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The Effects of Orientation on Ground Penetrating Radar

by

Robert A. Roffman

Submitted to the Department of Earth, Atmospheric, and Planetary Science
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

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Abstract

This paper discusses how changes in the orientation of a Ground Penetrating Radar's receiver with respect to its transmitter can affect the detection of radar pulses by the receiver. The orientation changes discussed in this paper are elevating the receiver, rotating the receiver in the surface plane, translating the receiver sideways, tilting the receiver backwards, tilting the receiver forwards, and tilting the receiver sideways. The effect of these movements will be measured by changes in the arrival times and amplitudes of the ground wave and the first reflection. From the data taken, it seems that, except for the change in amplitude from elevating the receiver, the change in orientation required to significantly effect the data is greater than the change that would occur during most uses of GPR and should not be a serious problem.

Thesis Supervisor: Frank Dale Morgan

Title: Professor of Geophysics

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Introduction

Ground Penetrating Radar (GPR) is a tool used in geophysics to gather information about underground structures. It consists of a transmitter and a receiver. The transmitter emits an electromagnetic pulse which enters the ground. In a simplified wave model, the electromagnetic pulse travels outward spherically (figure 1) and reflects off of any boundaries in its path (figure 2). The receiver detects both when the direct wave and the reflected waves reach it. With knowledge of the speed of the pulse in the ground, it possible to determine the depths of reflectors.

Ideally, the transmitter and receiver should be horizontal, parallel, and rectangular to each other (figure 3). Often when GPR is used, it is impossible, because of factors like terrain and human inaccuracy, to place the receiver exactly in its proper orientation with respect to the transmitter. Rocky terrain may cause the receiver to be elevated, or tilted with respect to the receiver. These perturbations may have an effect on the time the pulse arrives at the receiver and it's signal strength when it arrives. A change in arrival time could cause an error in the calculation of the depth of a reflector, and a weakened amplitude may cause a reflected pulse to be overlooked, or may effect any analysis done on the amplitude. It is, therefore, important to know how perturbations in the orientation of the receiver can effect its detection of electromagnetic pulses.

Statement of Purpose

This paper will discuss how changes in the orientation of the receiver with respect to the transmitter can effect the detection of radar pulses by the receiver. The receiver will be elevated, rotated in the surface plane, translated sideways, tilted backwards, tilted forwards, and tilted sideways (figure 4). The effect of these movements will be measured by changes in the arrival times and amplitudes of the ground wave and the first reflection.

Theory

Near Field vs. Far Field

The radar pulse's behavior can only be safely described as a ray after it has distanced itself from its source by at least eight wavelengths (7). The space outside of this distance is called the far-field. Within this distance, the wave's behavior is more complicated. The space whose distance from the dipole is comparable to the wavelength of the pulse is called the near-field, and the space in-between the near-field and the far-field is called the transition zone. From the velocity and the frequency of the wave, it will be possible to determine how many wavelengths the wave has traveled before reaching the reflection or the receiver. Because the behavior of an EM pulse in the near field is too difficult to describe, any model of the path of the pulse in this paper will make far field assumptions. Predictions about the amplitude decrease will assume near-field drop off, which is proportional to approximately $1/R^2$. The data will then be compared to any predictions to see whether there is a common trend.

Velocity

The velocity of a wave in the ground is dependent on the ground's conductivity, magnetic permeability, and electric permeability. Figure 5 gives examples of the velocities of an EM wave in different mediums. A Center-Mid-Point (CMP) analysis will be used to determine the velocities of the ground wave and the first reflection.

Reflection

When an EM pulse reaches a boundary, part of the pulse's energy is reflected off of the boundary, and part of the energy is transmitted through the boundary (figure 6). The angle to the incidence of the reflection is always the same as the incoming wave.
The energy of the reflection is modeled by equation 1.

Equation 1

$$\frac{Ei^2 \cos\theta 1}{n1} = Er^2 \cos\theta 1/(n1) + Et \cos\theta 2/(n2)$$

E = energy i = incident
r = reflection t = transmission
n = index of refraction Theta1 = angle to incidence of pulse
Theta 2 = angle to incidence of refraction

Only the reflection will be discussed in the data.

Polarization

Often, a wave can have an orientation in which it's amplitude is strongest. Most receivers are sensitive to the orientation of the wave, and the amplitude recorded for these types of waves will depend on the orientation of the receiver. Experiments involving the rotation and tilting of the receiver may show a signal reduction from this effect.

Signal loss

As a pulse propagates, several factors cause it to lose energy. One factor is spreading (figure 1). As a pulse propagates, the original energy, E, transmitted outwards from the source becomes distributed over a spherical shell of expanding radius. In the near-field of a dipole source, the amplitude decreases approximately proportionally to 1/r^2. When far-field assumptions take over, the energy decreases proportionally to 1/r (7).

Another cause of amplitude loss is attenuation. Attenuation is caused by scattering of the signal and absorption of the signal by the medium. Both absorption and scattering depend on the medium. EM waves with higher frequencies are attenuated faster (2).

Equipment limitations

Recording the arrival time and the amplitude of a radar pulse is only as exact as the PulseEKKO IV radar console unit allows it to be. The PulseEKKO IV measures amplitude in millivolts and takes a measurement every 800 picoseconds. Millivolt accuracy should be enough to detect a significant change in the amplitude of an arrival. However, the exactness in detecting the arrival time will be a limiting factor. If the velocity of a wave in the ground is 0.1m/ns, the wave would travel 8cm in 800 picoseconds. Thus a change of one picosecond in the arrival time could be interpreted as a change in path distance of anywhere between 0 and 16 cm. For these experiments, only a change in arrival time of 2ns or greater will be considered significant.

The data will also only have a limited resolution. This resolution is dependent on the wavelength.

Equation 2.

$$W = (2ZL)^{1/2}$$

W = Diameter of area of resolution
Z = Depth
L = Wavelength

The area of resolution is known as the fresnel zone. Because in this paper we will be assuming that the reflections are off of planes, the resolution will not be a concern.

Another limitation of the system is its consistency. The detection of the same signal may vary due to random error by the machine. This random error should have an upper limit.

Drift is also a source of error with the pulseEKKO IV radar. There are two types of drift that may effect the precision of the data: warm-up drift and system drift. Warm-up drift occurs when the machine is first turned on. This type of drift will cause arrival times to decrease and then level off. All data, except for the drift data, was taken after a sufficient warm-up period. The system may also experience a drift which is independent of the system warming up. System drift may be predictable or may eventually level off.

To reduce background noise, the system preformed 2048 stacks. This means that each trace is the average of 2048 recordings.

Data Expectations

Elevating the receiver

The effects of elevating the receiver should be a function of the change in path distance of the radar pulse and the amount of the path occurring in the ground.

As the receiver is raised, the path through the ground decreases, but the overall path increases (figure 7). Since the EM pulse travels faster through air than soil, the arrival times will increase, first slowly, and then rapidly. A similar effect should be seen in the amplitude because the radar pulse attenuates at a greater rate in soil than in air. The expected curve for the change in amplitude in figure 16 assumes a 1/R^2 decrease in amplitude from spreading alone.

Rotated in the surface plane

Rotating the receiver in the surface plane may have two effects on the data. First, the amplitude will be effected by the receiver being oriented differently with respect to the EM pulse. Second, ravel times may also be effected since the edge of the receiver will be closer to the transmitter (figure 8).

Equation 3.

$$T^2 = 4 \cdot \frac{\left(D^2 + \left(\frac{X + \Delta X}{2}\right)^2\right)}{V^2}$$

T = Travel time
D = Depth
X = Separation between transmitter & receiver
V = Velocity of wave
▲X = Change in X due to rotation

Equation three shows how the travel time will vary with increased separation between the transmitter and receiver. From equation 3, it can be shown that as D increases, T approaches 2D/V, and any change in arrival time from rotating the receiver becomes insignificant. Therefore any change in the arrival time from rotating the receiver will also be dependent on the depth of the reflector.

Tilted backwards & forwards

In this experiment, the receiver will be tilted until it is horizontal. The distance from the transmitter to the receiver does not change in these orientations; therefore, there should be no change in arrival times. Changing the orientation may cause a change in the amplitude due to polarization.

Tilted sideways

It is difficult to predict whether or not there will be any change in the arrival times as the receiver is tilted sideways. Part of the receiver is the same distance from the transmitter, and part of the receiver is farther away. The amplitude should be effected by its new orientation with respect to the radar pulse, and it may also weaken due to the increased path of the radar pulse.

Translation sideways

In this experiment, the receiver will be translated up to half a meter sideways. The distance between the centers of the transmitter and receiver will change by 21 centimeters, but like rotating the receiver sideways, part of the receiver will be the same distance to the transmitter. The expected curve for the change in arrival time in figure 32 uses equation 3, and assumes ▲x to be the change in distance between the centers of the transmitter and receiver.

A change in the amplitude could be caused by two factors. First, the distance between the receiver and the transmitter has increased. This will cause increased attenuation to the signal before it arrives at the receiver. Second, there may be a polarization effect. The expected curve for the change in amplitude in figure 16 assumes a 1/r^2 decrease in amplitude from spreading alone.

Equipment

Hardware

A) PulseEKKO IV radar console unit, 12-volt power supply and cable, and RS232 cable to connect the console to the computer.
B) 200 MHz antennae.
C) Two antenna cradle assemblies.
D) Transmitter electronics, two six-volt power supply and a single fiber optics cable.
E) Receiver electronics.
F) Any PC XT, AT, 386, 486, or Pentium running under MS-DOS 3.3 or higher. For data collection in the field, it is highly recommended that a battery powered portable or laptop computer be used.

Software

A) PulseEKKO Run software

Special Equipment

A) Blocks two centimeters in height (used to raise the antennae).

Data analysis

Cross section

Figure 9 is a cross section containing the place at which the measurements were taken. The trace in the middle, marked "site," is where the measurements were taken.

CMP

A Center Mid-Point (CMP) recording was taken at the site of the experiments. From the CMP it is possible to determine the velocity of the direct ground wave and of the first reflection. Figure 10 shows the CMP and gives the velocities of the ground wave and the first reflection. For all of the experiments, the arrival which occurs at 12ns on the first trace of the CMP will be the ground wave, and the arrival at 32ns on the first trace of the CMP will be the 1st reflection.

The ground wave is traveling at ~0.09m/ns. At a frequency of 200MHz, one wavelength is 0.45 meters (wavelength = velocity/frequency). The separation of the transmitter and receiver is 0.5 meters. This means the ground wave will be in the near-field.

The first reflection is traveling at ~ 0.06m/ns, therefore its wavelength is approximately 0.3 meters. Its depth to the reflector is approximately 0.9 meters, which is three wavelengths. This means the first reflector can be assumed to be either in the near-field or the beginning of the transition zone.

Drift

To determine drift, the machine was allowed to take 240 consecutive samplings without being moved. This took approximately two hours. The drift was measured both inside at room temperature, and outside at about 85 degrees Fahrenheit. These samplings were taken immediately after the machine was turned on. Figures 11 and 12 shows the traces for the two samplings of drift. Figures 13 and 14 plot the change in the amplitude and the arrival time for both drift recordings

Figures 13 and 14 show three stages of drift for the arrival time. First there is a decrease in the arrival time, then a steep increase, and then a gradual increase. The steep increase in arrival time is much more pronounced in the reading taken outside. This could be due to the heating up of the system.

The amplitudes for both measurements (figures 13 and 14) remained about the same, except for a few spikes which seem to be a result of random machine error.

Elevating the receiver

Figure 15 shows the traces taken for this experiment. The change in arrival times for the ground wave and the 1st reflector show no significant change (figure 17). The amplitudes (figure 16) of the ground wave and the first reflection do show a significant decrease. This can be explained by the increased path of both waves.

Rotated in surface plane

Figure 18 shows the traces for this experiment. The arrival times for the ground wave show a significant decrease of 4ns (figure19). This decrease is clearly not a result of drift since drift would cause the arrival times to increase. This decrease is probably due to the receiver edge moving closer to the transmitter. The edge of the receiver is 25 cm closer at the end of the experiment, and according to the velocity obtained from the CMP (figure10), this movement would reduce the arrival time by approximately three nanoseconds.

The arrival time of the first reflection was not effected. This lack of change is not surprising since decreasing the distance between the receiver and transmitter to 0.25 m should only decrease the arrival time by ~0.8 ns, which is far below the sensitivity of the instrument.

The amplitudes of both the ground wave and the first reflection show a significant decrease (figure 19). This decrease is probably due to the different orientation of the receiver with respect to the EM pulse.

Rotated backwards and forwards

Figures 21 and 24 show the traces for these two experiments. The arrival times of the ground wave and first reflection were unaffected significantly by either of these movements (figures 22, 23, 25, 26). There was a change, however, in the amplitude. This change can be explained by the change in the orientation of the receiver with respect to the incoming wave.

Rotated sideways

Figure 27 shows the traces for this experiment. Figure 28 shows a decrease in the amplitude for the ground wave. This decrease could be due to the polarization of the wave. At the beginning of the graph for the amplitude change of the first reflection, a large jump occurs. This jump is too large to be a result of tilting the receiver two centimeters and is probably a random error. The arrival time of the first reflection also shows a significant decrease (figure 28). There seems to be no reason for a decrease to occur since the machine is being moved away from the transmitter, and the drift usually causes an increase in arrival time.

Translation sideways

Figure 30 shows the traces for this experiment. Only the amplitude of the first reflection (figure 31) shows a significant decrease. A decrease in amplitude is expected since the receiver is moving away from the transmitter. However, the arrival times for the first reflection are also decreasing (figure 32), which would only happen if the path were shorter (for instance if the reflector were sloping upwards). There are two ways this apparent contradiction can be resolved. The first possibility is that the arrival time data is erroneous, since it is only slightly significant. The second is that the arrival times are actually decreasing for the first reflection, but the amplitudes are decreasing from a polarization effect.

Conclusion

The results from the experiments are both interesting and concerning. In most of the experiments, the arrival times did not significantly change. Some possible reasons for the lack in significant change are 1) the inability of the pulseEKKO to detect small changes in the arrival times, 2) a drift which may have either canceled out any decreases in arrival times from the experiment or been indistinguishable from increasing arrival times, and 3) the seemingly random spikes in the machine which were greater than the expected change from the experiments. Only rotating the receiver in the surface plane showed a significant and predictable change in the arrival time.

Several of the experiments showed a change in the amplitude of the arrivals, despite significant error-bars. While a few spikes, such as in the data from rotating the receiver sideways, seem to be too large and unpredictable to be anything other than machine error, the majority of the changes in

the amplitude seem to occur in a stable manner. Most of the changes in amplitude can either be explained by an increased path distance, causing greater attenuation, or a polarization effect.

Not all of the changes seen in the first reflector will necessarily be seen in deeper reflectors. Whenever a change in amplitude is due to polarization, the change should occur independent of the depth of the reflector. A change in amplitude due to changing path distance will not be as noticeable with deeper reflectors, as can be shown from equation 3 and figure 7. Arrival times should only be effected by path distance, which means that changes in the arrival time of a reflection from rotating the receiver in the surface plane and shifting it sideways will decrease as the depth of the reflector increases. Changes in the arrival time of a reflection from elevating the receiver should be approximately independent of the depth of the reflector.

Figure 33 lists which experiments showed significant changes and when the changes occurred. While not all of the changes shown in figure 33 are necessarily from the changes in orientation of the receiver (as labeled on the chart), this chart can still provide an idea as to what types of orientations can affect the amplitudes and arrival times of the data. Except for the change in amplitude from elevating the receiver, the change in orientation required to significantly affect the data is greater than the change that would occur during most uses of GPR and should not be a serious problem.

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7) John Sogade, Graduate Student at MIT, Personal Communication.

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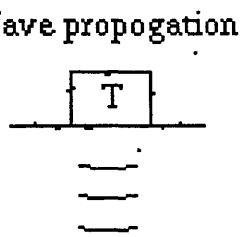


Figure 1. This figure shows how a wave propagates under far-field assumptions.

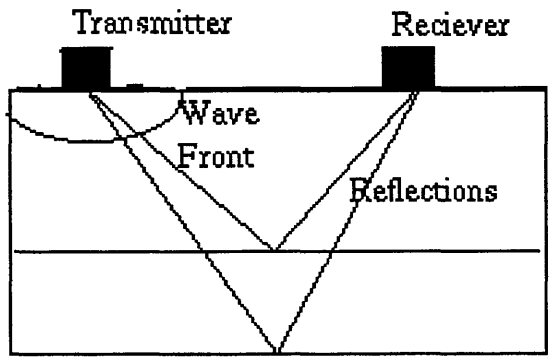


Figure 2. Under far-field assumptions, a wave's path can be modeled as a ray

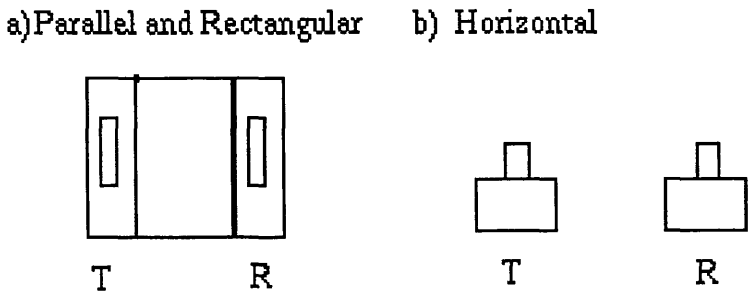


Figure 3. Diagram of how the receiver should ideally be placed with respect to the transmitter (T= transmitter, R= Receiver).

