Horizontal and Vertical Eye Deviations in Response to Linear Accelerations

by

Brenda Joyce Kitchen

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Bachelor of Science
at the
Massachusetts Institute of Technology
May, 1983

Signature of Author. ....
Department of Electrical Engineering, Date

Certified by... ....
Thesis Supervisor

Certified by...
Thesis Supervisor

Accepted by...
Chairman, Departmental Committee on Theses

ABSTRACT

Horizontal and Vertical Eye Deviations in Response to Linear Accelerations

Author: Brenda Joyce Kitchen

Thesis Supervisors: Dr. Charles M. Oman
Senior Research Engineer
Mr. Anthony P. Arrott
Ph.D. Candidate
Department of Aeronautics and Astronautics

In order to determine the effects of periodic, whole body, linear accelerations on compensatory eye movements a series of experiments were performed on 23 normal subjects using a rail mounted linear acceleration sled. Subjects were accelerated sinusoidally at amplitudes between 0.06g (60 cm/s^2) and 0.9g (900 cm/s^2) at frequencies ranging from 0.1 Hz to 0.8 Hz. Subjects were tested in two orientations with respect to the direction of motion and the direction of gravity: i) Y-Z: lateral acceleration in the upright position; and ii) Z-X: longitudinal acceleration in the supine position. Eye movements were recorded using standard electro-oculography. Horizontal eye movements were recorded for the Y-Z orientation and vertical eye movements were recorded for the Z-X orientation.

All subjects from whom measurements were obtained showed consistent evidence of horizontal compensatory eye movements in the Y-Z orientation. Only two subjects exhibited distinct vertical compensatory eye movements. Vestibular nystagmus similar to that elicited by head rotation was observed under conditions of complete darkness. Lighting conditions were significant in that even very dim, diffuse light caused the distinctly nystagmic response of total darkness to be transformed into lower amplitude smooth eye movements with few or no saccades.

Significant compensatory eye movements were obtained only for stimulus amplitudes of 0.2g or greater. Slow phase eye velocity was determined by digitial filtering and fit by a sinusoid of the same frequency as the stimulus. The amplitude of slow phase eye velocity appears to be linear with respect to acceleration. The sensitivity was determined to be 9.8 deg/sec/g for motion between 0.2g and 0.9g at 0.4 Hz. The amplitude was found to increase with frequency over the range 0.28 Hz to 0.8 Hz. Phase tends to increasingly lag the stimulus motion over this same range.

ACKNOWLEDGEMENTS

I would like to thank everyone in the Man Vehicle Lab who has helped me with this thesis.

A special thanks goes to my thesis supervisors, Dr. Charles M. Oman and Mr. Anthony P. Arrott, for their invaluable assistance.

An additional thanks to Anthony Arrott for his continuous guidance and encouragement. Without his help and support, this thesis would not have been such a great learning experience.

A big thanks to Robert "MONTY" Grimes, for everything...

I would like to thank Mohammed Massoumnia, Bob Renshaw, and Joyce Lee their valuable help. Also, thanks to Sherry Modestino and Margaret Amour for helping with the final document.

I am very grateful to all of the subjects who gave so freely of their time and patience. Without their cooperation this thesis would not have been possible.

A very special thanks to my family for the enormous amount of support, encouragement and love they have given me. Without them I could never made it through the "Institute," let alone this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The objective of this thesis is to determine the effects of periodic linear acceleration on compensatory eye movements. By analyzing these effects it is hoped that a better understanding of the otolith-ocular reflex can be gained.

There has been a great deal of experimental work done to determine the role of the semicircular canals in producing compensatory eye movements. However there is not much data on the behavior and role of the otolith organs. Much of the evidence cited in the literature is contradictory. Niven, Hixson, and Correia (1966) found that horizontal nystagmus could regularly be elicited, while no signs of vertical nystagmus were found. All of their tests were conducted along the y-axis. In parallel swing tests, Bles and Kapteyn (1973) found both horizontal and vertical eye movements. Thus, one of the main purposes of this thesis is to take a closer look at the response of the otoliths.

