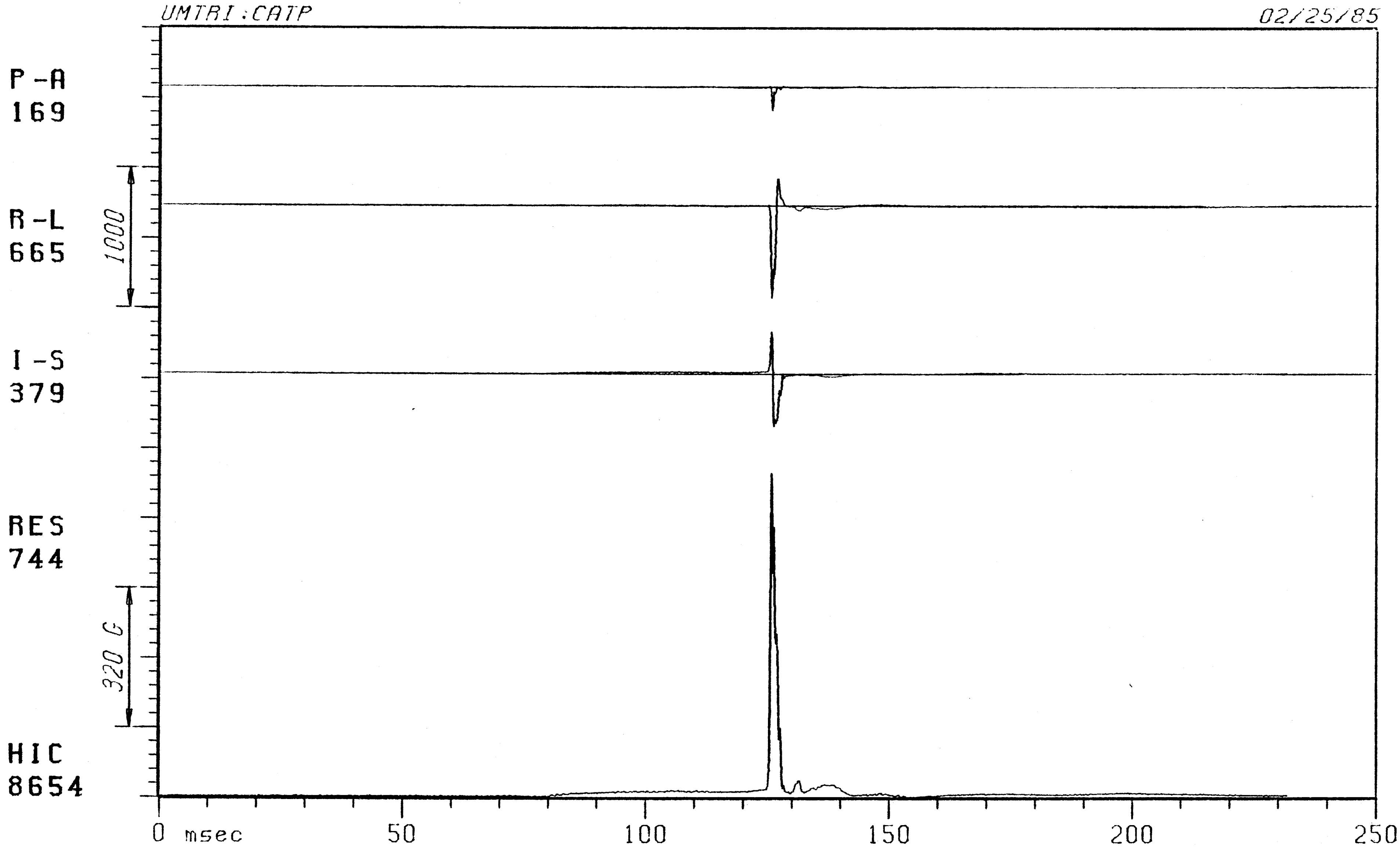
UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
320
100 G
P-A 52
R-L 196
I-S 217
RES 246
HIC 600
HEAD ACCEL.
C-XH