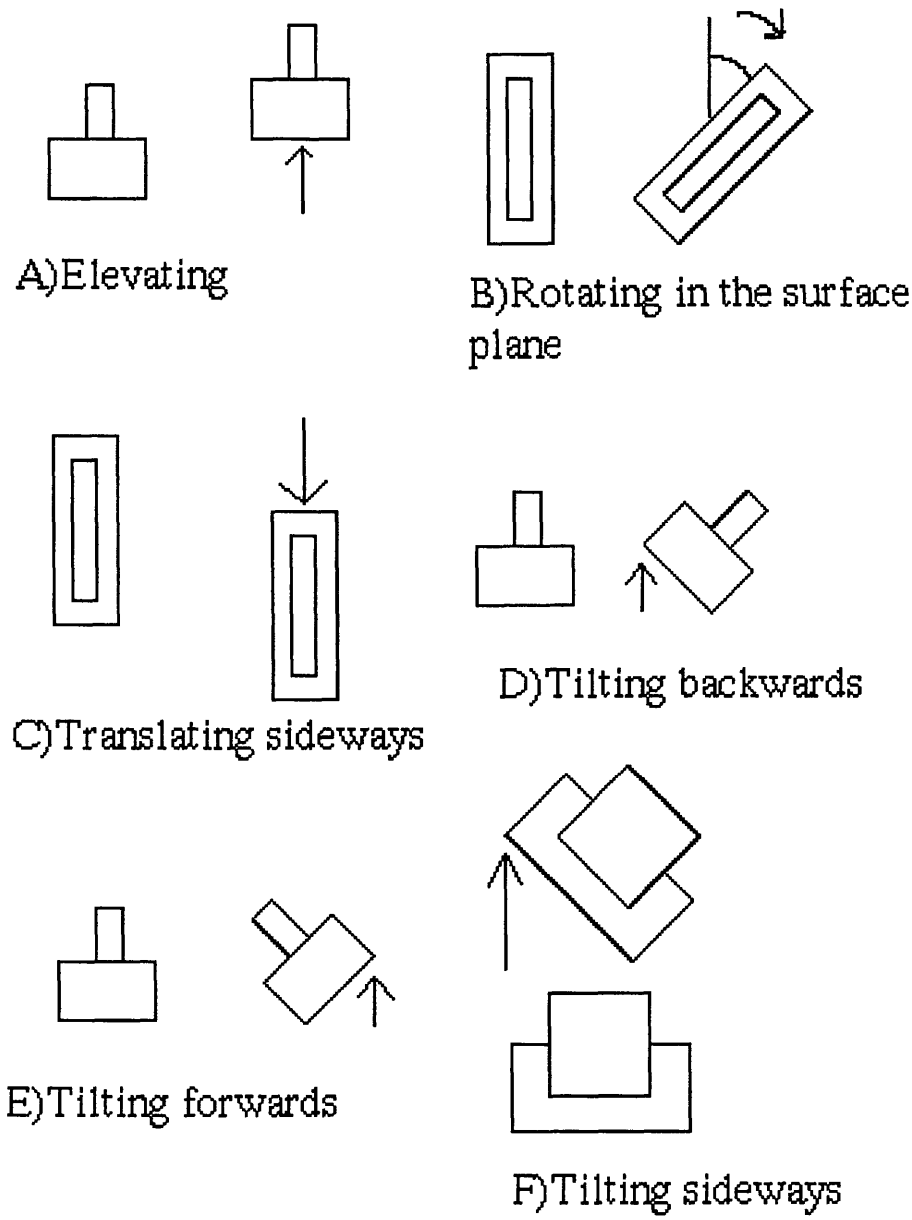


Figure 4. Shown in figure 4 are the six variations in the positioning of the receiver to be tested.

Medium	Air	Sea Water	Dry Sand	Saturated Sand	Limestone	Shale	Granites
Velocity(m/ns)	0.3	0.01	0.15	0.06	0.12	0.09	0.13

Figure 5. This table gives examples of the velocity of an EM wave in different mediums.

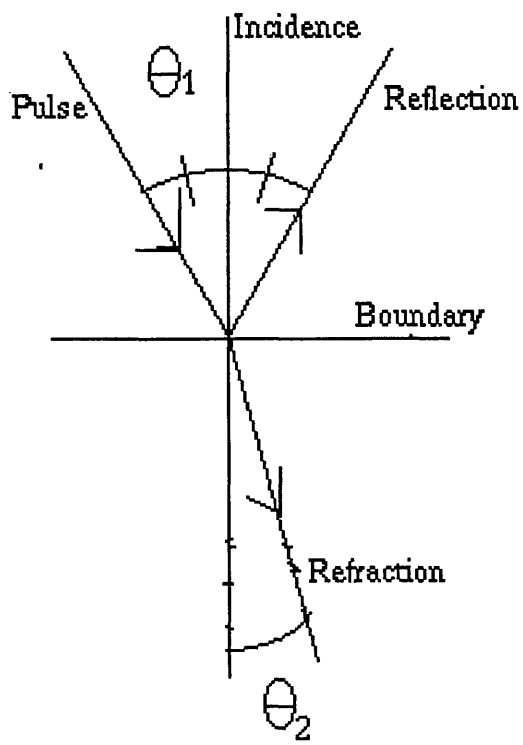
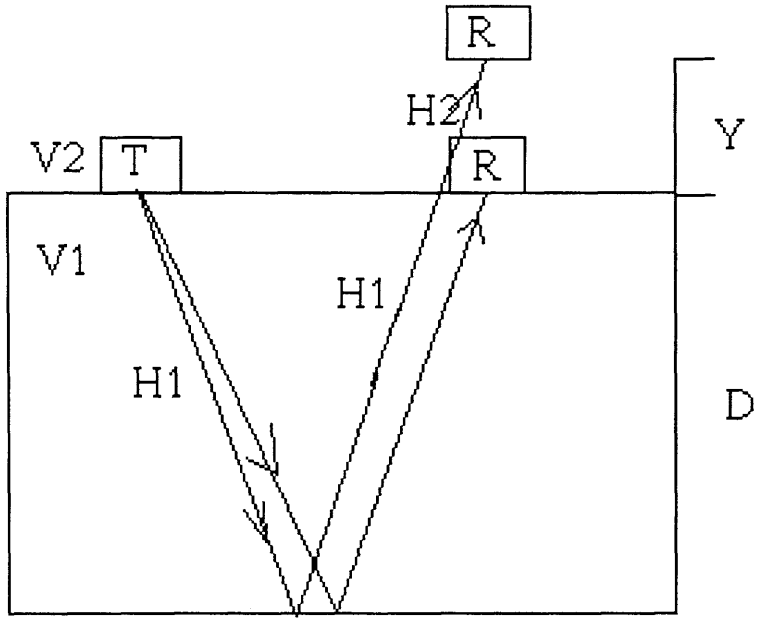


Figure 6. This diagram shows a simplified example of reflection and refraction.



T = Transmitter
R = Receiver
H1 = 1/2 of the path in the ground
H2 = Path in the air
Y = Elevation
D = Depth to 1st reflector
V1 = Velocity of pulse in ground
V2 = Velocity of pulse in air

Given

$$\frac{H1}{H2} = \frac{D}{Y}$$

$$\frac{(0.5 - X)}{Y} = \frac{X}{2D}$$

$$H1^2 = \left(\frac{X}{2}\right)^2 + D^2$$

Solving for H1 and H2 in terms of D and Y

$$H1^2 = \left[\frac{D}{4D + 2Y}\right]^2 + D^2$$

$$H2^2 = Y\frac{D}{(4D + 2Y)^2} + YD$$

Travel Time is a function of H1 & H2

$$TravelTime = 2\frac{H1}{V1} + \frac{H2}{V2}$$

Figure 7. This figure shows how the travel time varies as the receiver is raised to a height of Y.

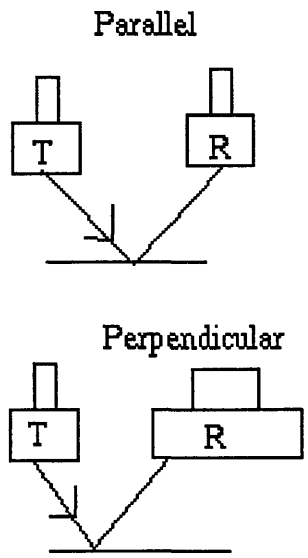


Figure 8. When the receiver, which has a rectangular bottom, is rotated in the surface plane around its center, its edge is closer to the transmitter. This may cause a decrease in travel times.

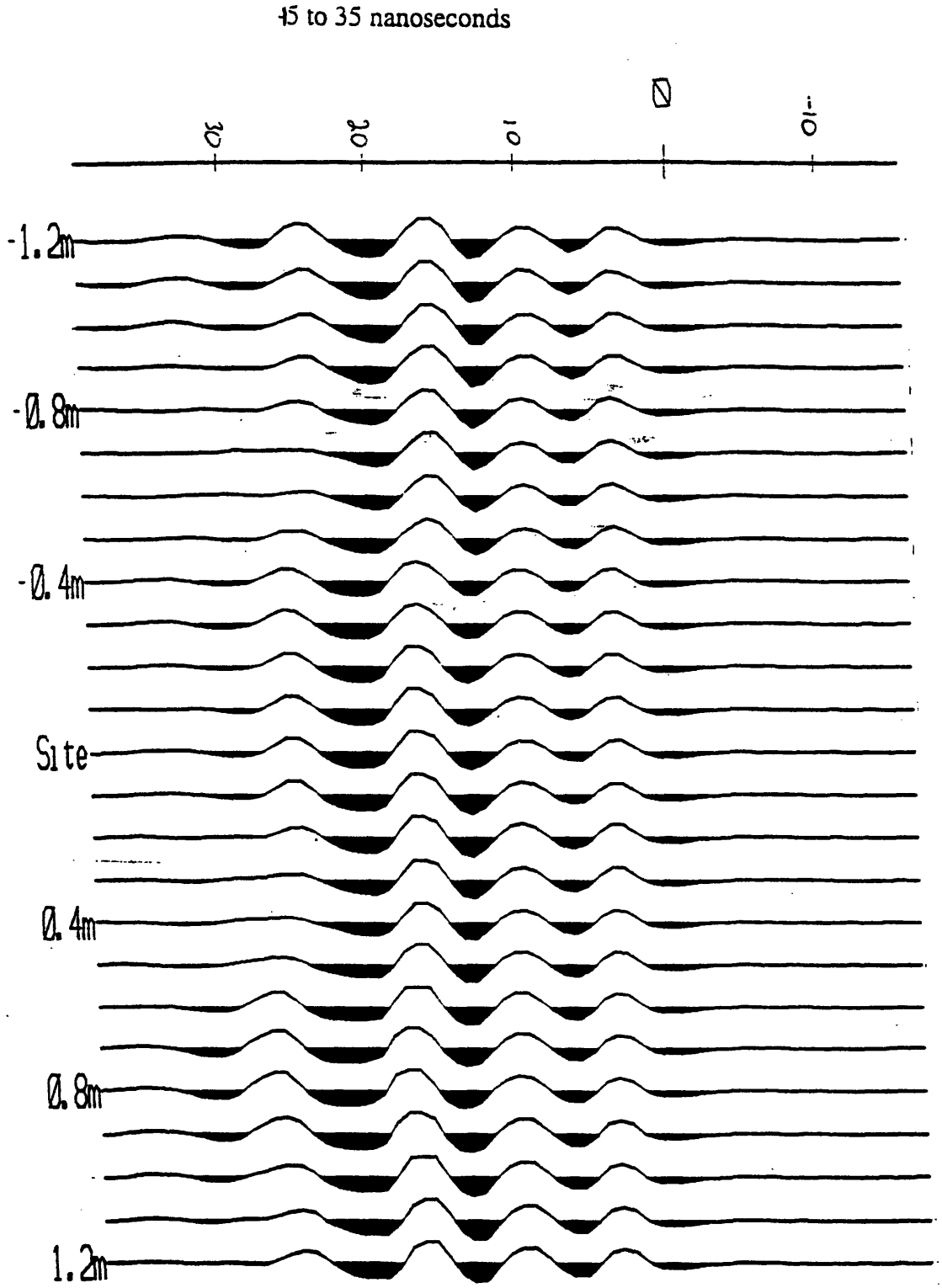
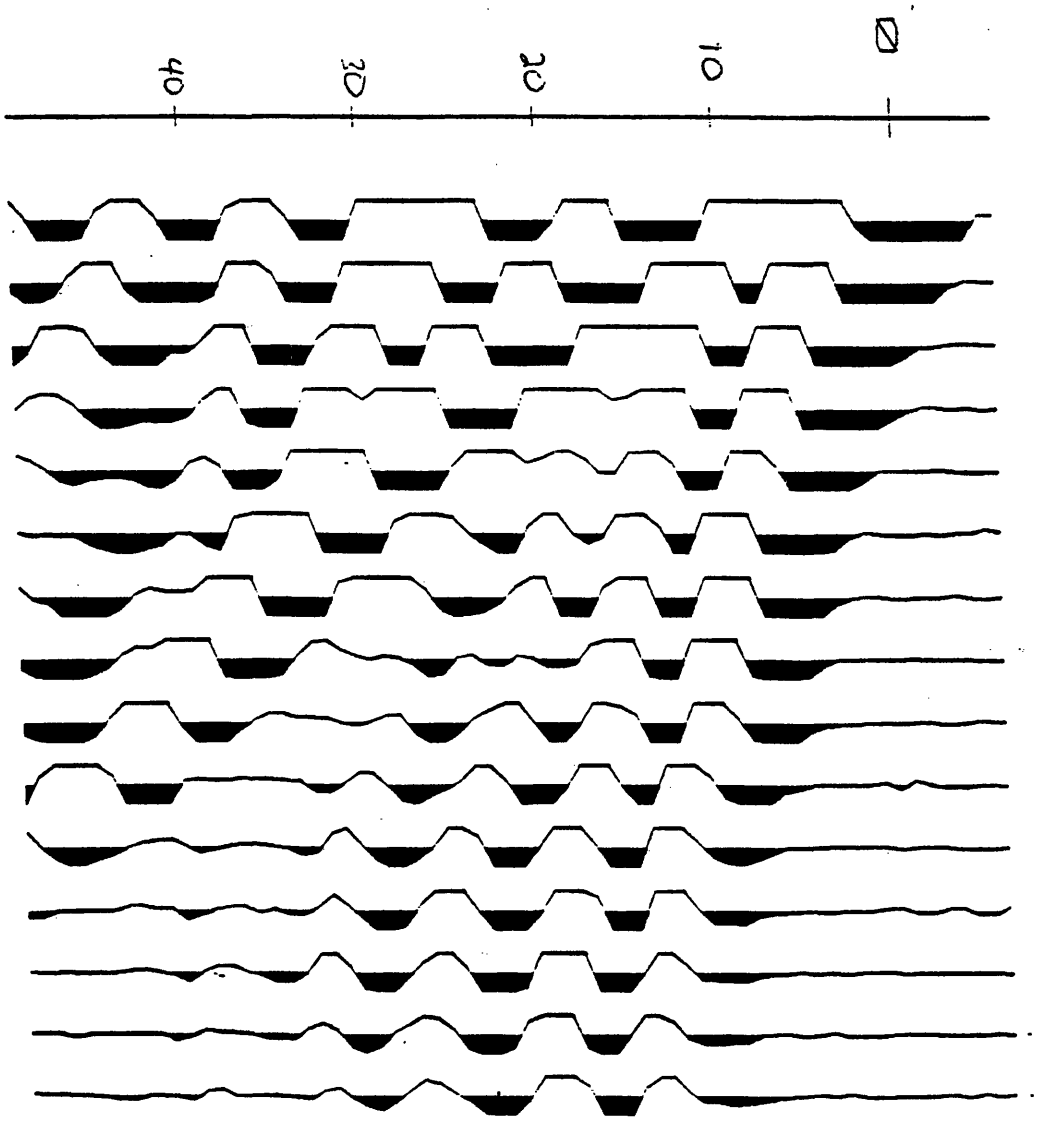


Figure 9. These traces make up a cross section 2.5 meters wide. Each trace is 0.1 meter apart. The site at which the experiments were done is at the middle, and labeled "site".

-5 to 50 nanoseconds



Velocity of ground wave ~ 0.09m/ns
Velocity of reflection ~ 0.06m/ns
Depth to 1st Reflector ~ 0.9m

Figure 10. This figure shows a Center Mid-Point (CMP) of the site. A CMP is a method used to determine the velocity of the EM wave at different depths. The ground wave starts at ~12 ns on the first trace, and the 1st reflection starts at ~32ns on the first trace.