The research contained in this thesis is part of a battery of tests which are being conducted for NASA as part of the 1NS102 Spacelab 1 experiments. The aim of this series of tests is to gain a better understanding of the adaptation of the vestibular system to weightlessness and learn how space motion sickness is related to this adaptation.

The central aim of this thesis is to determine a set of conditions under which consistant manifestations of the otolith-ocular reflex can be obtained. From this an indicator of otolith function might be obtained which can be used to moniter the process of adaptation to weightlessness and subsequent re-adaptation to the earth's 1g bias.

BACKGROUND

Physiology

The vestibular system, located in the non-auditory inner ear, consists of two specialized portions, the semicircular canals and the otoliths (figure 1). This system has three major functions. First it is responsible for a great deal of the information we use to determine spatial orientation as well as sensation of motion. Secondly, the canals and otoliths are very influential in the maintenance of posture. Finally, stabilization of the visual field is also controlled by the vestibular system.

The semicircular canals are fluid-filled ducts which act as angular accelerometers (figure 2). They are stimulated by angular accelerations of the head normal to the plane of the given ring. For frequencies between 0.1 Hz and 5 Hz the canals transduce angular velocity. Thus perception of rotation and stabilization of the visual field on the retina are based on the interpretation of the canal signals as representations of angular velocity. The semicircular canals are relatively insensitive to linear inertial forces.

The utricular and saccular otoliths, however, do perform the functions of detecting gravitational and linear inertial forces, but can not distinquish between the two. The utricular and saccular macculae both consist of hair cells and supporting cells. Hair cells transduce mechanical energy to initiate nerve impulses which emanate from these endorgans. Hair-like cilia project into a gelatenous mass called the otolithic membrane. On top of this membrane lies a dense layer of