HEAD ACCEL. D-1



UMTRI:CATP
02/25/85
0 msec
50
100
150
200
250
800
250 G
P-A 110
R-L 561
I-S 287
RES 605
HIC 4362
HEAD ACCEL.
D-2

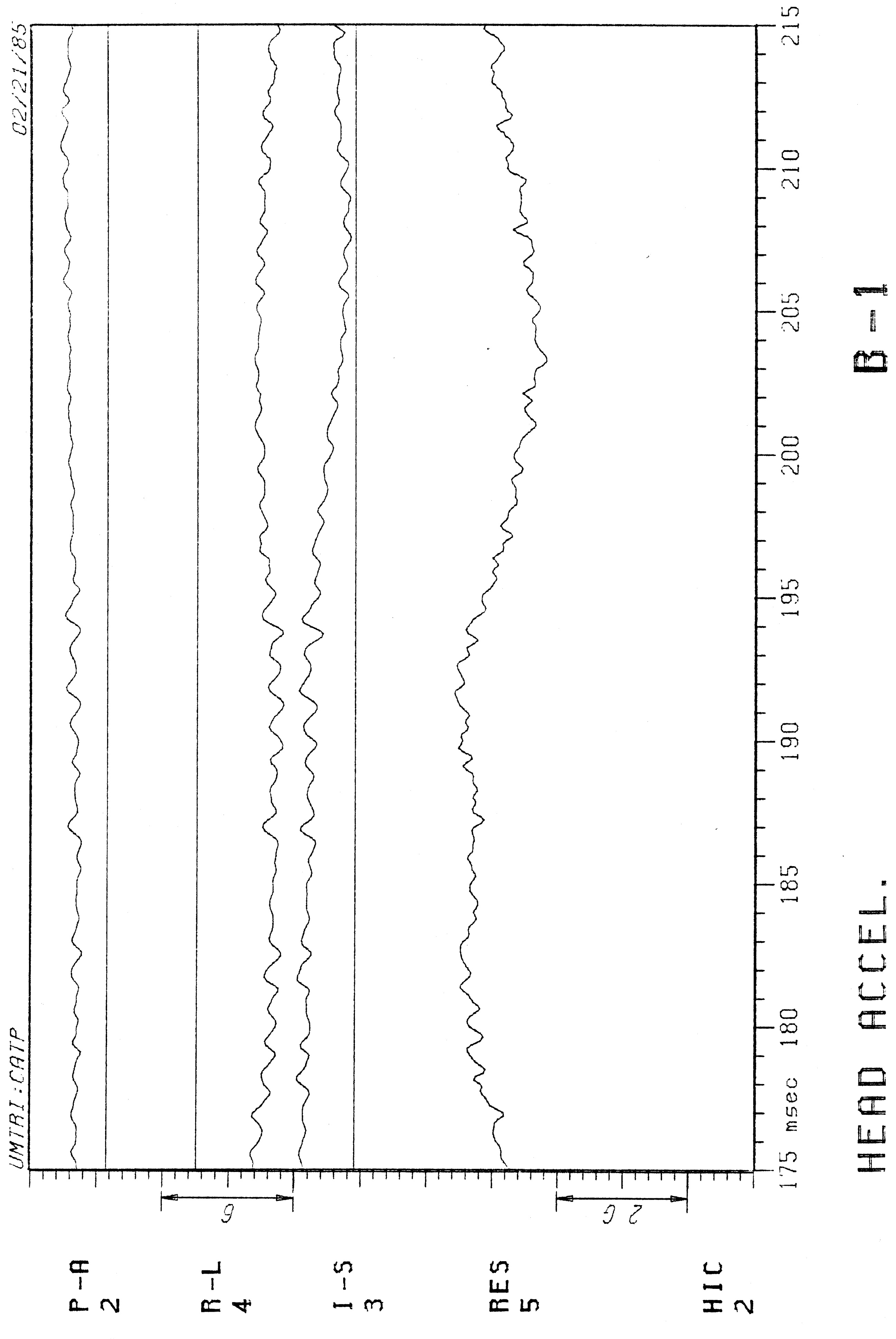


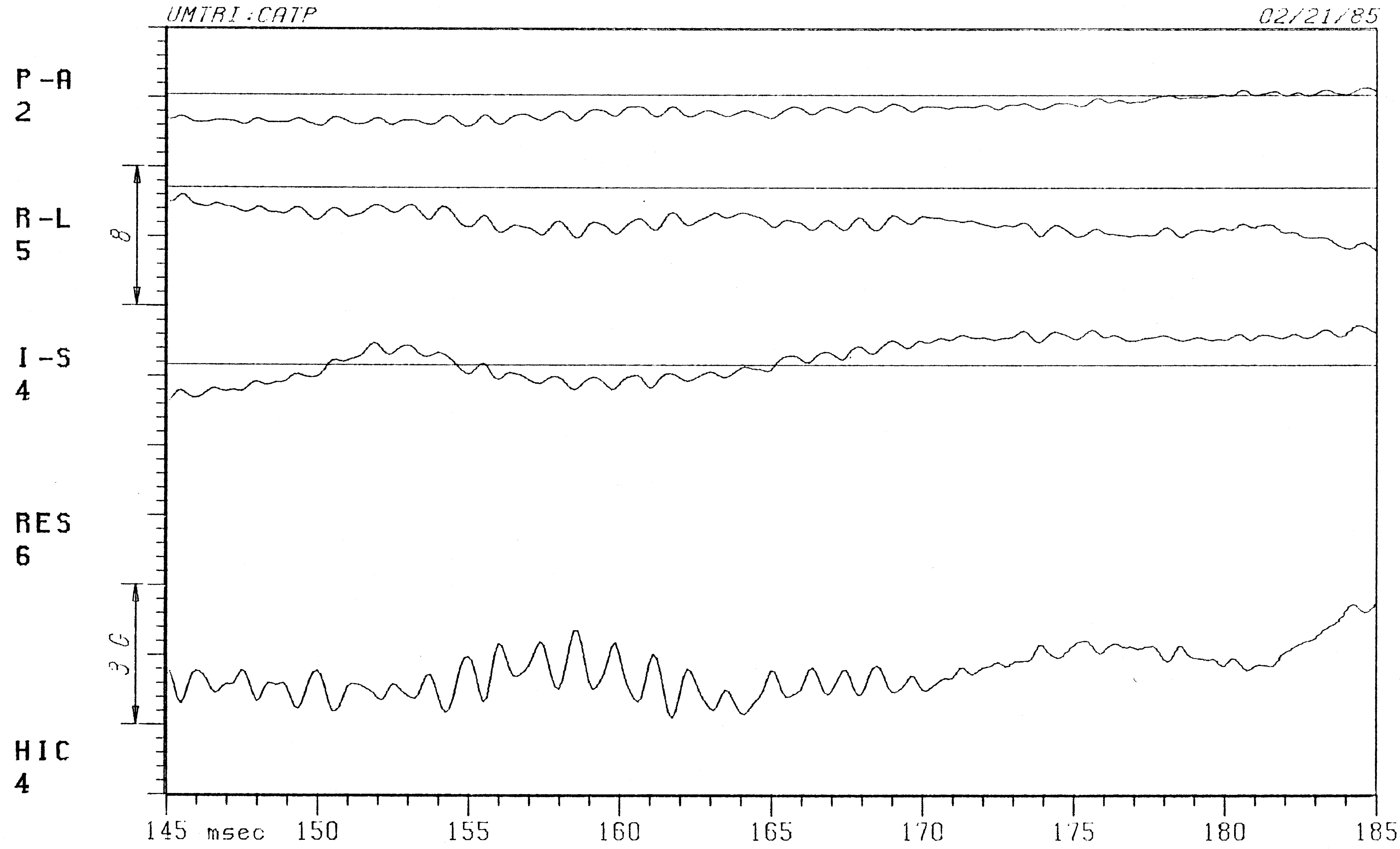
HEAD ACCEL.