-5 to 35 nanoseconds

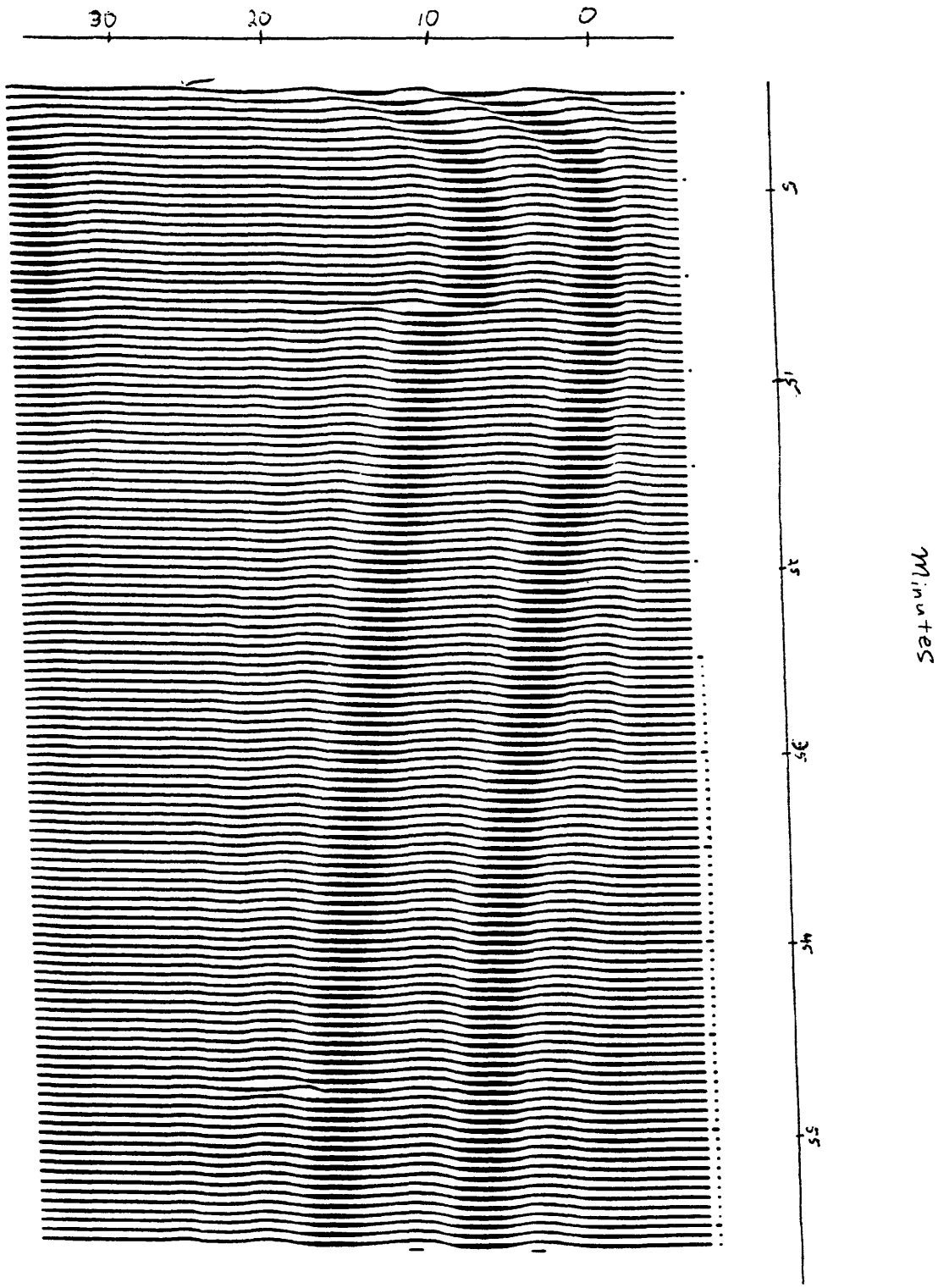


Figure 11. These traces show the drift of the machine at room temp. The system was placed in one spot, and allowed to take 240 consecutive samplings over two hours.

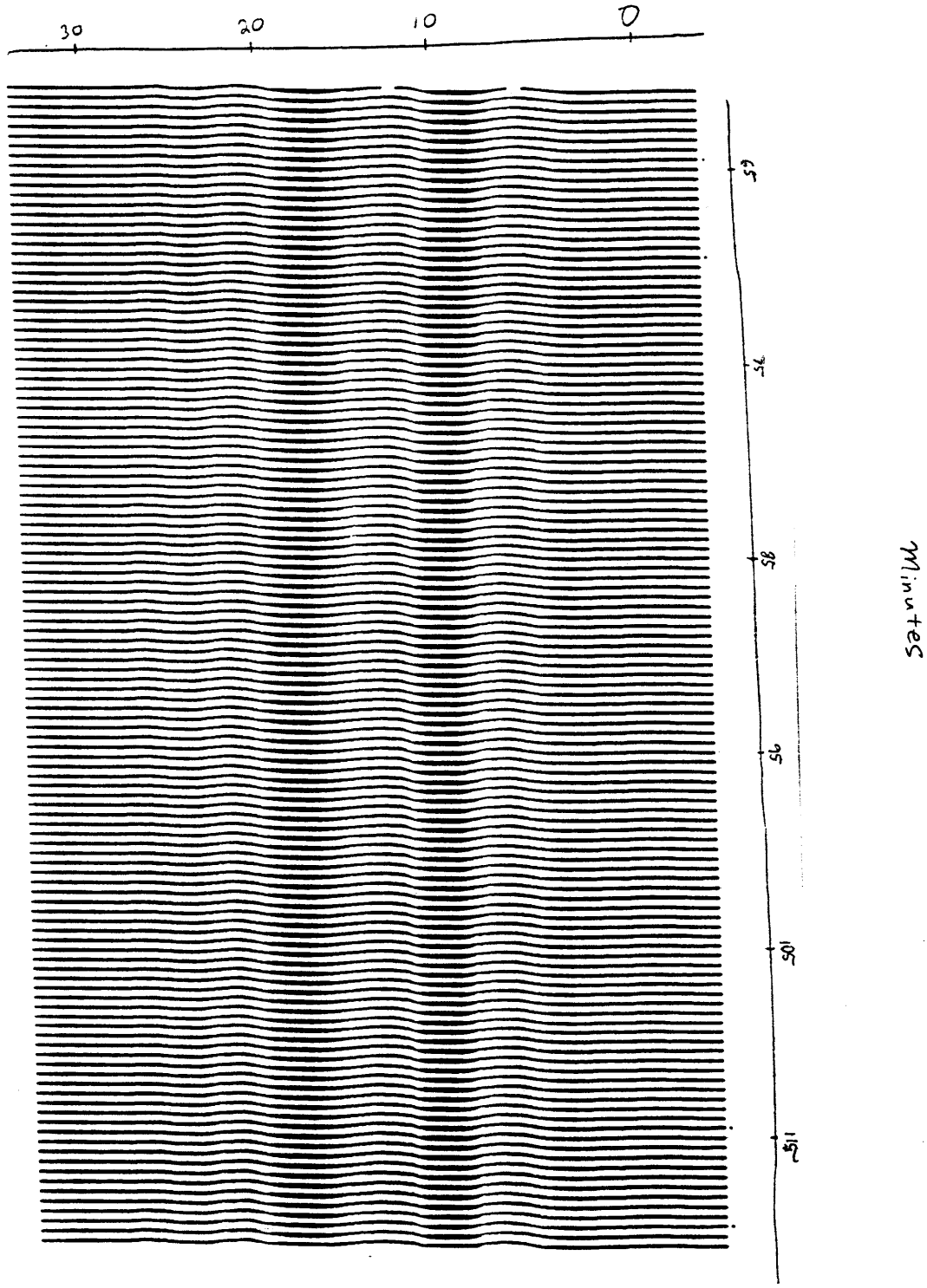


Figure 11. Continued.

-5 to 35 nanoseconds

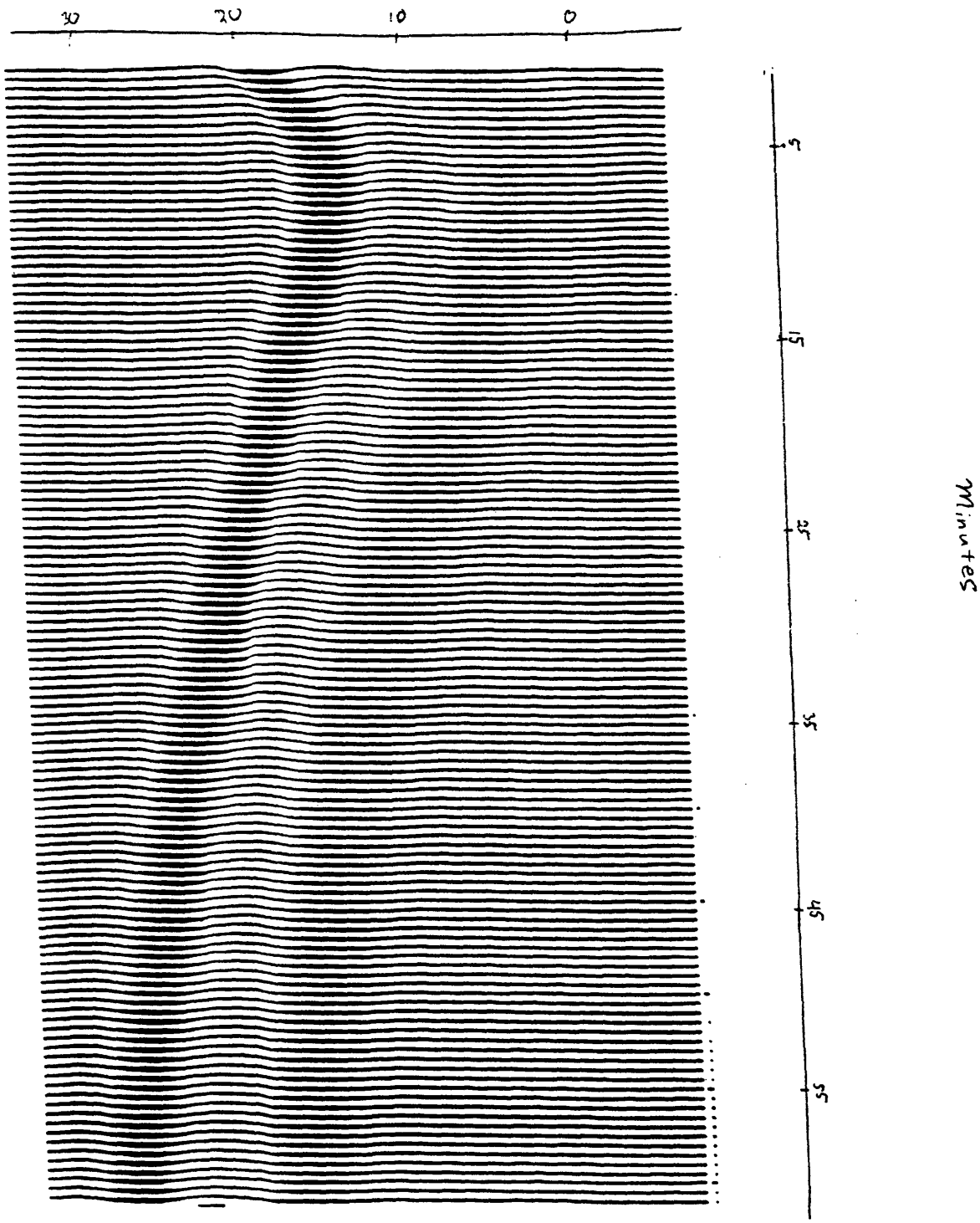


Figure 12. These traces show the drift of the machine at approximately 85 Fahrenheit. The system was placed in one spot, and allowed to take 240 consecutive samplings over two hours.

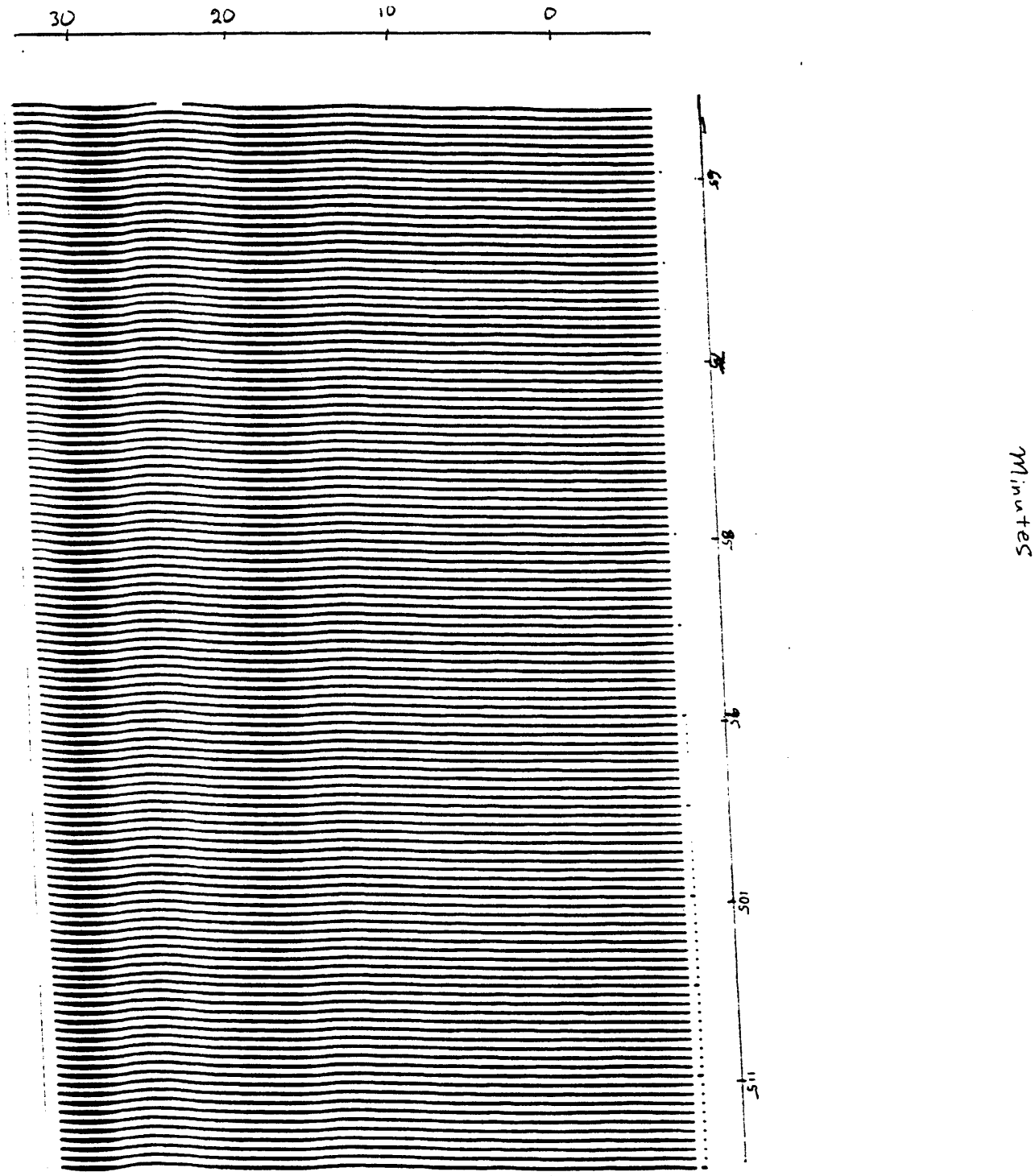


Figure 12. Continued.

DRIFT AT ROOM TEMP.

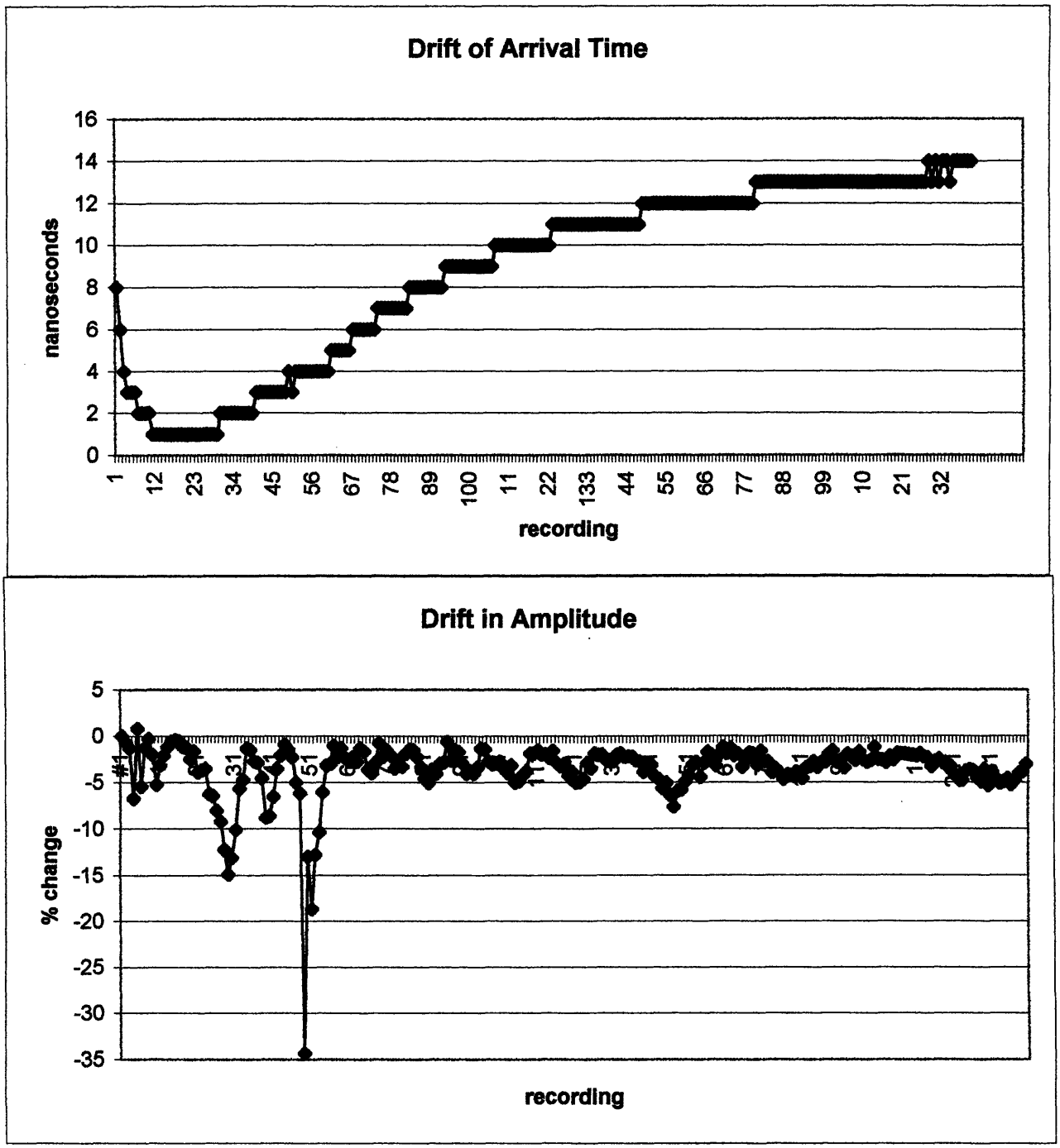


Figure 13. These two graphs represent the variation in the arrival time and amplitude over 240 recordings (2 hrs.) while the machine was at room temperature.