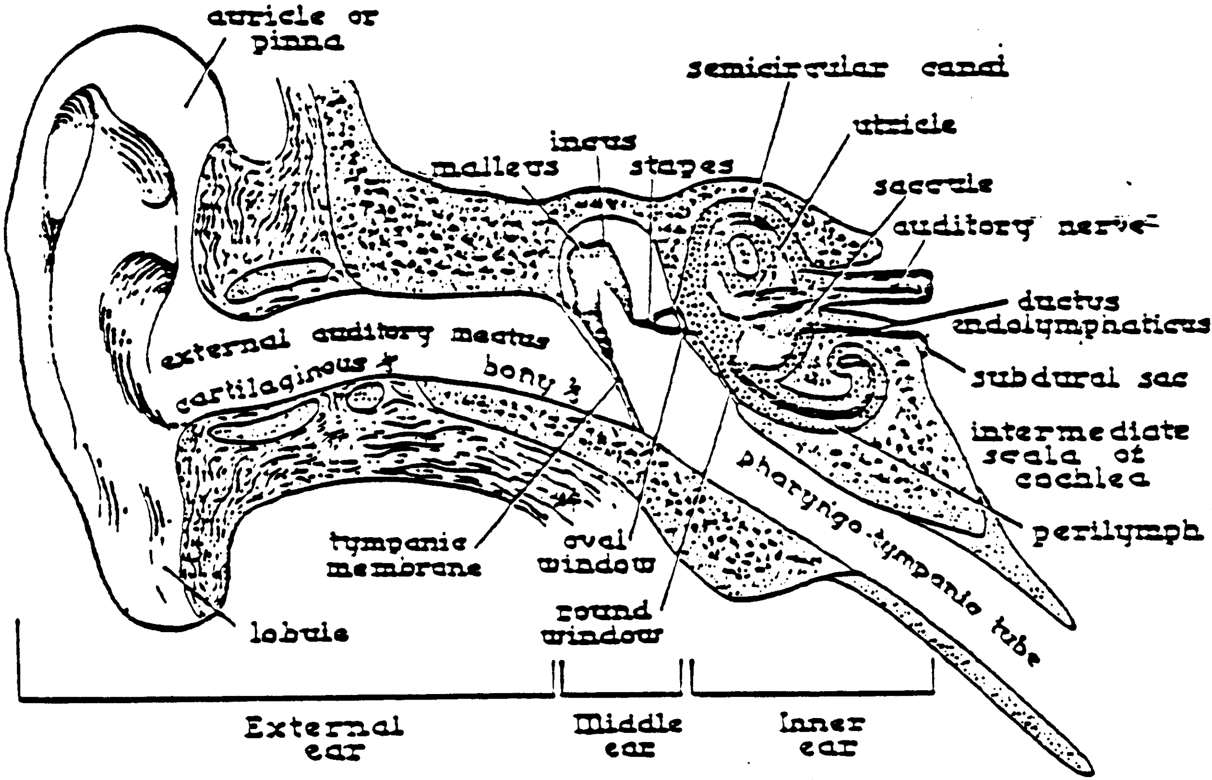


Figure 1. Diagram of an ear, showing the relations of the external, the middle, and the inner ear.(Addison: Piersol's Normal Histology, ed. 15. Lippincott, Philadelphia)

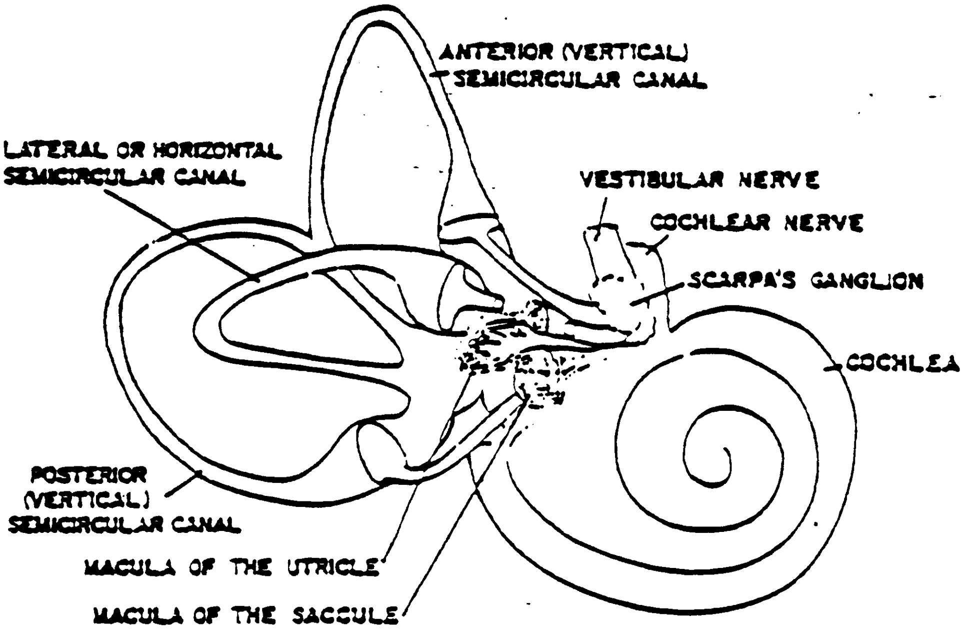


Figure 2. Labyrinth of left ear as viewed from the medial aspect. (Bioastronautic Data Book, NASA SP-3006)