D-3

SECTION 6

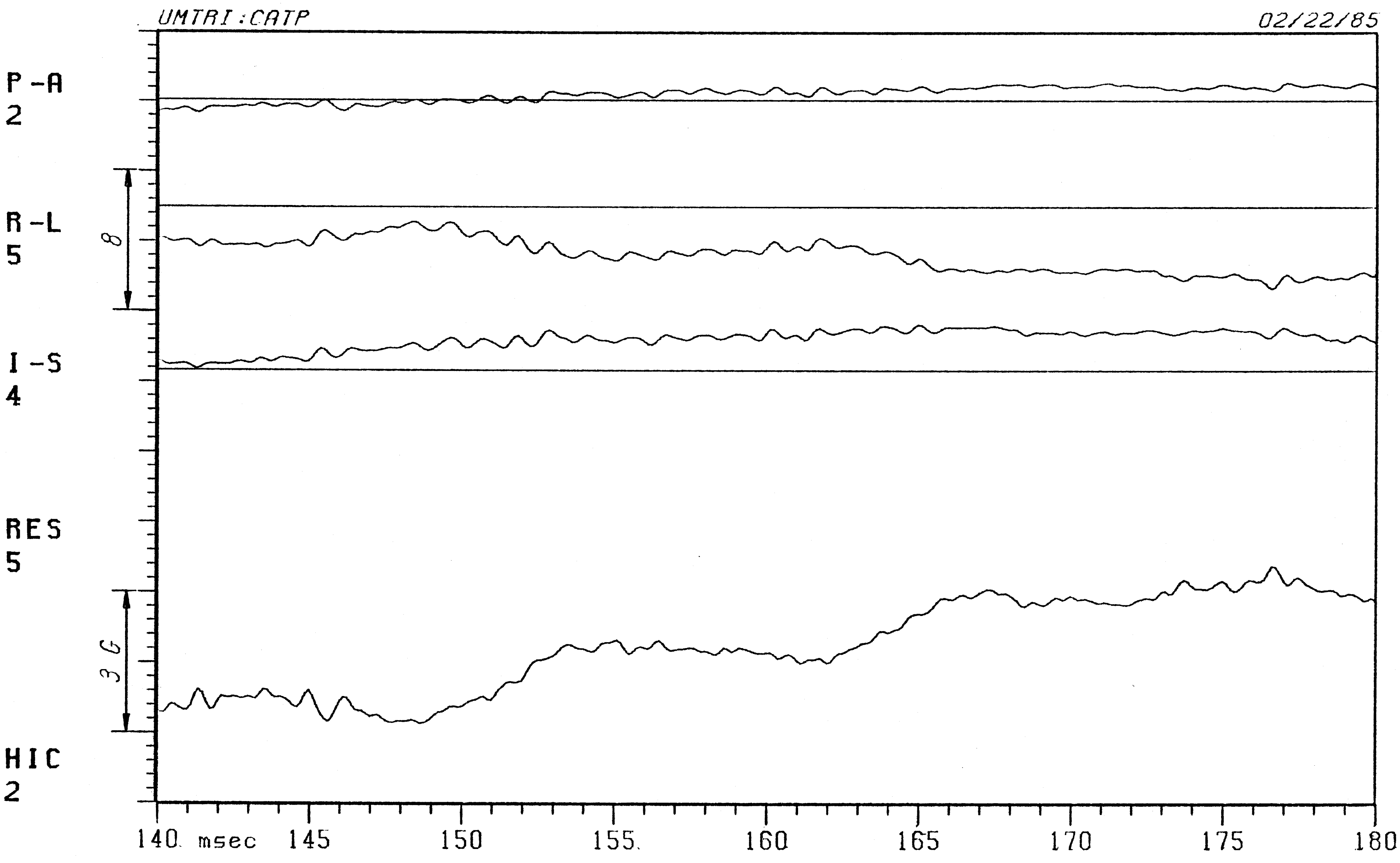
Expanded Head Accelerations


HEAD ACCEL.
B-1
UMTRI:CATP
02/21/85
175 msec
180
185
190
195
200
205
210
215
g
2 G
P-A 2
R-L 4
I-S 3
RES 5
HIC 2



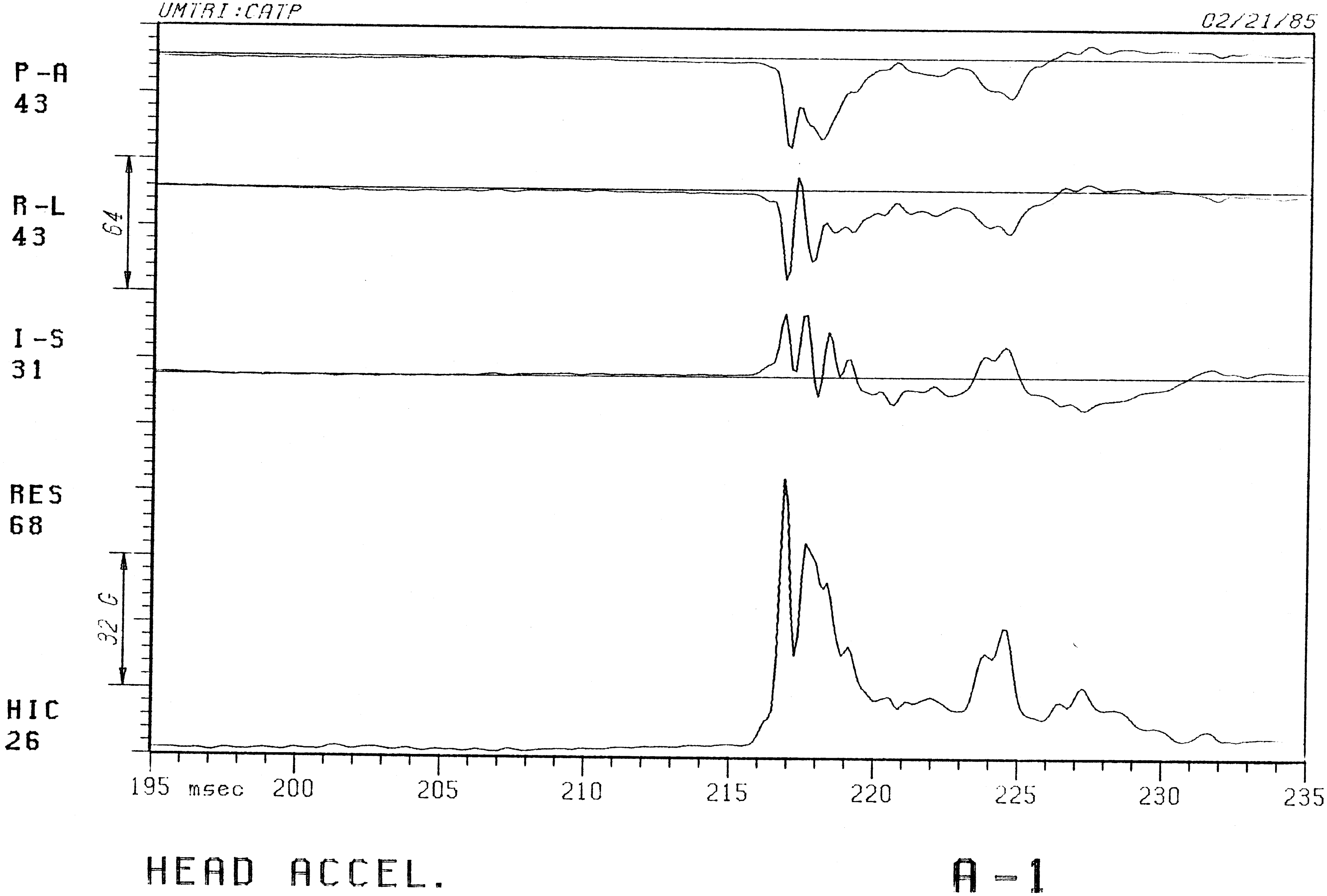
HEAD ACCEL.