DRIFT AT APPROXIMATELY 85 DEG. F.

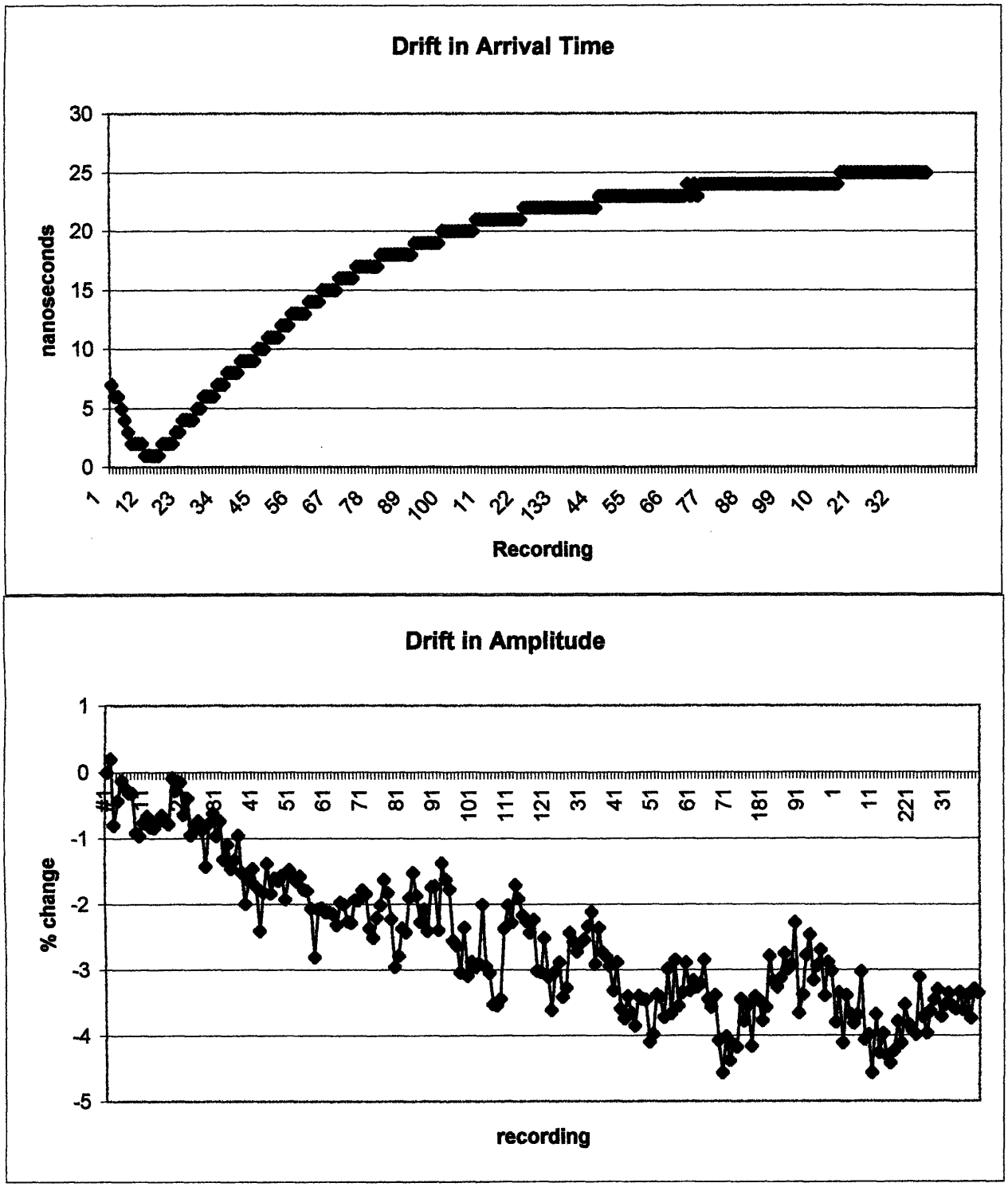


Figure 14. These two graphs represent the variation in the arrival time and amplitude over 240 recordings (2 hrs.) while the machine was outside at a temperature of approximately 85 degrees.

-15 to 40 nanoseconds

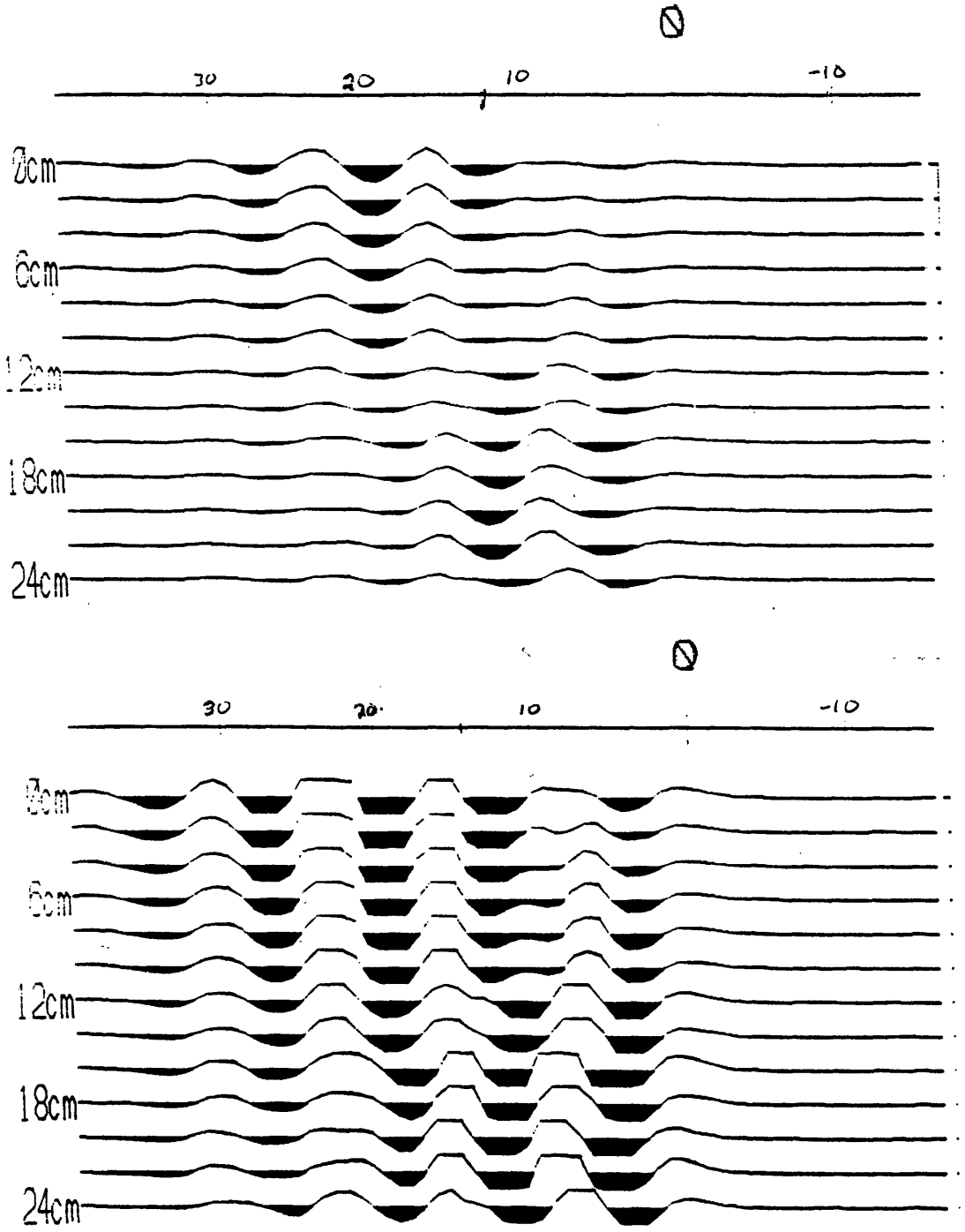


Figure 15. These two sets of traces are from elevating the receiver. Two sets are provided at different gains in order to display both the ground wave and the first reflection without overgain.

CHANGE IN AMPLITUDE CAUSED BY ELEVATING THE RECEIVER

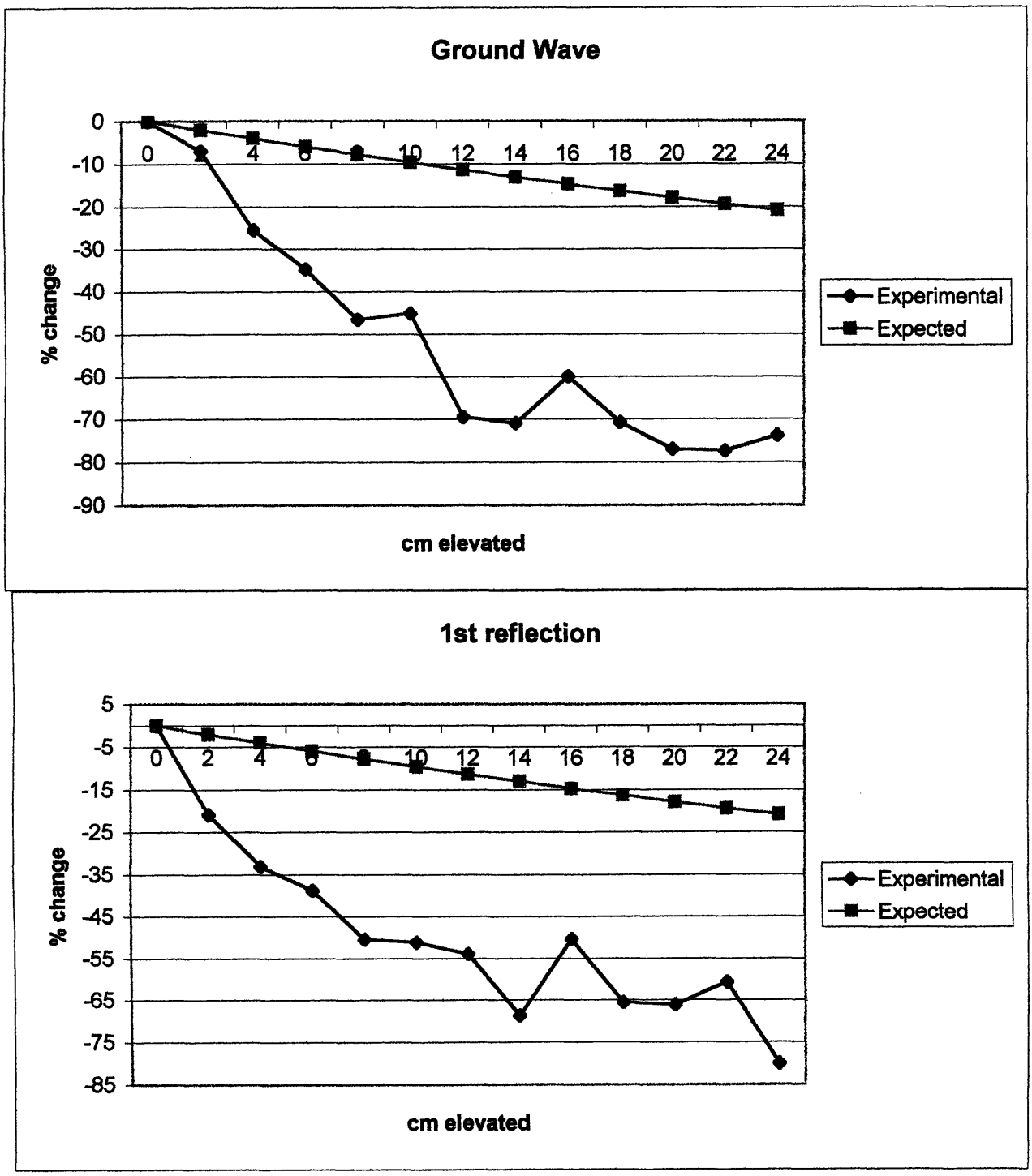


Figure 16. These graphs show how the amplitudes of the ground wave and the first reflection change from elevating the receiver

CHANGE IN ARRIVAL TIME CAUSED BY ELEVATING THE RECEIVER

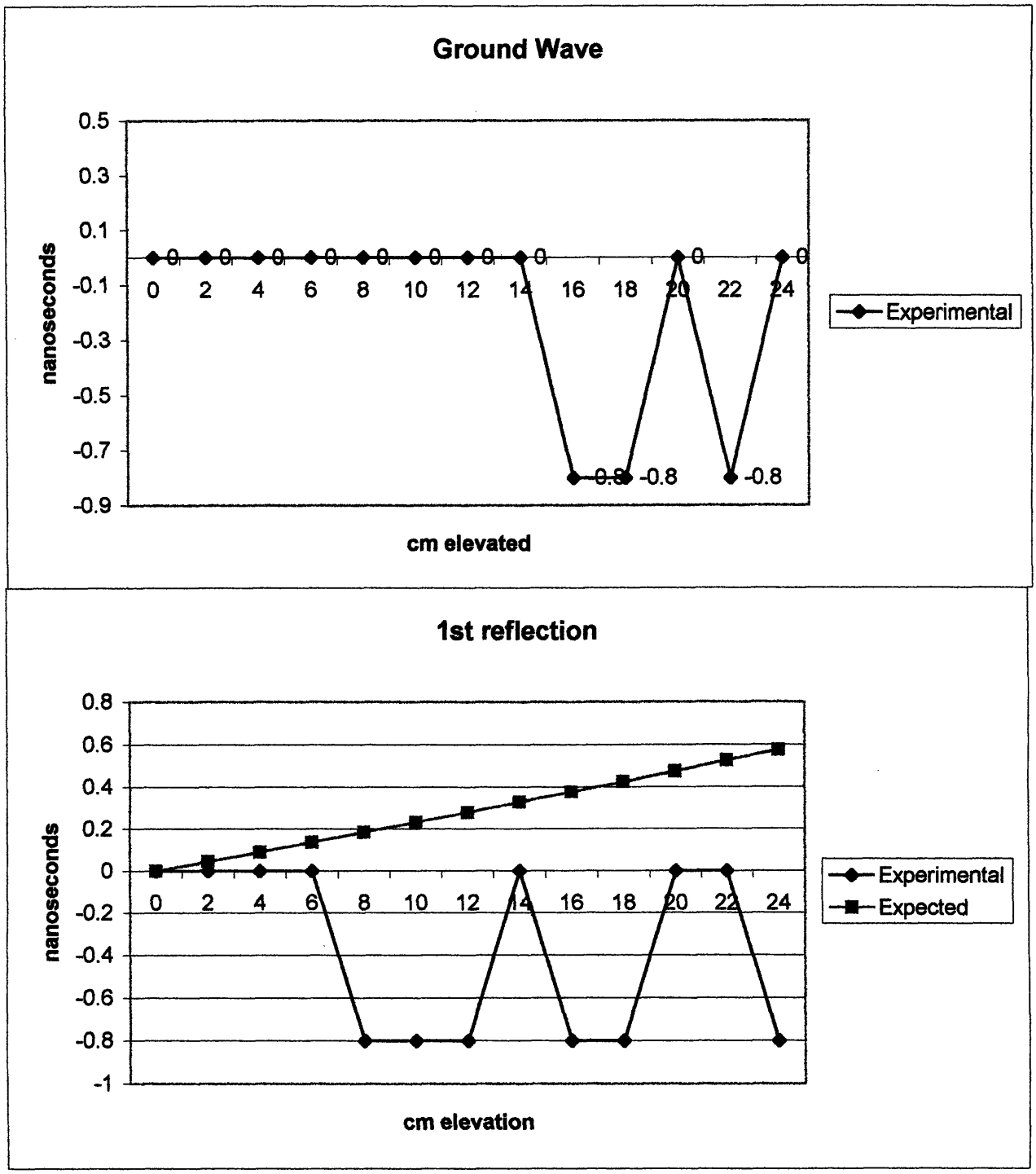


Figure 17. These graphs show how the arrival times of the ground wave and the first reflection change from elevating the receiver