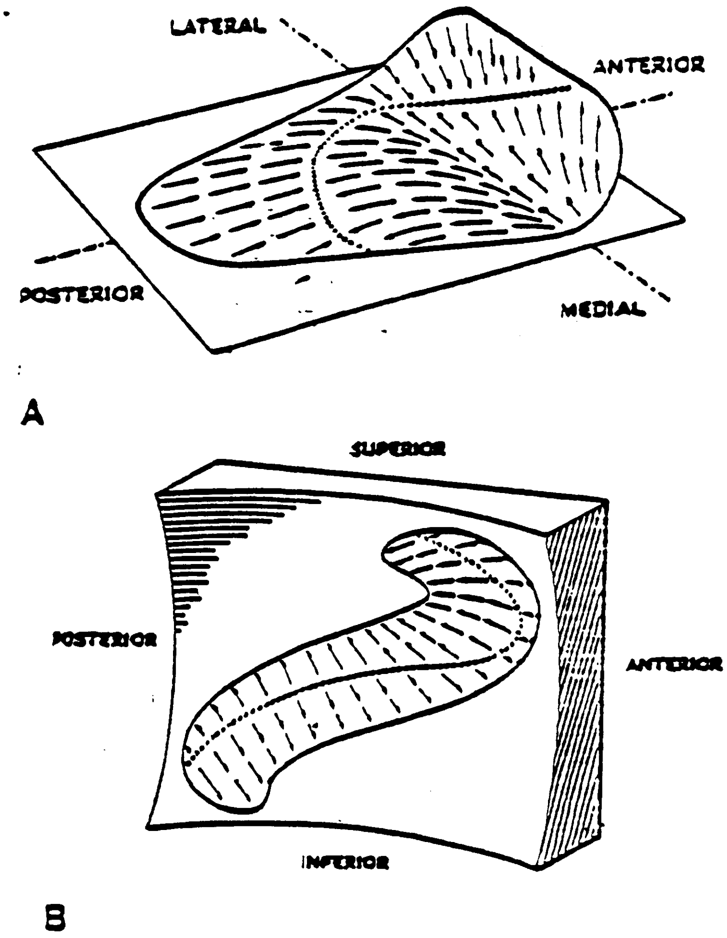


Figure 3. General orientation and distribution of morphological polarization vectors of (A) utricular and (B) saccular maculae. (Spoendlin, 1966)

calcite crystals called otoconia. During accelerations of the head these crystals tend to "lag" behind as they move across the dense otolithic membrane. When the head is tilted, they tend to "slide" downhill. The threshold response is approximately 0.005g (Young and Meiry, 1970), where g = 9.81 m/sec/sec. The geometrical distribution of sensory cells along the macculae provides sufficient information so that both the magnitude and direction of the gravito-inertial stimulus can be determined. The utricles are most sensitive to gravitational and inertial forces along the transverse plane of the head while the saccules are most sensitive to these forces along the sagital plane (figure 3).

Eye Movements

Saccadic eye movements are characterized by rapid conjugate movements whereby the eyes "jump" from one point of fixation to another. The initial acceleration as well as the final deceleration of these saccadic eye movements is very high (ranging up to 40,000 deg/sec/sec). Both the peak velocity and duration are dependent on the magnitutde. The amplitude of the peak velocity may be as high as 600 deg/sec, while the duration varies from 30 to 120 msec.

Smooth pursuit eye movements are used when tracking slow moving visual targets (ranging from 1 to 30 deg/sec.) Apparently the purpose of this type of conjugate eye movement is to maintain a moving image on the fovea without the influence of saccades. The velocity of smooth pursuit movements seem to be limited to less than 40 deg/sec. An important characteristic of this slow-tracking mechanism is that it requires the existence of an actual moving target. Attempts to track "imaginary" slow moving targets, normallly do not result in smooth conjugate eye movements. Nakayoma (1978) however found that, with feedback, subjects can be trained to make these smooth movements.

Compensatory eye movements are generally smooth movements which are very much like pursuit movements, except that instead of maintaining a target on the fovea, compensatory eye movements attempt to stabilize the entire visual field on the retina. The maximum velocity is faster than foveal smooth pursuit movements, ranging as high as 120 deg/sec. Compensatory eye movements occur in response to coherent motion of the entire visual field (optokinetic eye movements) as well as in response to movements of the head (vestibulo-ocular reflex) or neck (cervico-ocular reflex). Vestibular eye movements are influenced by both the semicircular canals and the otoliths.