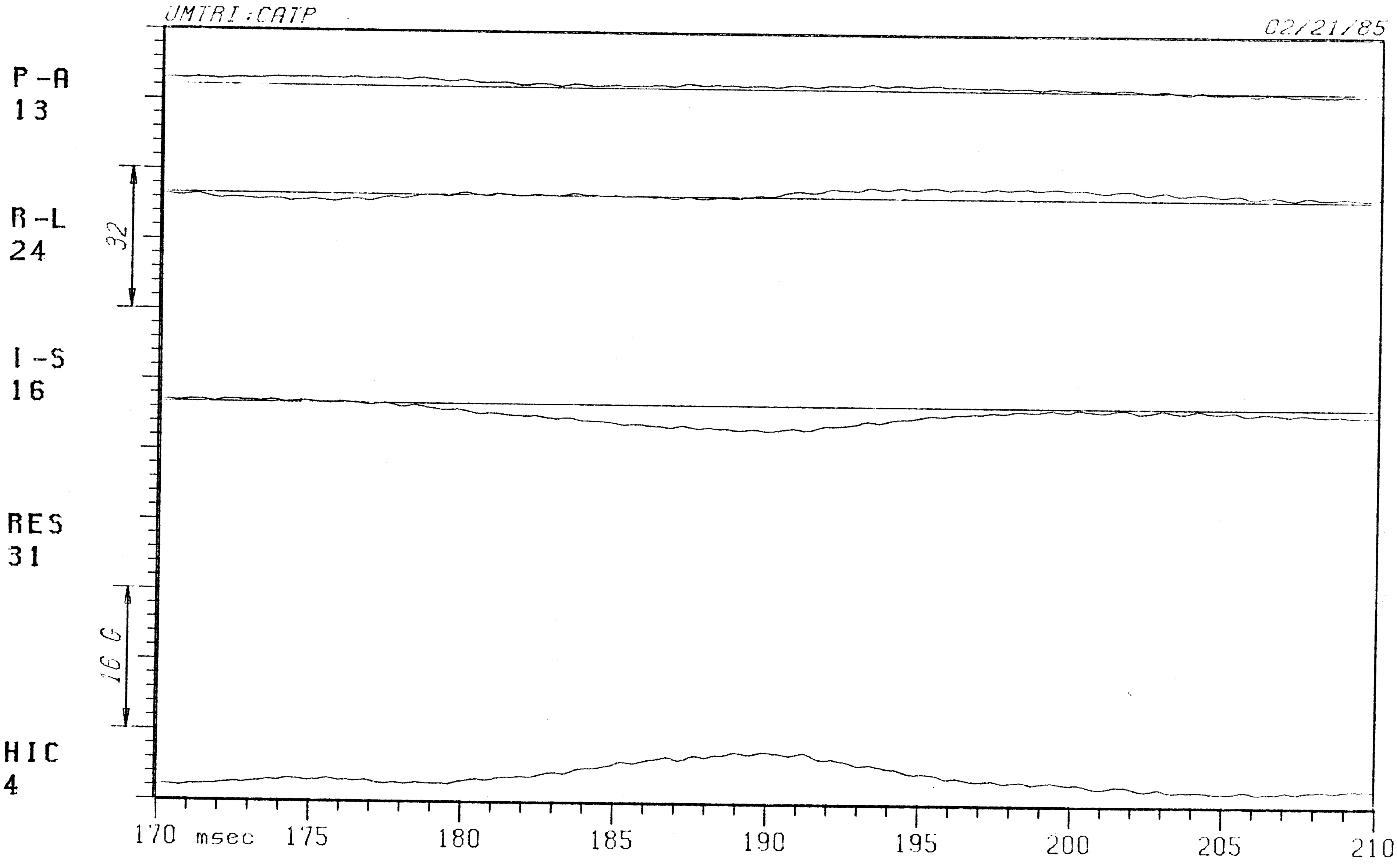
B-2



HEAD ACCEL.