-15 to 40 nanoseconds

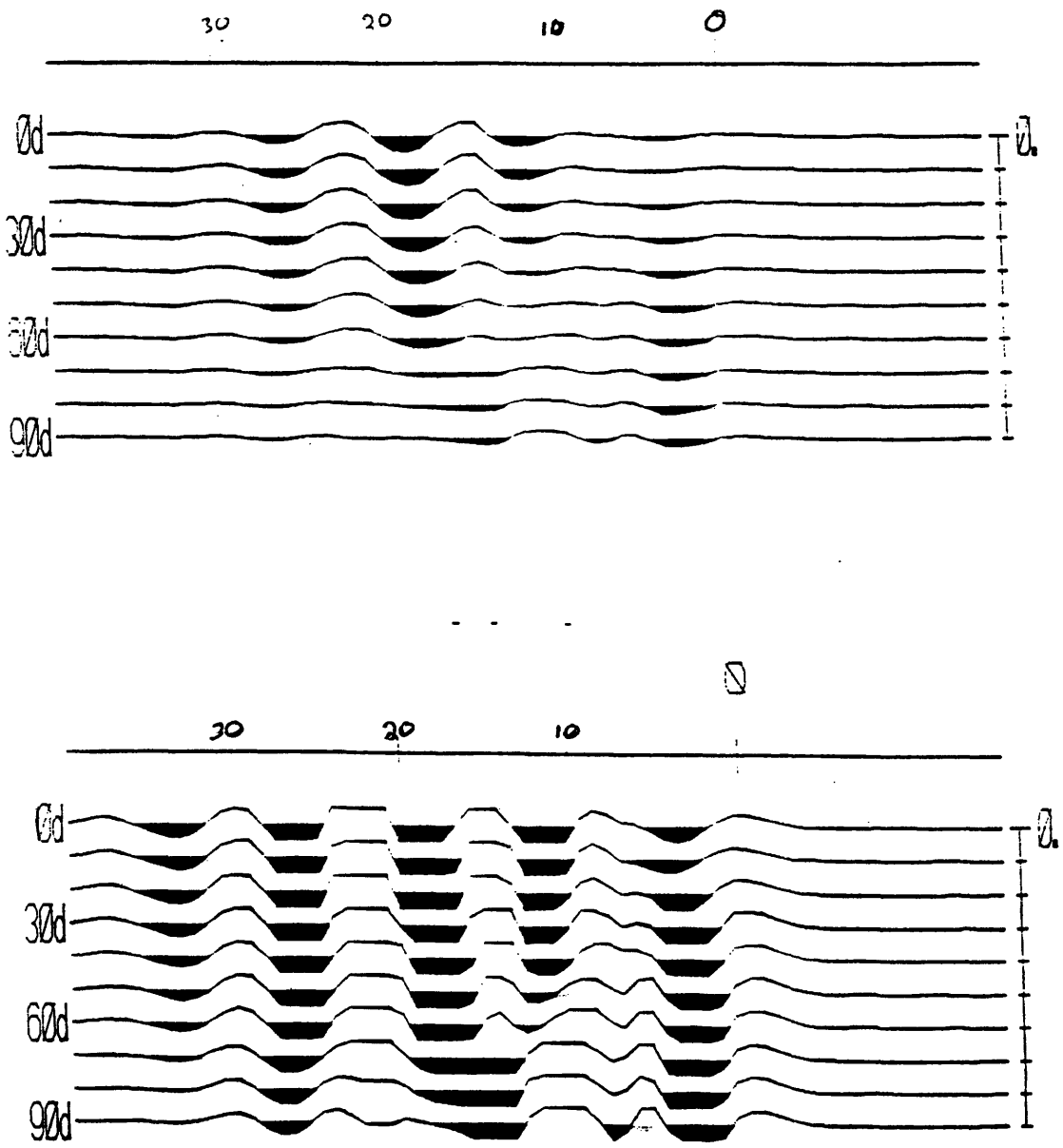


Figure 18. These two sets of traces are from rotating the receiver in the surface plane. Two sets are provided at different gains in order to display both the ground wave and the first reflection without overgain.

CHANGE IN AMPLITUDE FROM ROTATING THE RECEIVER IN THE SURFACE PLANE

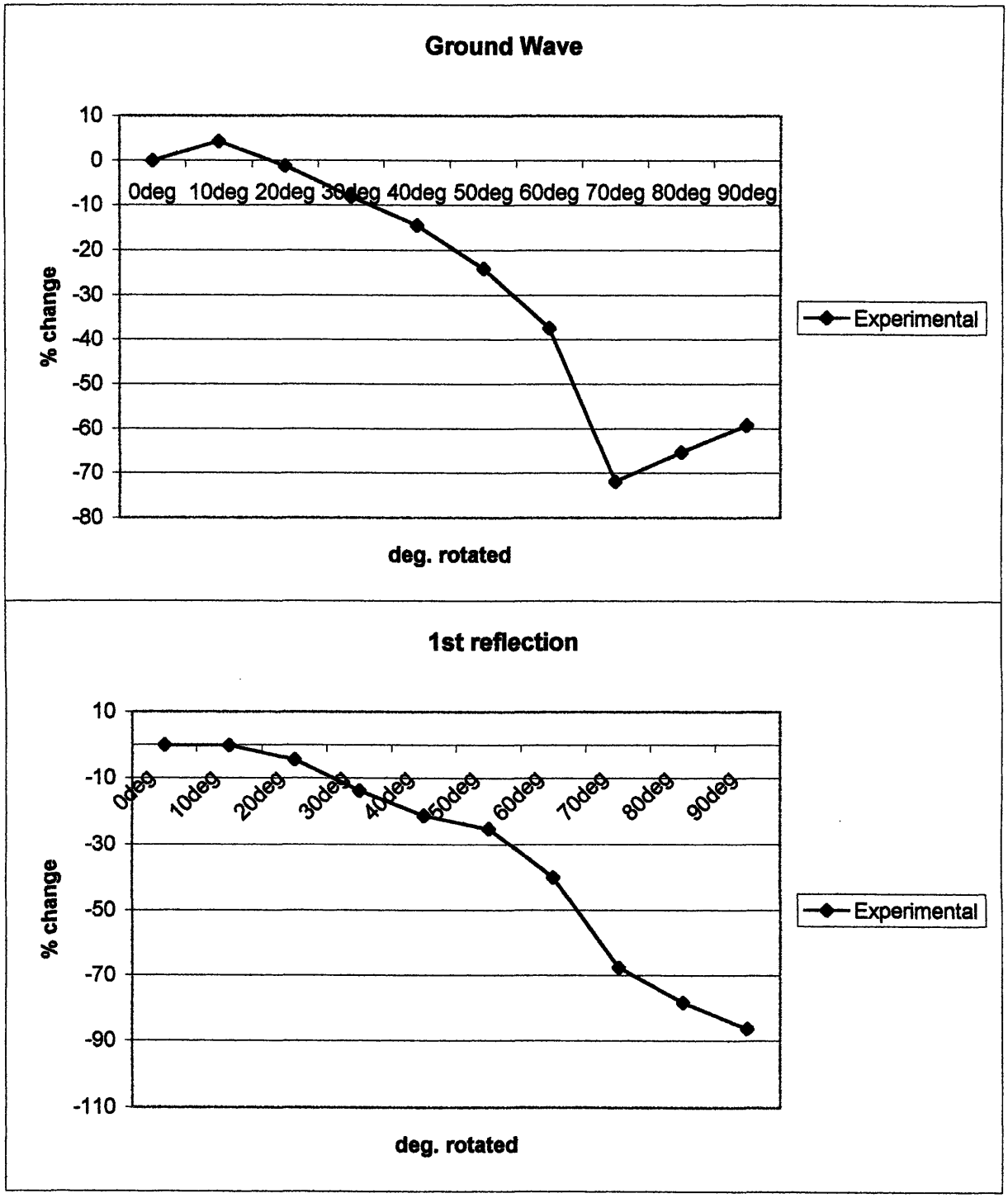
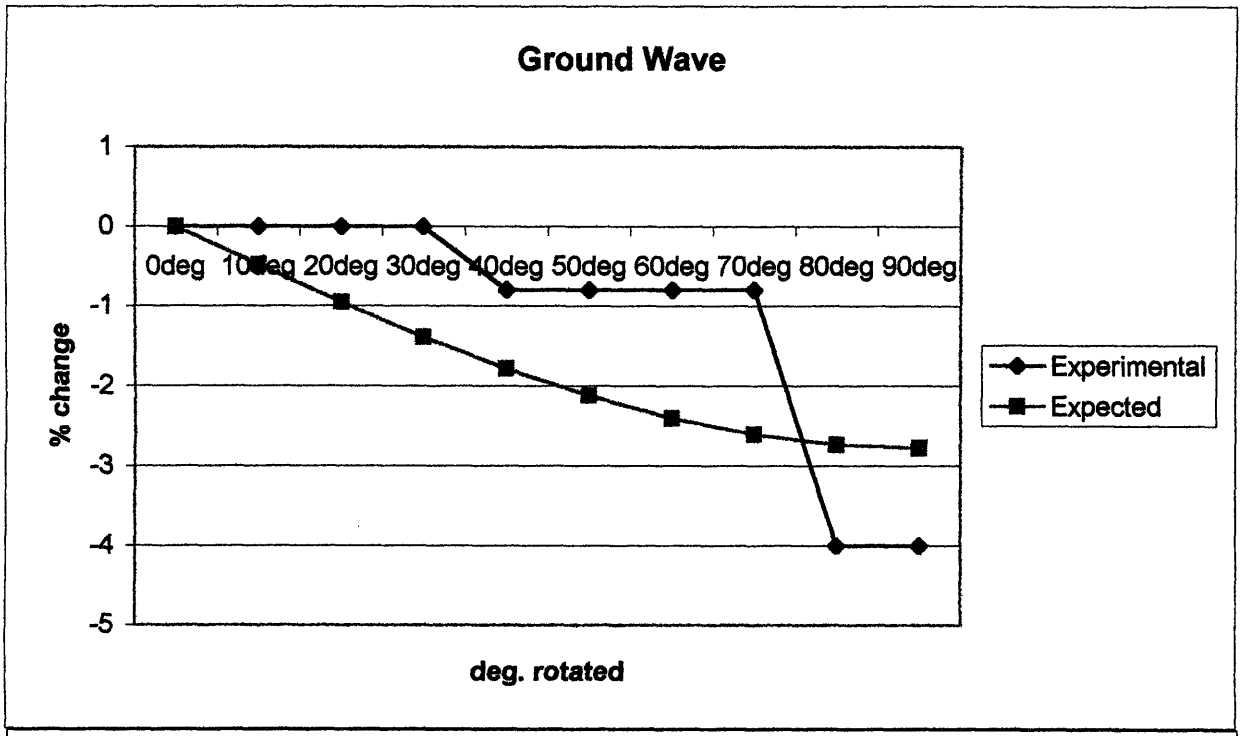


Figure 19. These graphs show how the amplitudes of the ground wave and the first reflection vary with rotating the receiver in the surface plane.

CHANGE IN ARRIVAL TIME FROM ROTATING THE RECEIVER IN THE SURFACE PLANE



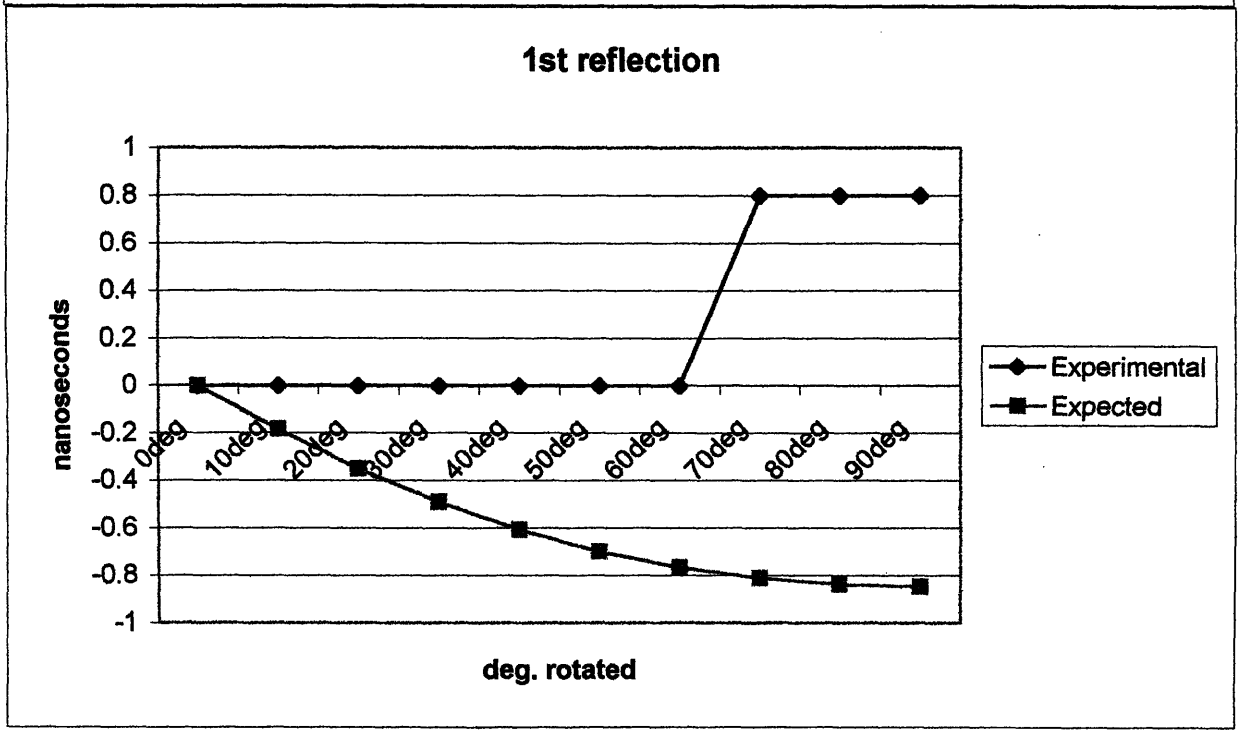


Figure 20 These graphs show how the arrival times of the ground wave and the first reflection vary with rotating the receiver in the surface plane.