If the amplitude of the compensatory movement is sufficiently great, nystagmus results. Nystagmus consists of both a slow and fast phase. The slow phase corresponds to a smooth pursuit movement where an image is stabilized on the retina. The fast phase is a saccadic movement where the eyes "jump" to pick up another image. This new image is then tracked during another slow phase component. Thus, a saw-tooth pattern emerges during this oscillatory motion.

Recording Eye Movements

A corneo-retinal potential difference between 0.2 and 1 mv normally exists during steady state illumination. This is the basis for one of the simplest, most inexpensive techniques of recording eye movements - electro-oculaography (EOG). This bioelectric potential varies with the level of light adaptation. Thus, for stable EOG recordings, the subject should be allowed to adapt to the ambient light level to be used during the actual experiment. Ideally this adaptation should occur for 30 to 60 minutes prior to the experiment (Young and Sheena, 1975). Realistically 5 to 15 minutes should prove to be sufficient (see appendix C).

As the eye rotates or moves, the corneo-retinal dipole rotates with it. Therefore the potential difference measured by electrodes attached to the temples varies as the sine of the angle of deviation. For small angles $w < pi/4$ (45 degrees) $\sin w = w$ is within 10%.

The major difficulties encountered with EOG are muscle artifacts, particularly interference of the eyelids during blinking, and variations in the corneo-retinal potential. These variations are caused by several factors such as light adaptation and subject alertness. The recording electrode/skin interface is also a major source of drift (see Appendix C).

Vestibular Nomenclature

When refering to these experiments it is helpful to have a consistent frame of reference. Using the nomenclature found in Figure 4 as well as Figure 5 the four positions utilized are: 1) Y-Z, lateral acceleration while seated upright; 2) Y-X, lateral acceleration while lying supine; 3) X-Z, fore-aft acceleration while seated upright; and 4)

Z-X, longitudinal acceleration while lying supine. (Note, the first vector refers to the direction of motion relative to the head while the second vector corresponds to the direction of gravity relative to the head.)