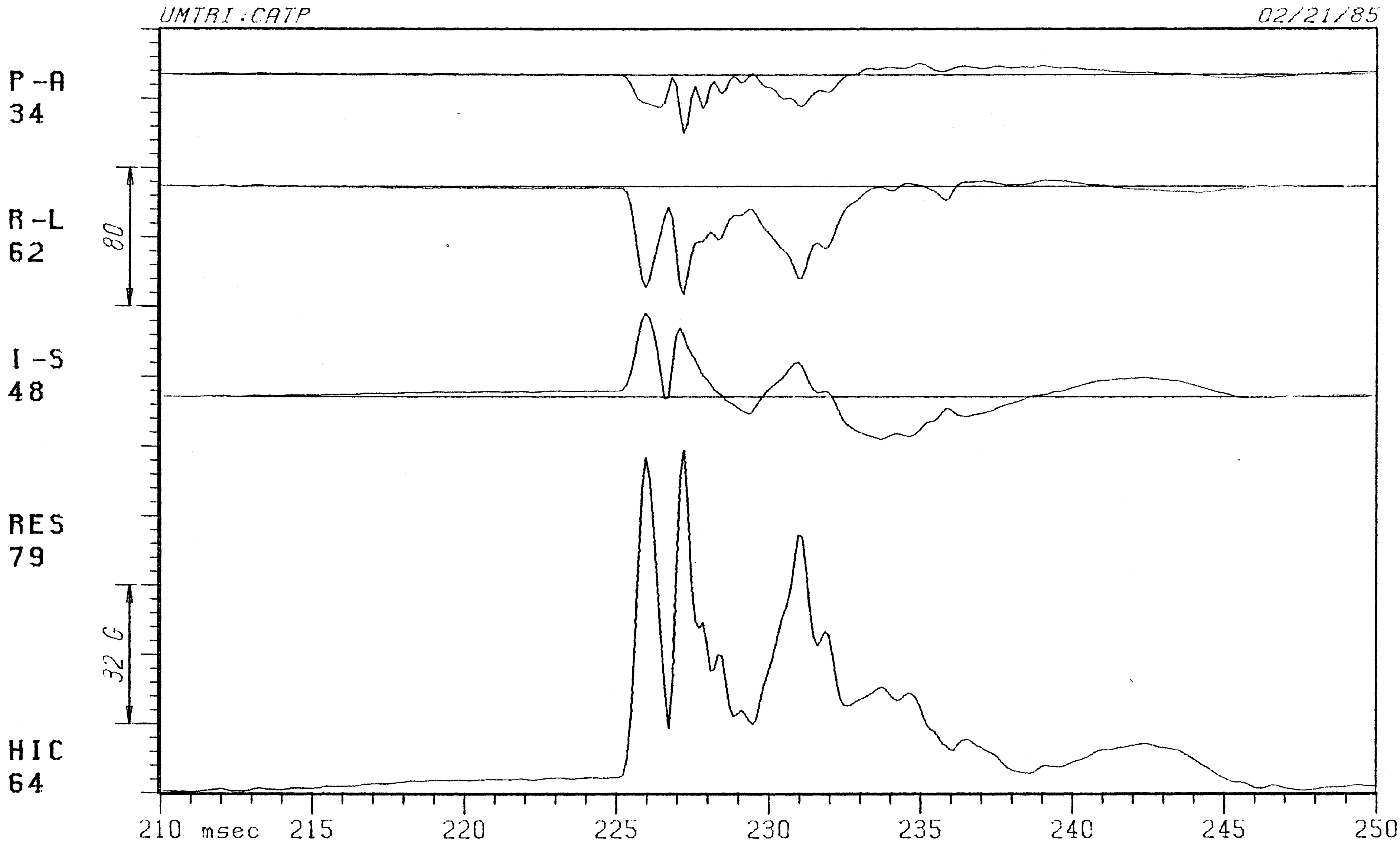
B-3


UMTRI:CATP
02/21/85
P-A
43
R-L
43
I-S
31
RES
68
HIC
26
64
32 G
195 msec 200 205 210 215 220 225 230 235
HEAD ACCEL.
A-1