-15 to 40 nanoseconds

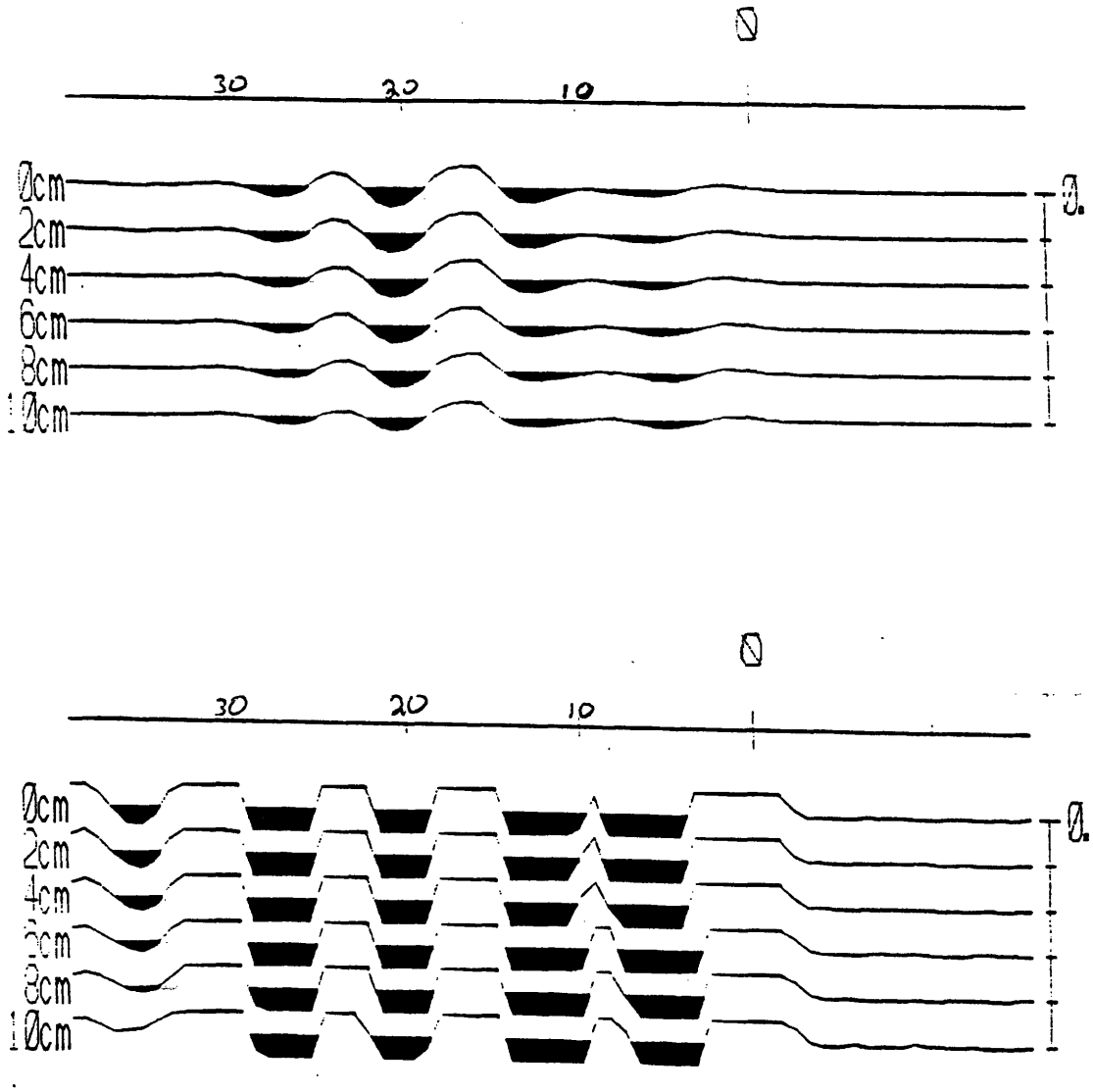
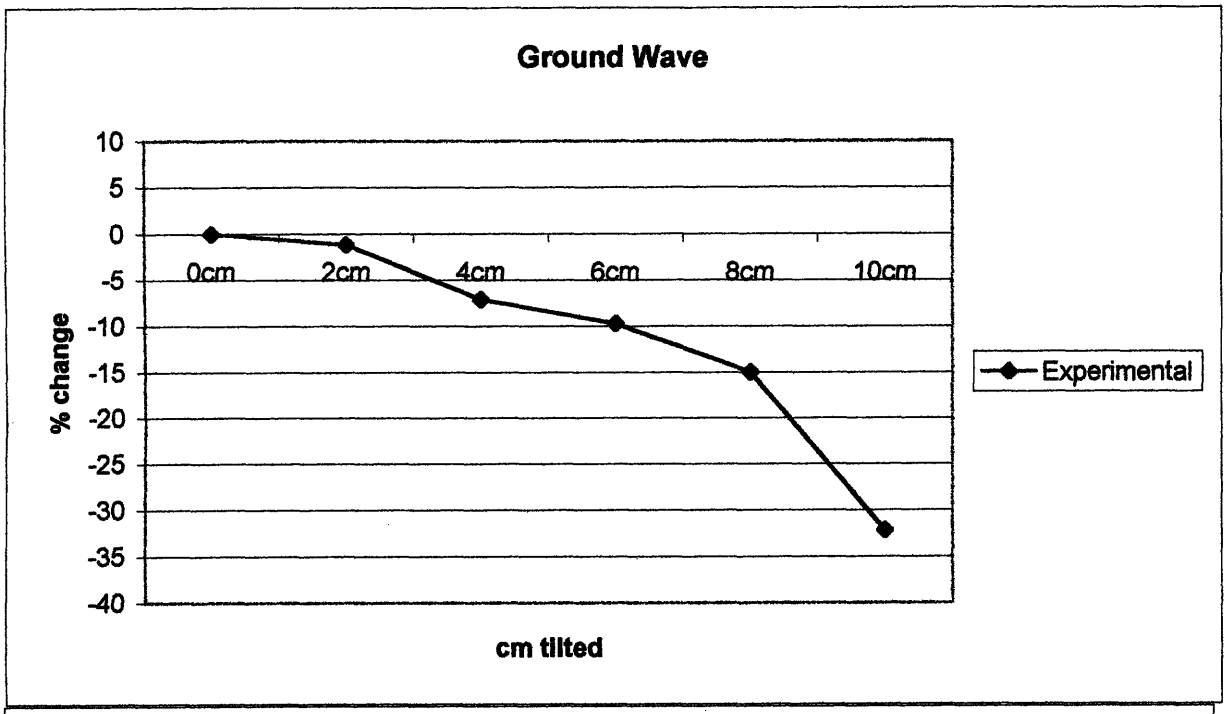


Figure 21. These two sets of traces are from tilting the receiver backwards. Two sets are provided at different gains in order to display both the ground wave and the first reflection without overgain.

CHANGE IN AMPLITUDE AS RECEIVER IS TILTED BACKWARDS



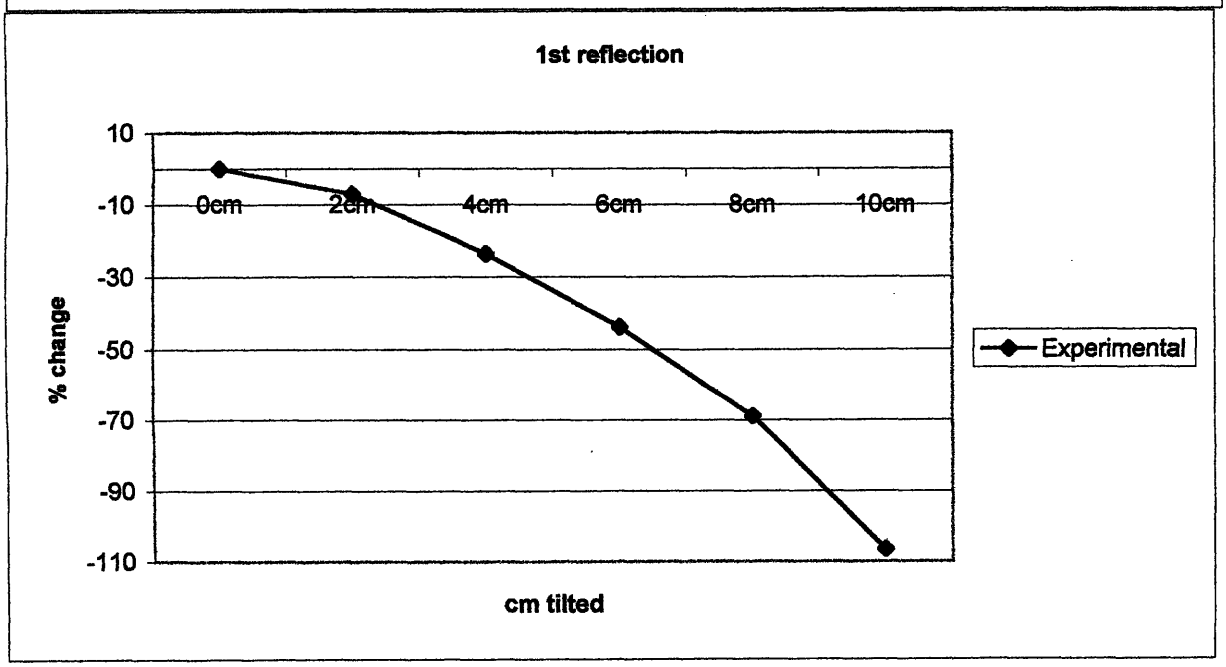


Figure 22. These graphs show how the amplitude of the ground wave and the first reflectors change from tilting the receiver backwards.

CHANGE IN ARRIVAL TIME AS RECEIVER IS TILTED BACKWARDS

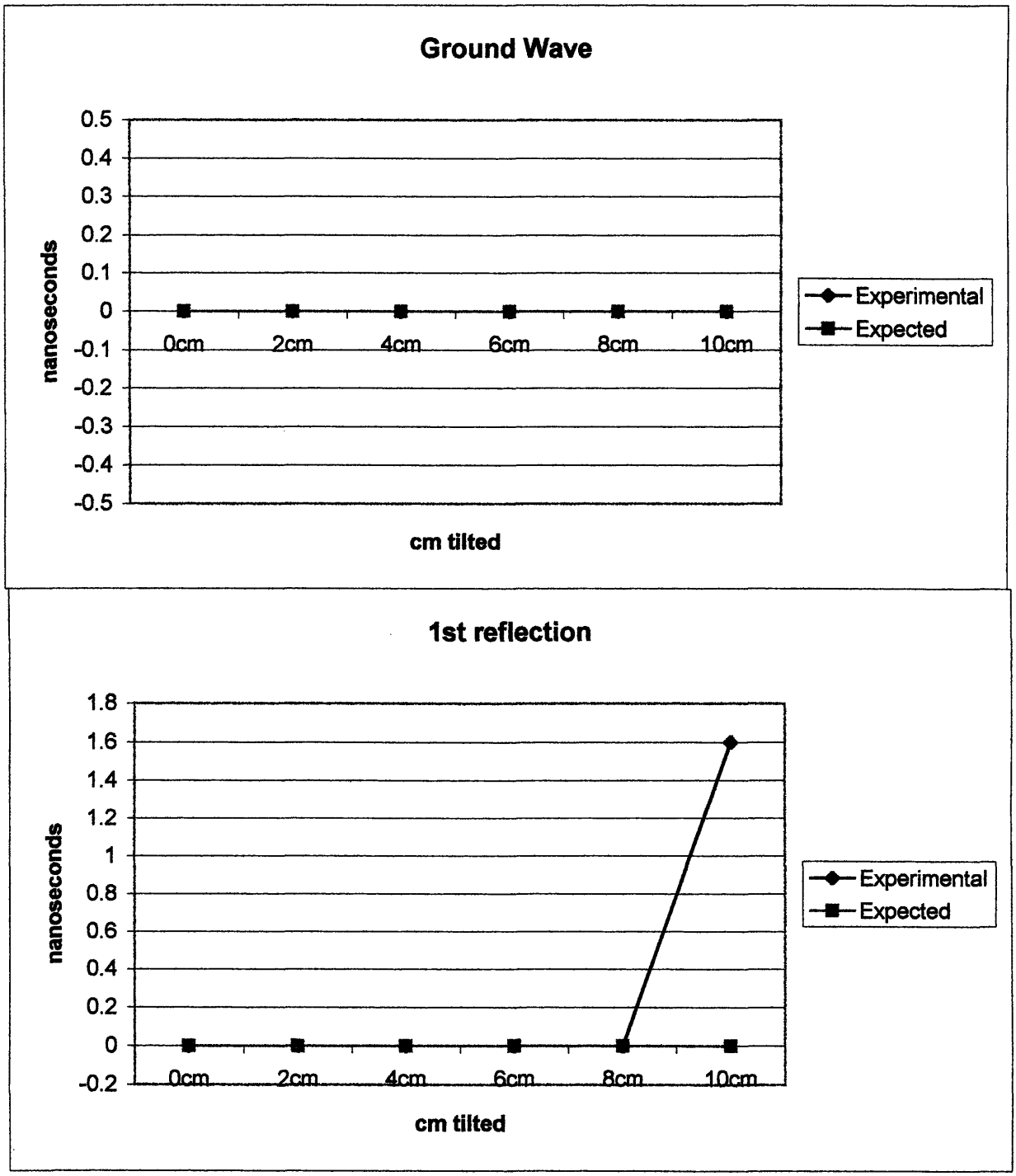


Figure 23. These graphs show how the arrival times of the ground wave and the first reflector change from tilting the receiver backwards.

-15 to 40 nanoseconds

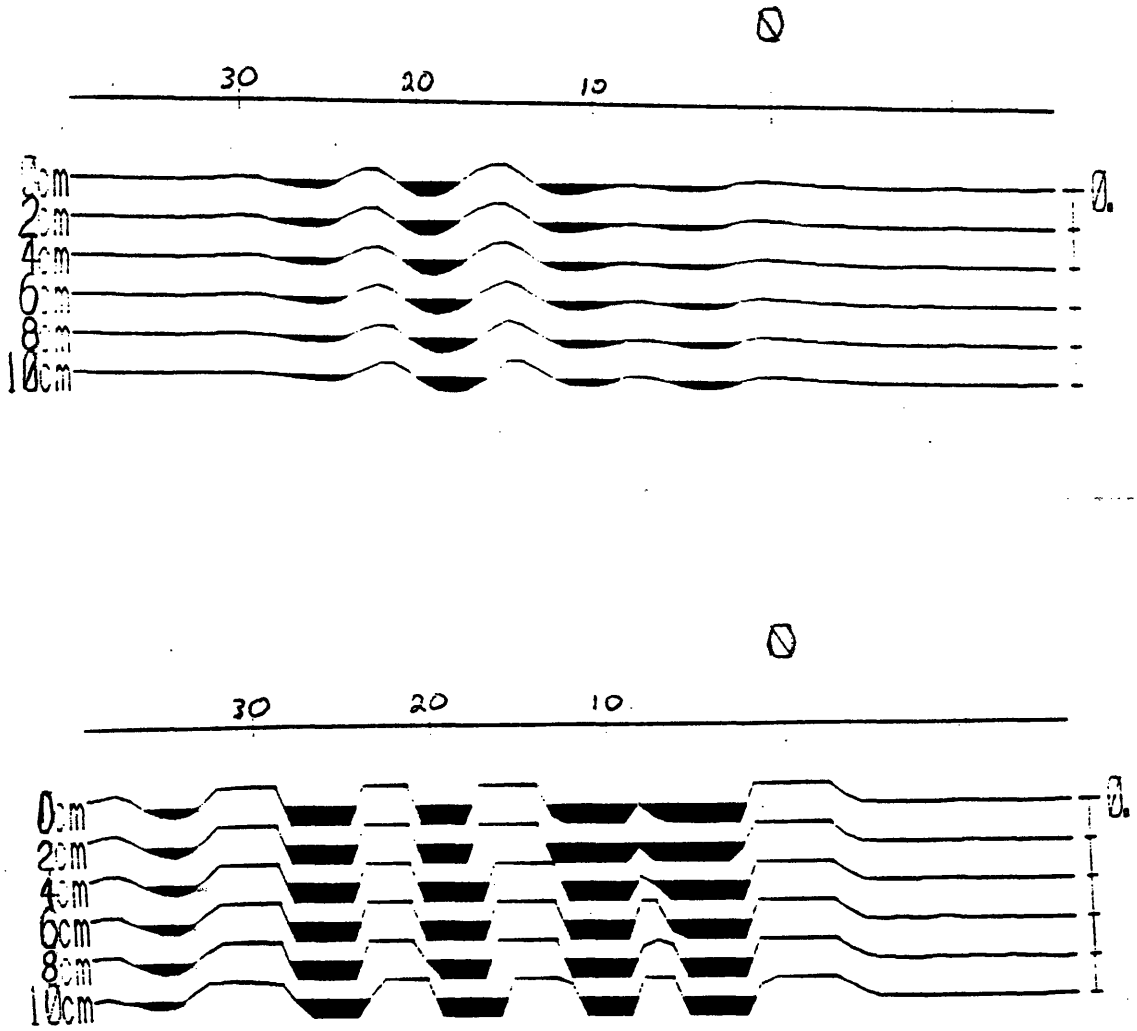


Figure 24. These two sets of traces are from tilting the receiver forwards. Two sets are provided at different gains in order to display both the ground wave and the first reflection without over-gain.

CHANGE IN AMPLITUDE AS RECEIVER IS TILTED FORWARDS

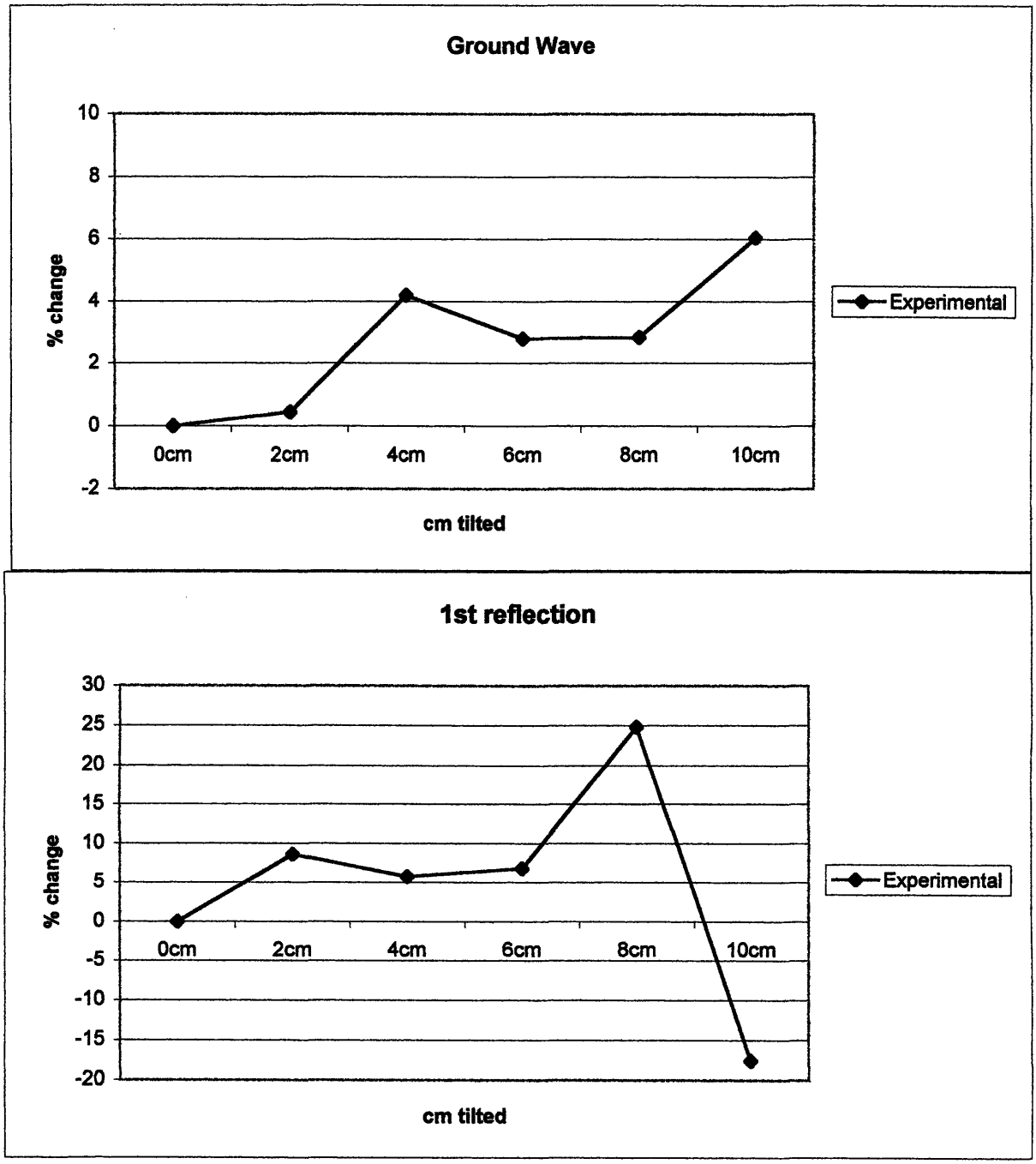


Figure 25. These graphs show how the amplitudes of the ground wave and the first reflection change from tilting the receiver forwards.