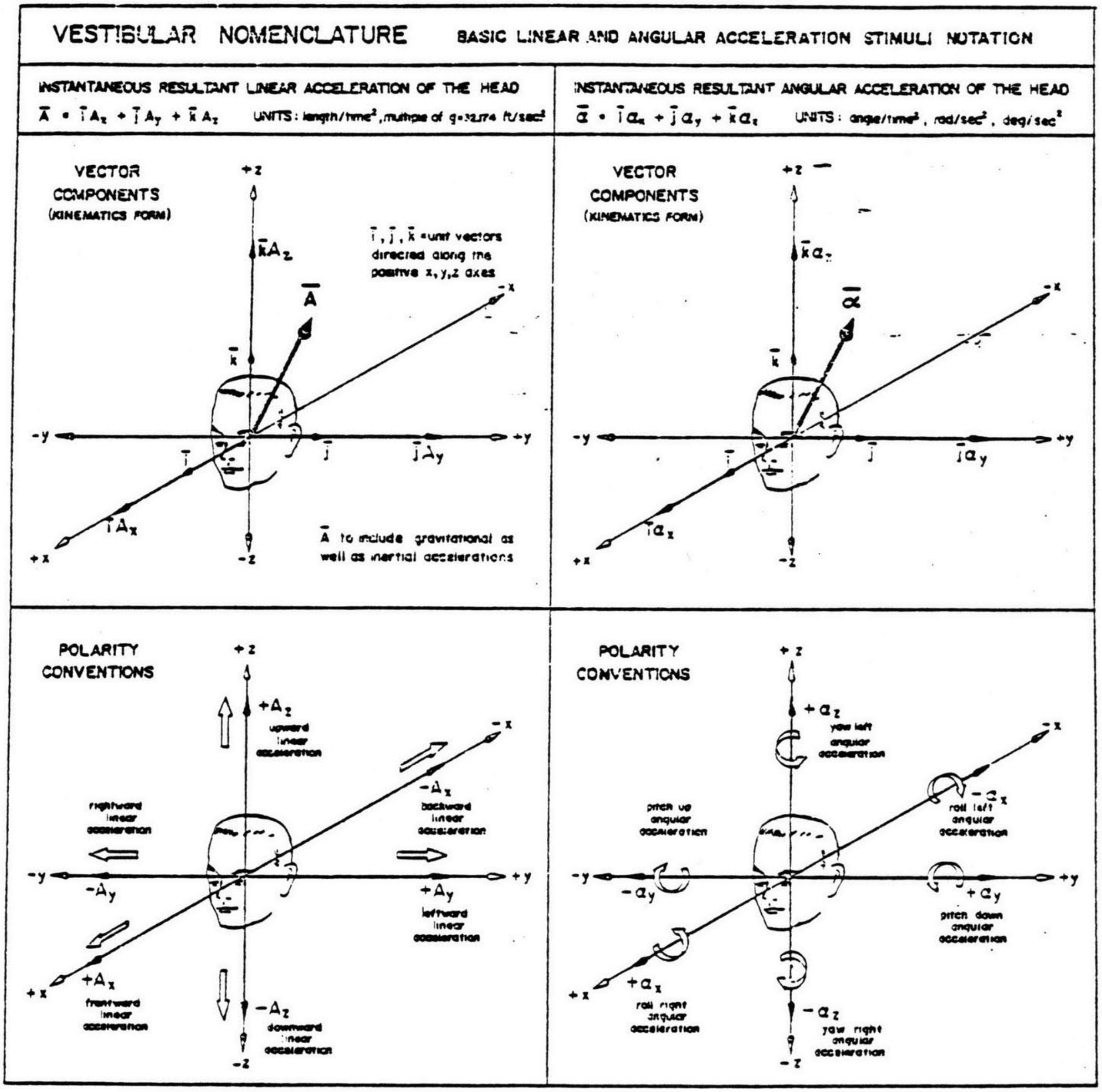


Figure 4. Vestibular nomenclature. (Hixson, Niven, and Correia, 1966)