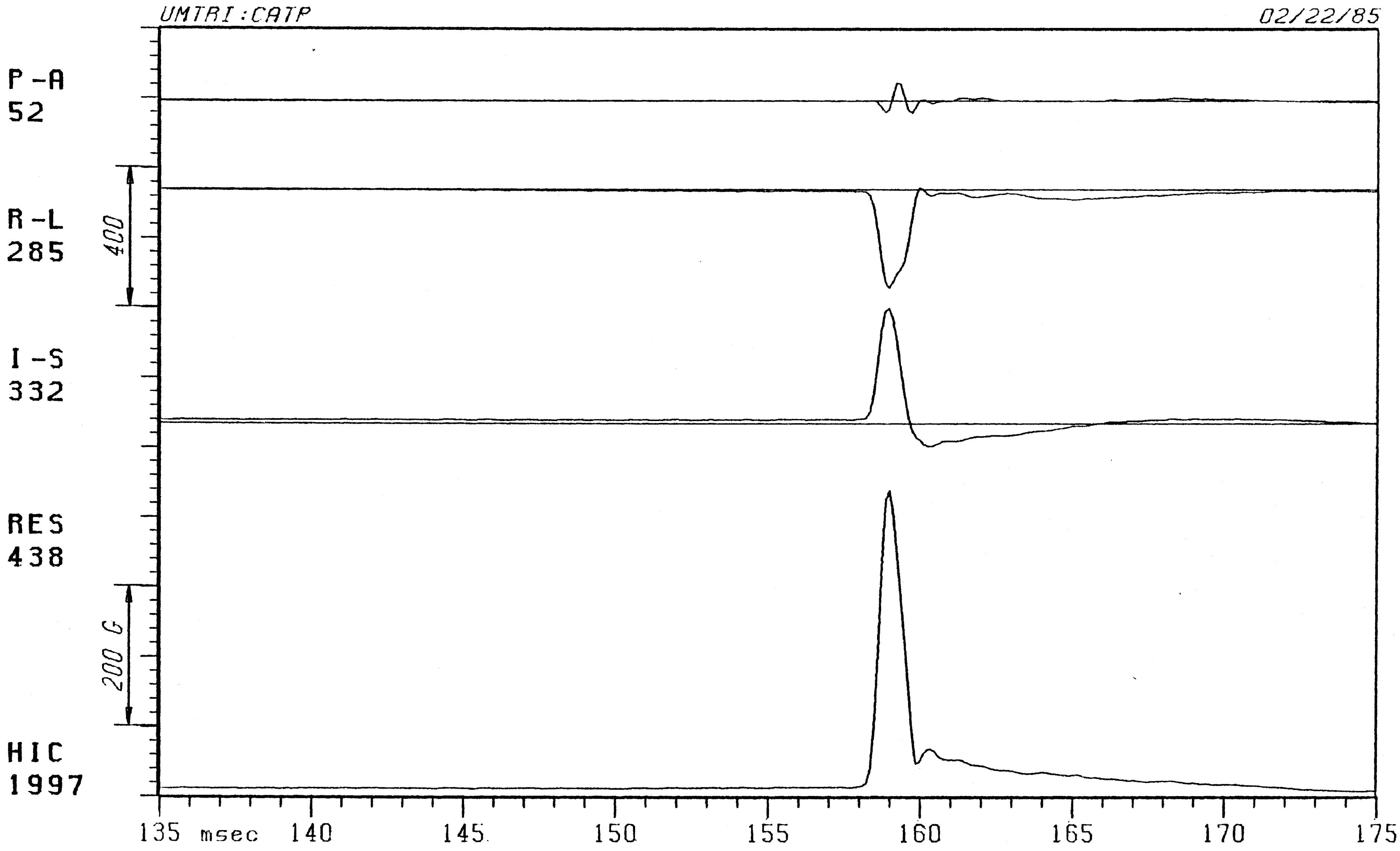


HEAD ACCEL.

A-2



HEAD ACCEL. A-3



HEAD ACCEL. C-1

C-2

MISSING DATA

HEAD ACCEL.

HIC
3438

HEAD ACCEL. C-3

HIC
1815

MISSING DATA

C-XL

HEAD ACCEL.