CHANGE IN ARRIVAL TIMES AS RECEIVER IS TILTED FORWARDS.

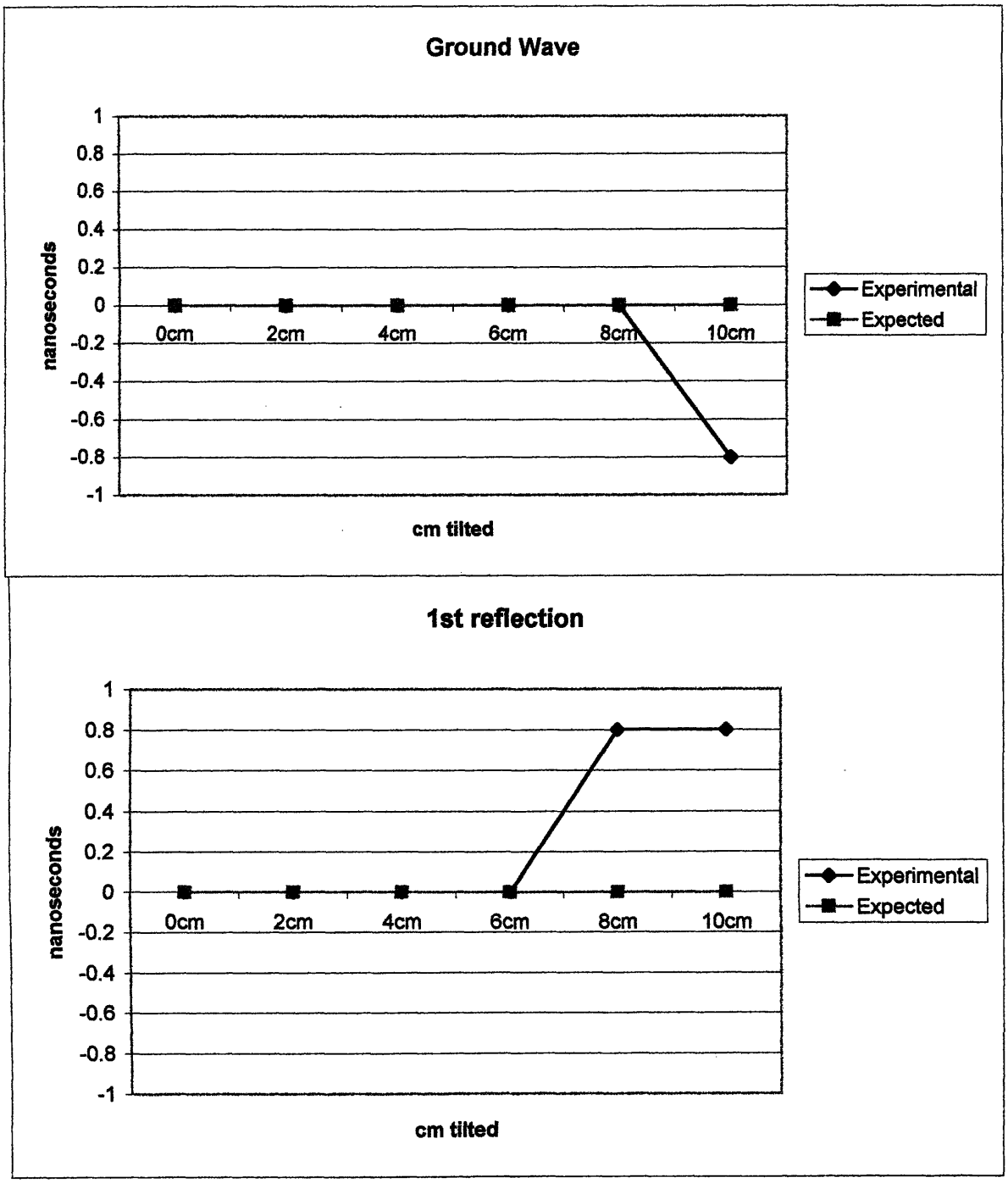


Figure 26. These graphs show how the arrival times of the ground wave and the first reflection change from tilting the receiver forwards.

-15 to 40 nanoseconds

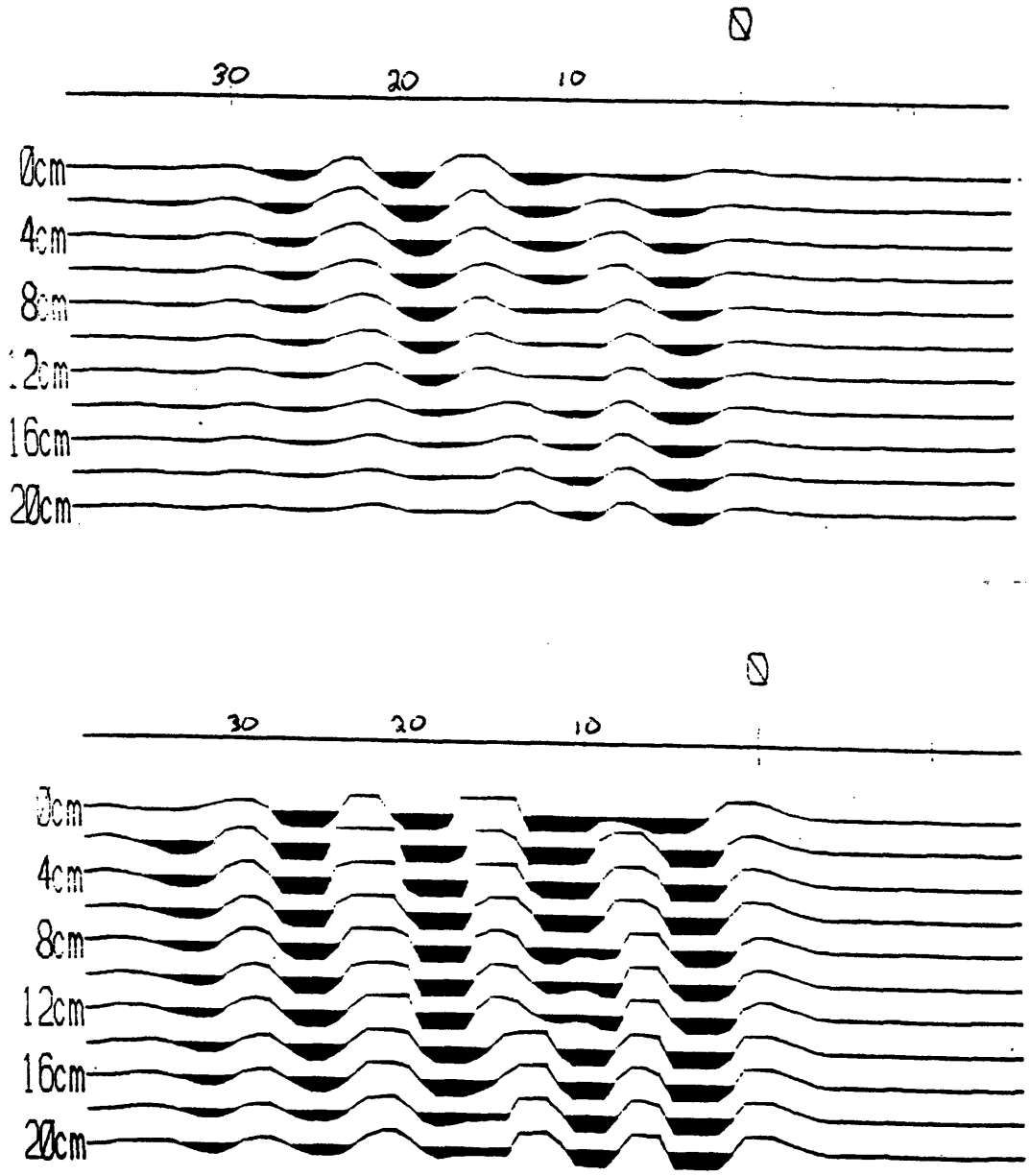


Figure 27 These two sets of traces are from tilting the receiver sideways. Two sets are provided at different gains in order to display both the ground wave and the first reflection without over-gain.

CHANGE IN AMPLITUDE DUE TO TILTING THE RECEIVER SIDEWAYS

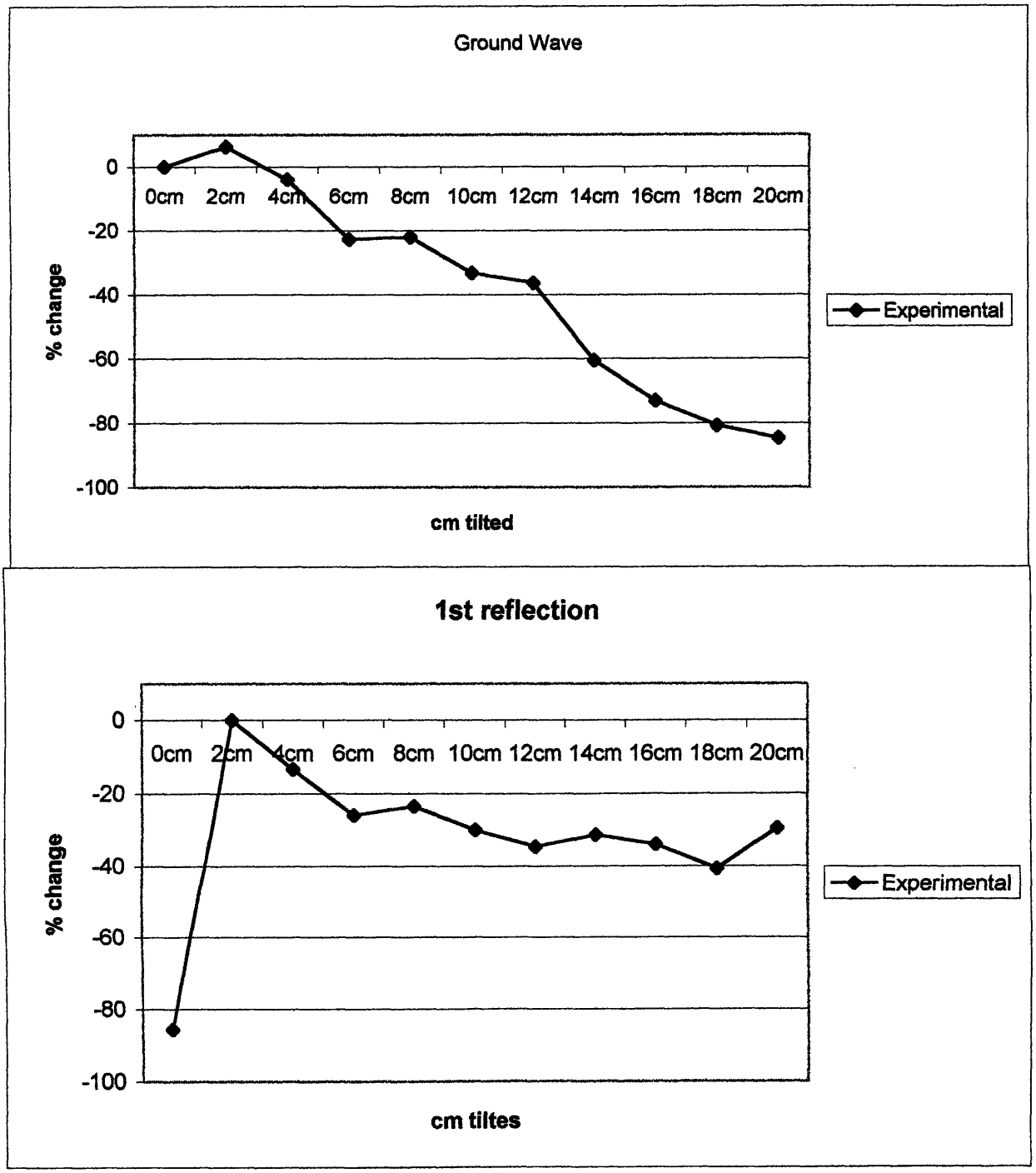
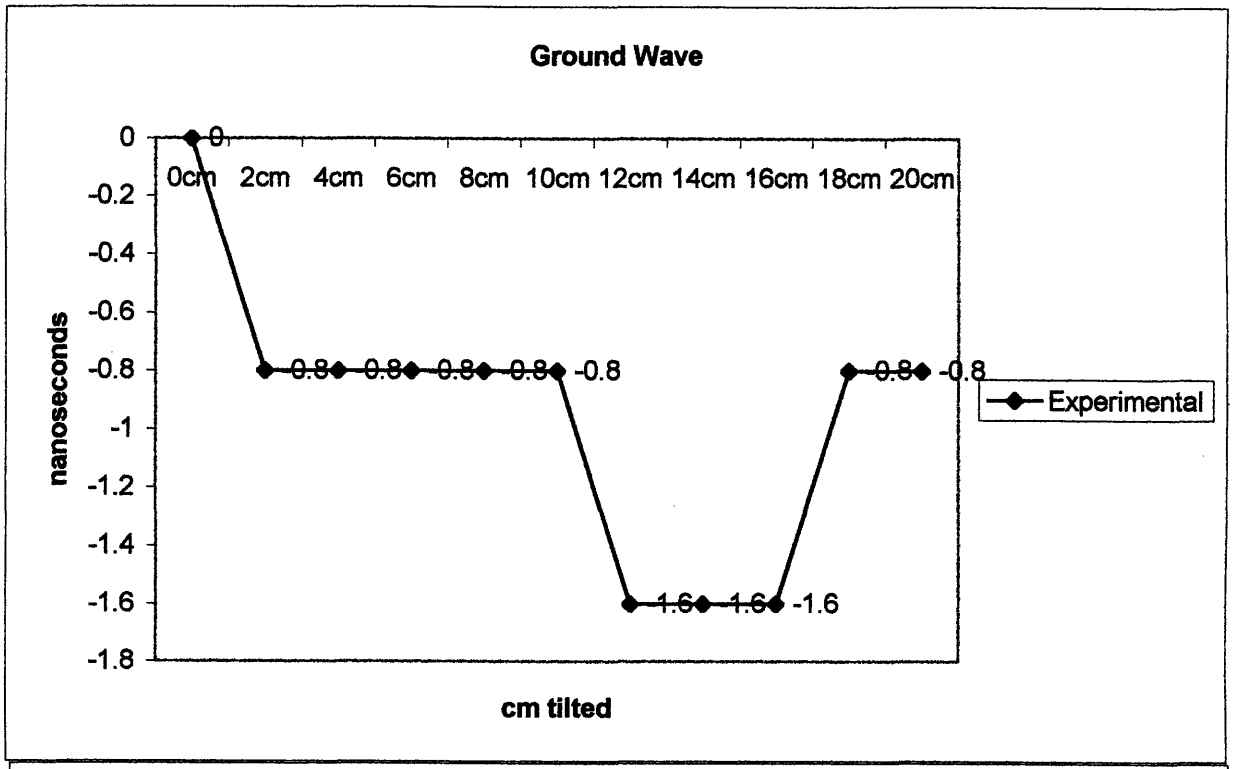


Figure 28. These graphs show how the amplitudes of the ground wave and the first reflection change with tilting the receiver sideways.