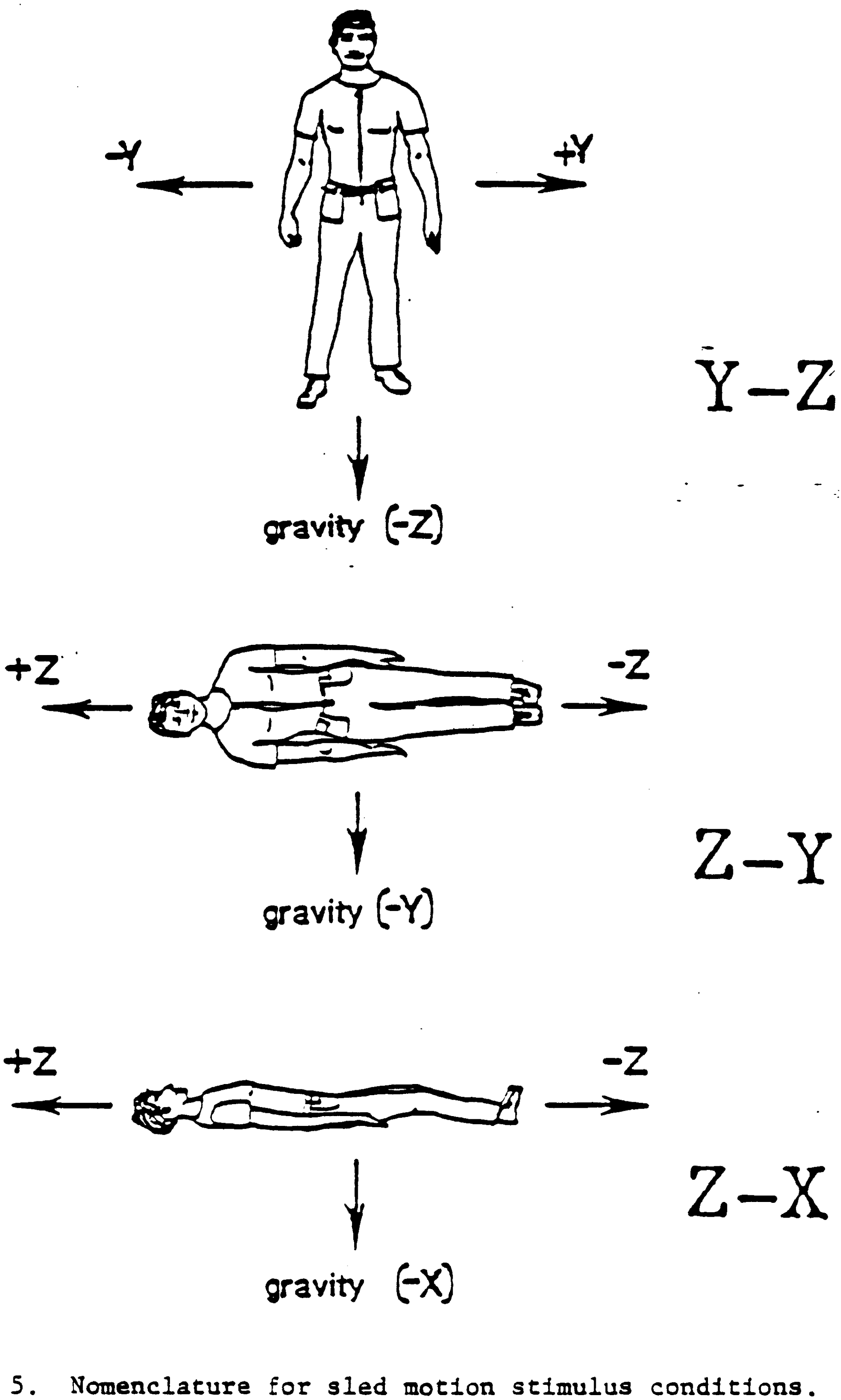


Figure 5. Nomenclature for sled motion stimulus conditions. The direction of motion is given first, followed by the direction of gravity. (Arrott, 1982)

Past Experimentation

Previous experiments on both animals and humans have been conducted to study the effects of linear acceleration on eye movements. Sjoberg (1931) found that vertical eye movements could be elicited in rabbits using horizontal linear accelerations. He could reproduce these responses in either dogs or humans. Jongkees (1961) conducted human experiments on a parallel swing, but found the eye movements to be regular, not nystagmic. McCabe (1964) tested cats, chinchillas and humans using vertical linear accelerations. He found that rhythmic vertical linear acceleration could elicit nystagmus in all three.

Two more recent experiments on humans were conducted by Bles and Kapteyn (1972) and Niven, Hixson, and Correia (1966). Bles and Kapteyn generated a combination of horizontal and vertical linear accelerations using a parallel swing. The subject's head was suspended so that it moved with the body. The subjects were instructed to keep their eyes closed and assume a reverie state. They were placed in each of three positions: 1) lying on the back; 2) lying on the right side; 3) lying on the left side. All accelerations were along the lengthwise axis of the body (Z-X supine). Bles and Kapteyn observed both horizontal and vertical eye movements for each eye. However the patterns seen were disconjugate (right eye moving differently for the left eye) and not consistent. For the twenty-two subjects tested, the following results were obtained: 1) Lying on the back, six subjects exhibited horizontal sinusoidal movements, even though there was no acceleration stimulus in the horizontal direction. Two of these six showed disconjugate sinusoidal movements with double the swing frequency. Two other subjects had vertical disconjugate eye movements. 2) Lying on the right side, only one subject exhibited vertical eye movements. Fifteen subjects showed horizontal sinusoids, in six of these, it was present int the lower eye only; 3) Lying on the left side, they observed fourteen subjects with horizontal sinusoidal eye movements. Eleven subjects exhibited vertical eye movements only in the lower eye. Bles and Kapteyn claim that their head suspension system eliminated the possibility that the eye movement signals seen were artifacts due to electrode and skin motion.