HIC
6425

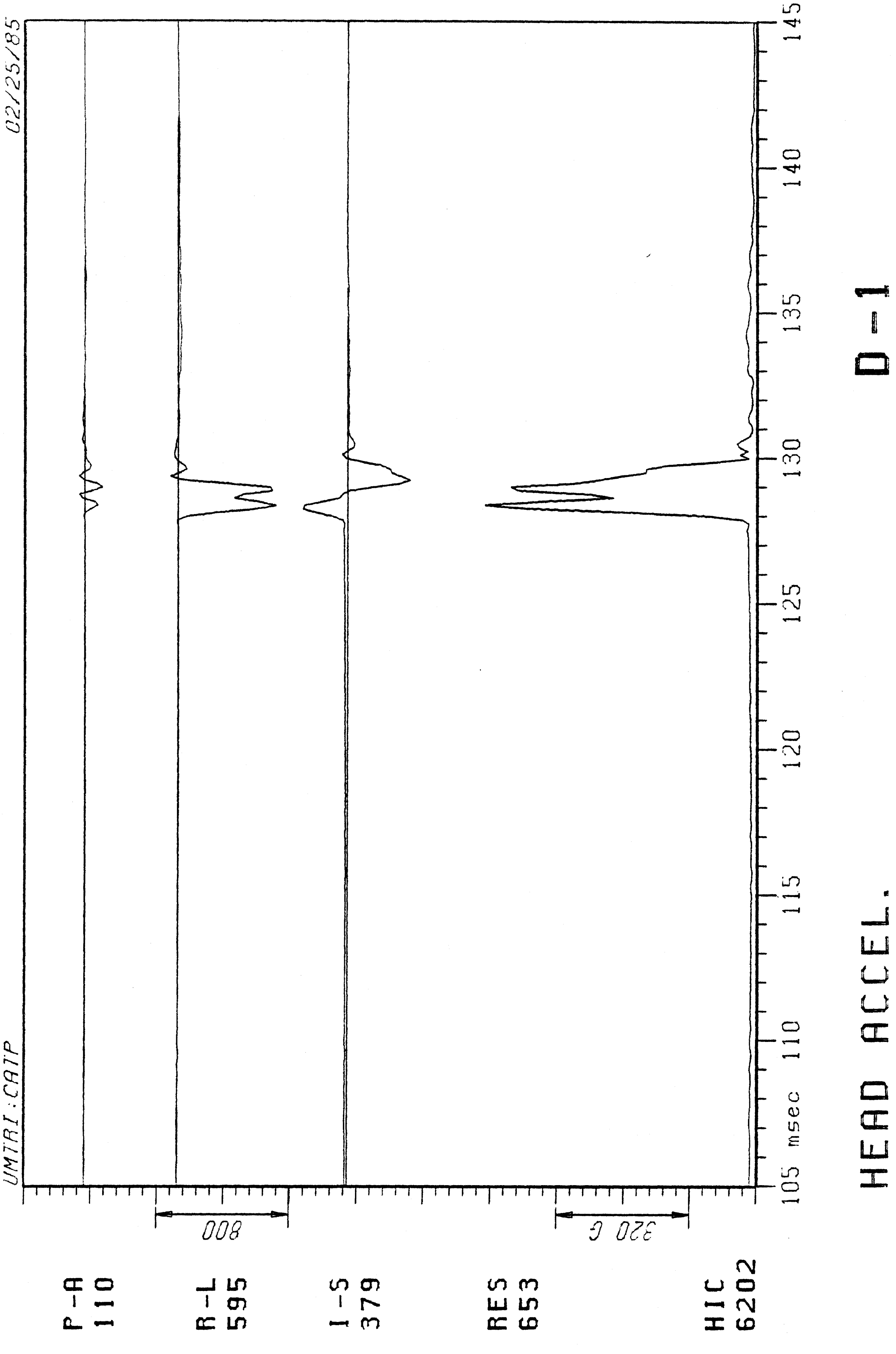
MISSING DATA

MISSING DATA

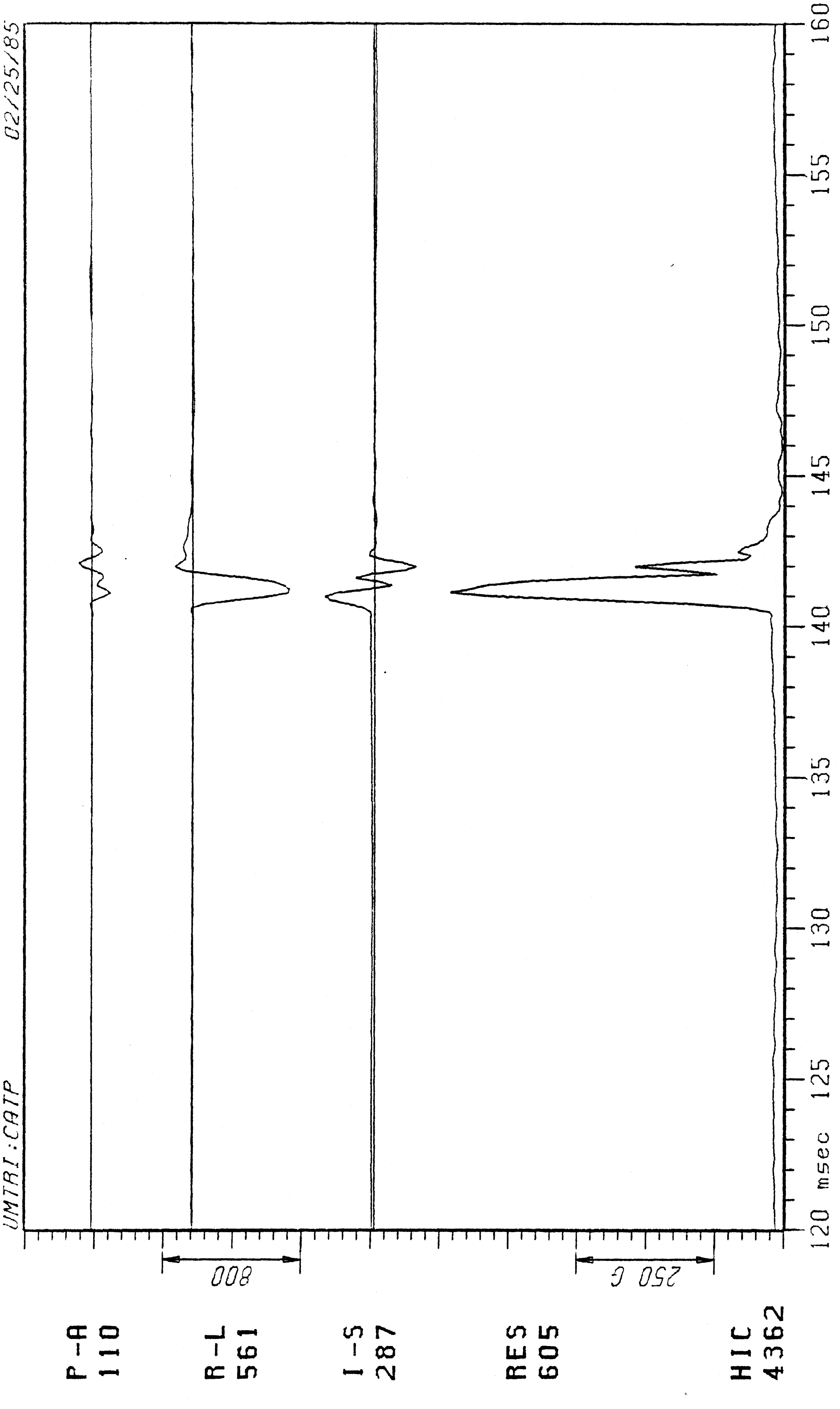
HEAD ACCEL.