CHANGE IN ARRIVAL TIME FROM TILTING THE RECEIVER SIDEWAYS



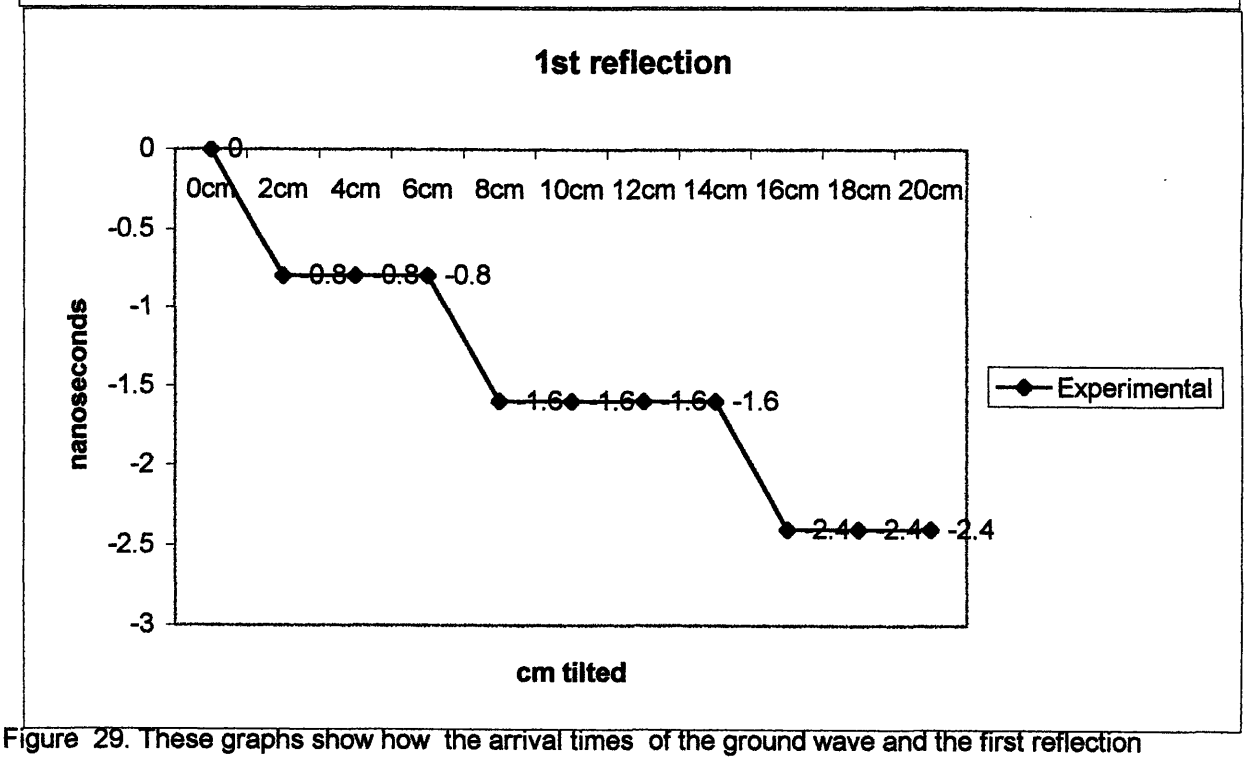


Figure 29. These graphs show how the arrival times of the ground wave and the first reflection change with tilting the receiver sideways.

-15 to 40 nanoseconds

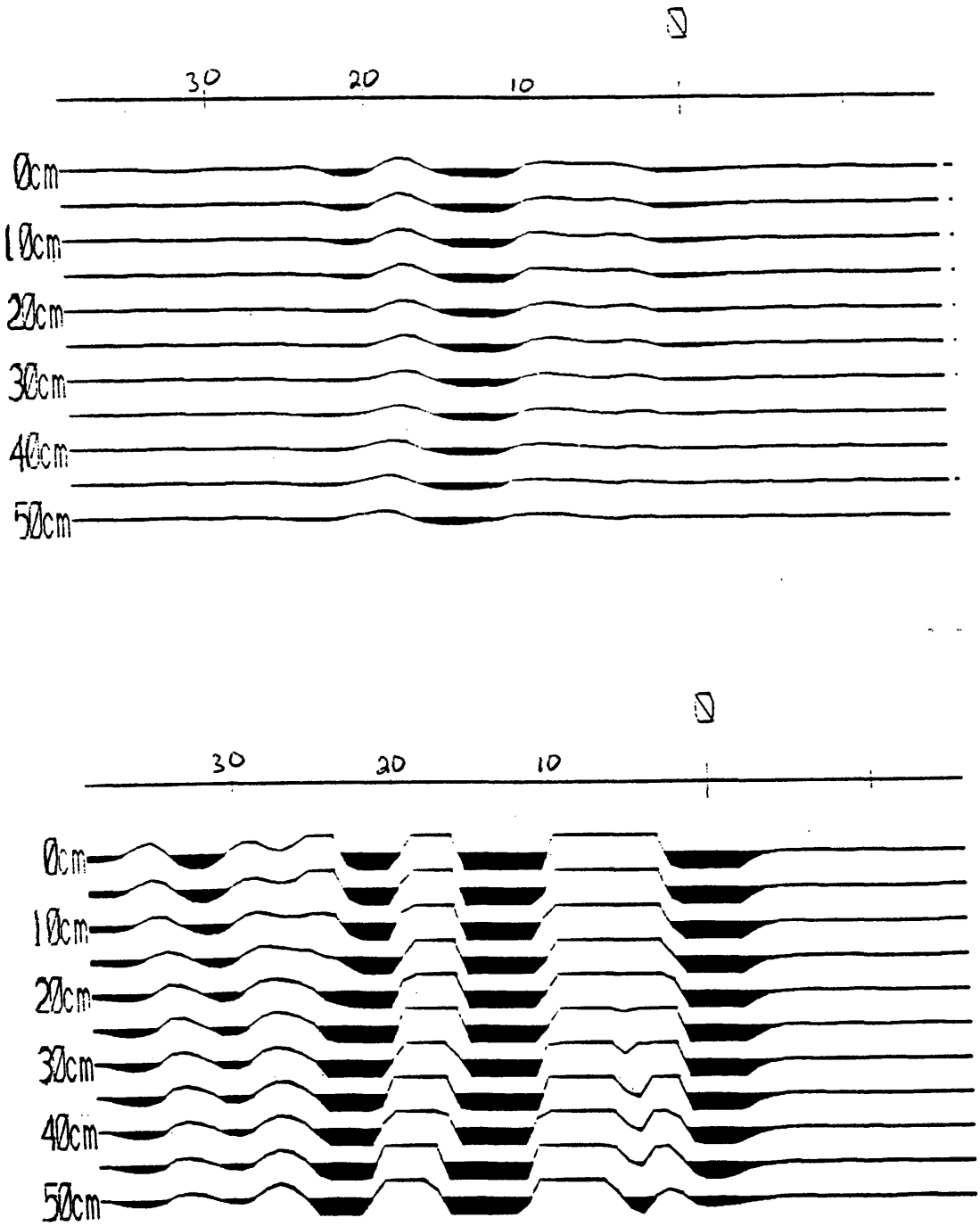


Figure 30. These two sets of traces are from translating the receiver sideways. Two sets are provided at different gains in order to show the ground wave and the first reflector without overgain.

CHANGE IN AMPLITUDE FROM SHIFTING THE RECEIVER SIDEWAYS

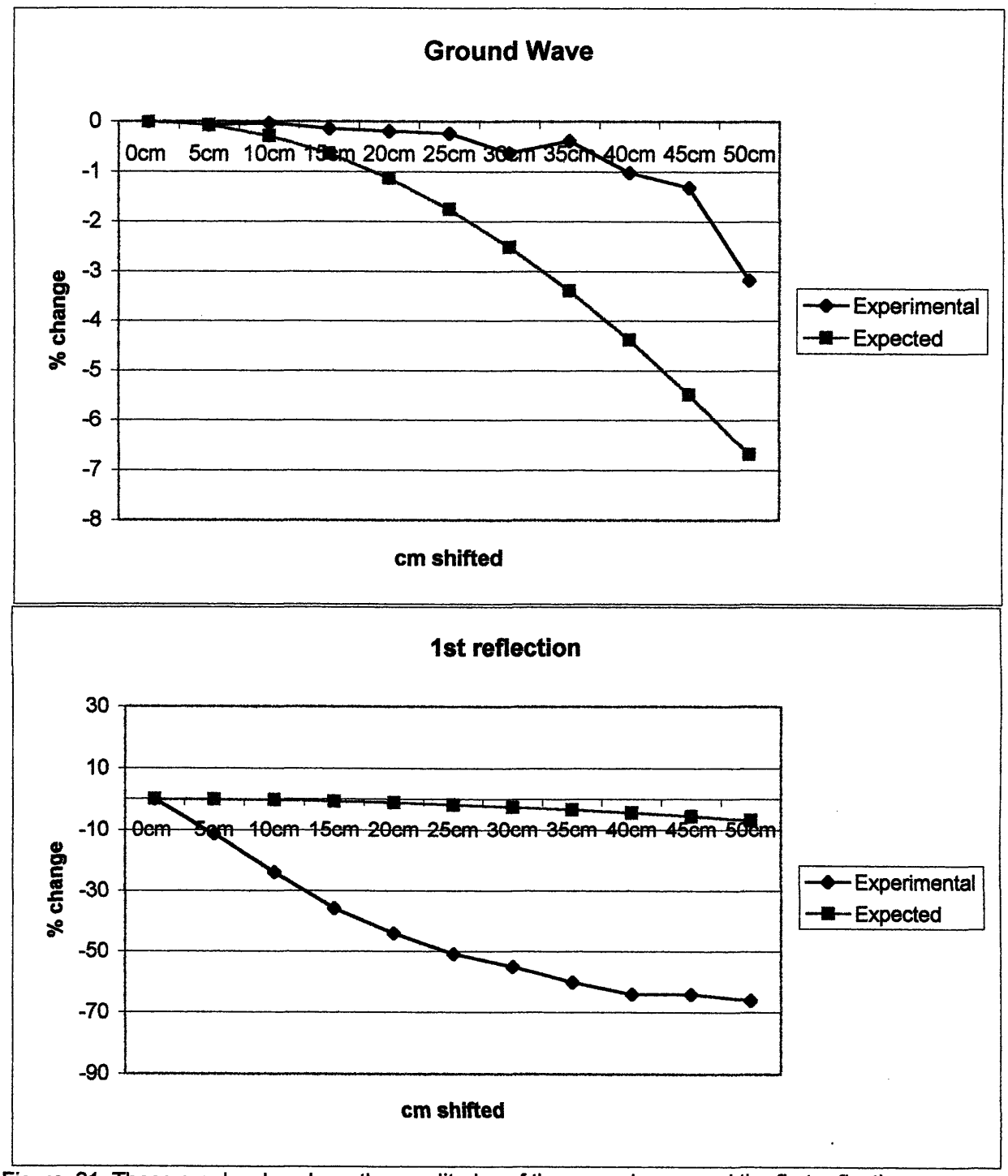
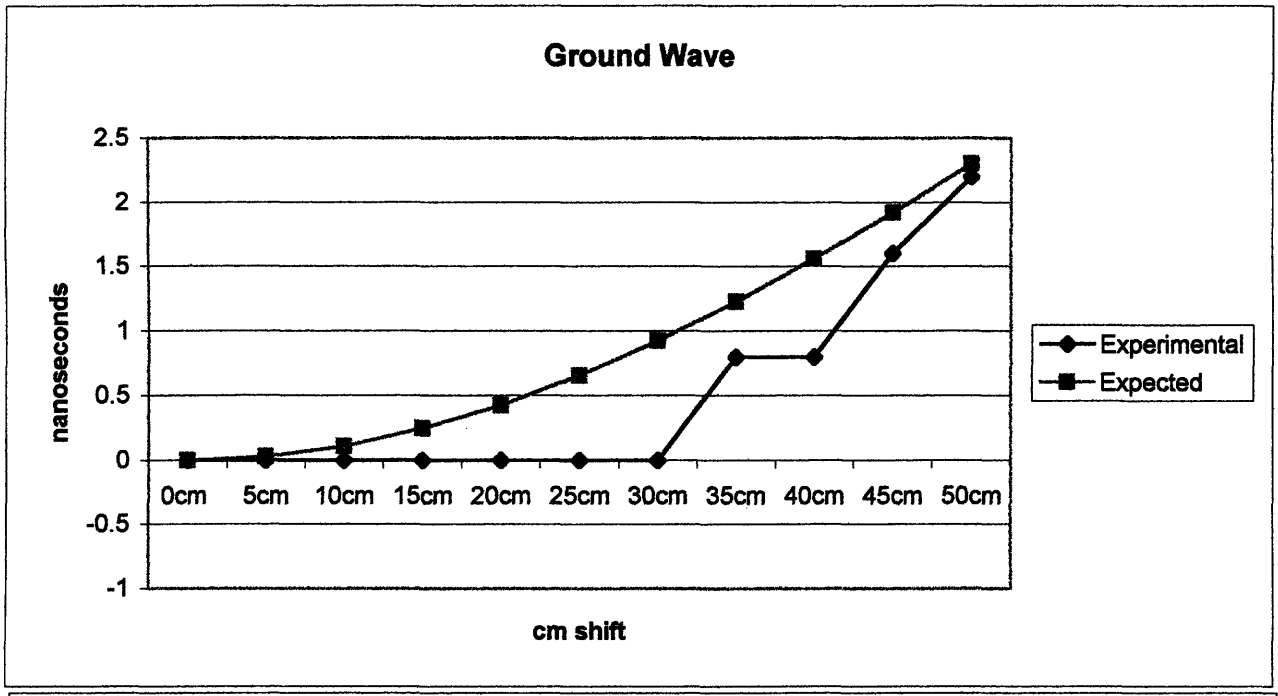


Figure 31. These graphs show how the amplitudes of the ground wave and the first reflection change with shifting the receiver sideways.

CHANGE IN ARRIVAL TIME FROM SHIFTING THE RECEIVER SIDEWAYS



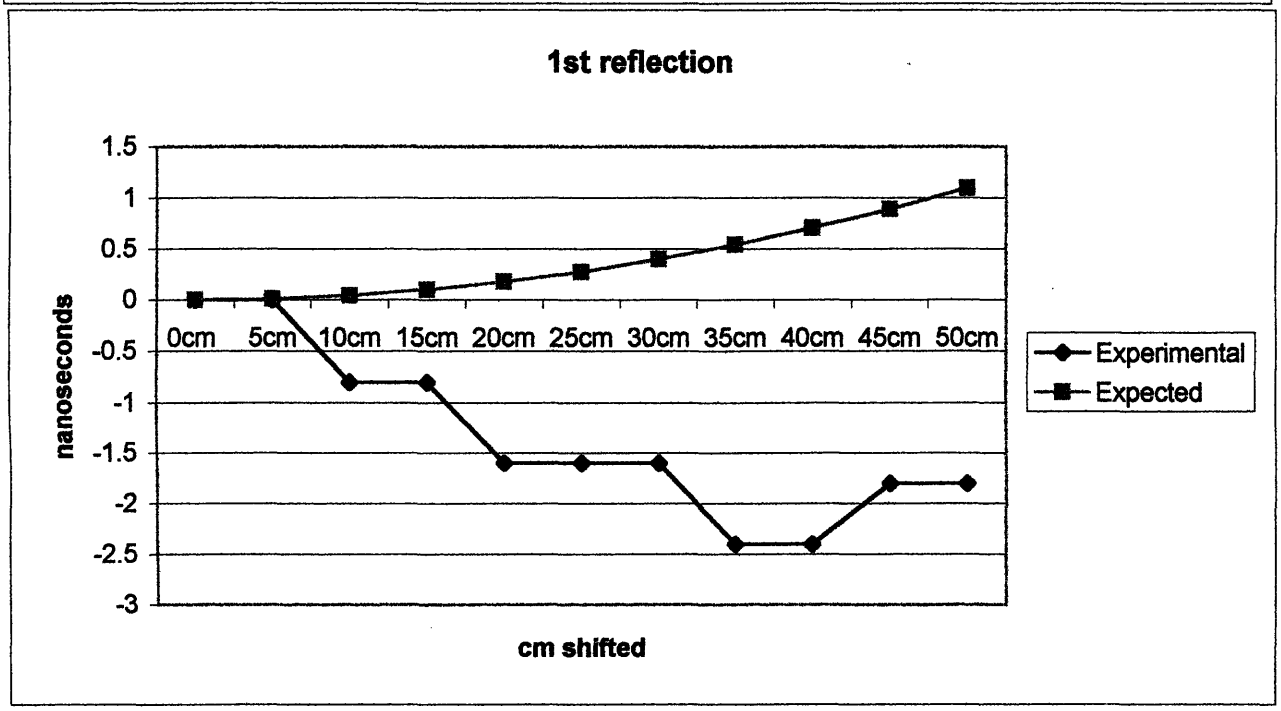


Figure 32. These graphs show how the arrival times of the ground wave and the first reflection change with shifting the receiver sideways.

Experiment (See figure 4)	Ground wave	1st reflection
Elevating the receiver:		
Amplitude	6cm	4cm
Arrival time	none	none
Rotated in surface plane:		
Amplitude	60deg	60deg
Arrival time	80deg	none
Tilted backwards:		
Amplitude	10cm	6cm
Arrival time	none	none
Tilted forwards:		
Amplitude	none	none
Arrival time	none	none
Tilted sideways:		
Amplitude	10cm	*12cm
Arrival time	none	16cm
Translated sideways:		
Amplitude	none	15cm
Arrival time	50cm	**35cm

* The first measurement on this plot is probably due to machine error and was not considered for this chart.
** This change is unexpected (see analysis)

Figure 33. This chart lists when significant changes occurred in the experimental data. A significant change in amplitude is a 30% change, and a significant change in arrival time is a change of at least two nanoseconds.