C-XH

HIC
600

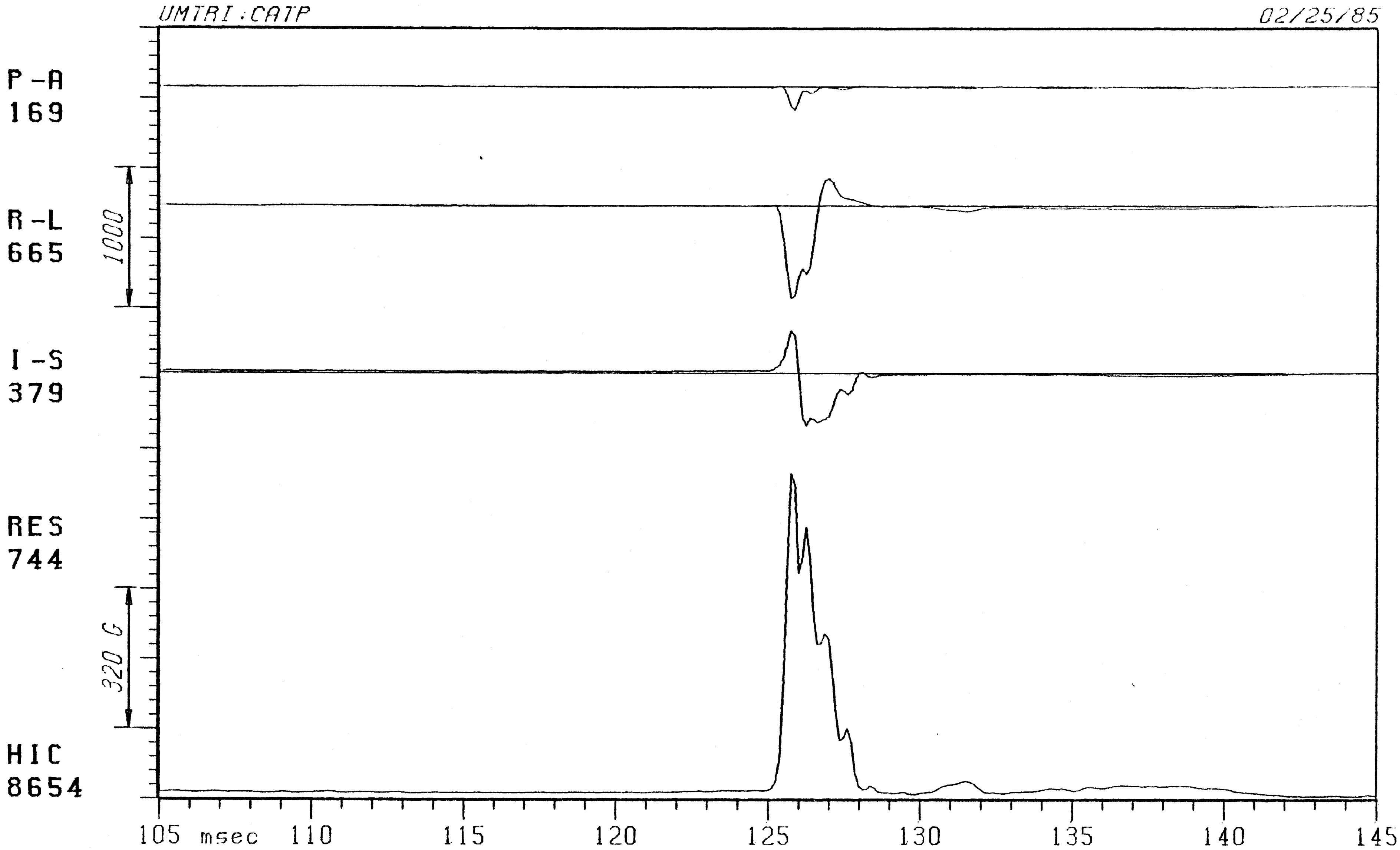


UMTRI:CATP
02/25/85
P-A 110
R-L 595
I-S 379
RES 653
HIC 6202
800
320 G
105 msec 110 115 120 125 130 135 140 145
HEAD ACCEL.
D-1



HEAD ACCEL.

D-2



HEAD ACCEL.

D-3