Niven, Hixson, and Correia conducted their tests on the Coriolis Acceleration Platform (CAP), a device which is capable of producing horizontal linear accelerations on a 45 foot track. The stimulus used consisted of three sinusoidal oscillations, all with a peak acceleration of 0.58g. The frequencies were 0.2, 0.4, 0.8 Hz. In these experiments, the subject's head was rigidly fixed in a custom-molded plaster cast, while the body was secured to the seat with straps. Each of four subjects was placed in four different orientations and exposed to all three frequencies of oscillation. These orientations were: 1) Y-X, subject lying on the back such that the sagital xz head plane was perpendicular to the acceleration vector; 2) Y-Z subject in same position as in 1 except subject sitting upright; 3) Z-X, subject lying on the back with transverse xy head plane perpendicular to the acceleration vector and 4) Subject sitting upright with frontal yz head plane normal to the track motion. The subjects were instructed to "maintain a straight ahead gaze at all times" during cab oscillations.

After the subjects' eye movements had been calibrated the cab was closed light-tight and the tests were conducted in this configuration. Some of the recordings were made with eyes closed. Each test run lasted 2 minutes with the first 60 seconds being ignored due to transient effects that supposedly take place during that time. To increase the nystagmic response mental arithmetic and verbal "chatter" were used. In these experiments, the subject's head was rigidly fixed in place with a custon-made plaster cast, while the body was secured to the seat with straps.

For eyes open and eyes closed, horizontal nystagmus was elicited in the 1st and 2nd orientations, in which the acceleration stimulus was applied to the subject's y-axis. Horizontal nystagmus was not observed in orientations 3 and 4, in which the stimulus was in the z-axis planes. Vertical nystagmus was never observed. The mean peak eye velocity remained constant at approximately 10 deg/sec for all frequencies for both Y-Z and Y-Z axis stimuli. The phase lags for the frequencies 0.2, 0.4, and 0.8 were 20, 31, and 38 degrees respectively. These phase lags are relative to the negative acceleration vector.

Vidic (1976) investigated the role of the otoliths in tracking fixation points during earth vertical displacements of the body. During fixation tests conducted in the dark, very erratic eye movements were recorded. These movements were primarily saccadic, with very little smooth tracking movements. Normal subjects that were instructed to look straight ahead exhibited no signs of vertical nystagmus.

METHODS

By studying the compensatory eye movements exhibited during periodic linear accelerations, a better understanding of the otolith-ocular response can be gained.

Experiments were conducted on twenty-three subjects in four phases of development. Seven subjects were used in preliminary experiments to determine motion profiles, recording conditions, and subject instructions. Results were obtained from fourteen subjects using three distinct protocols.

Subjects were placed on a rail-mounted linear acceleration cart which provides earth horizontal sinusoidal accelerations. In addition to varying acceleration, a range of frequencies was also used. Eye movements were recorded using standard EOG techniques.

Equipment

The MIT Sled Facility

The MIT Sled (Lichtenberg, 1979) consists of a cart which runs along two circular rails on four ball bushings (figure 6). A newly designed chair (Abramson, 1983) is mounted on top of the cart which is driven by a torque motor connected to a winch drum, cable, and pulley assembly. Subjects are placed in the chair and restrained by an adjustable four point seat belt. The head is firmly restrained in a special helmet which is attached to the frame of the cart. This helmet is a prototype of the helmet to be used in the Spacelab experiments.

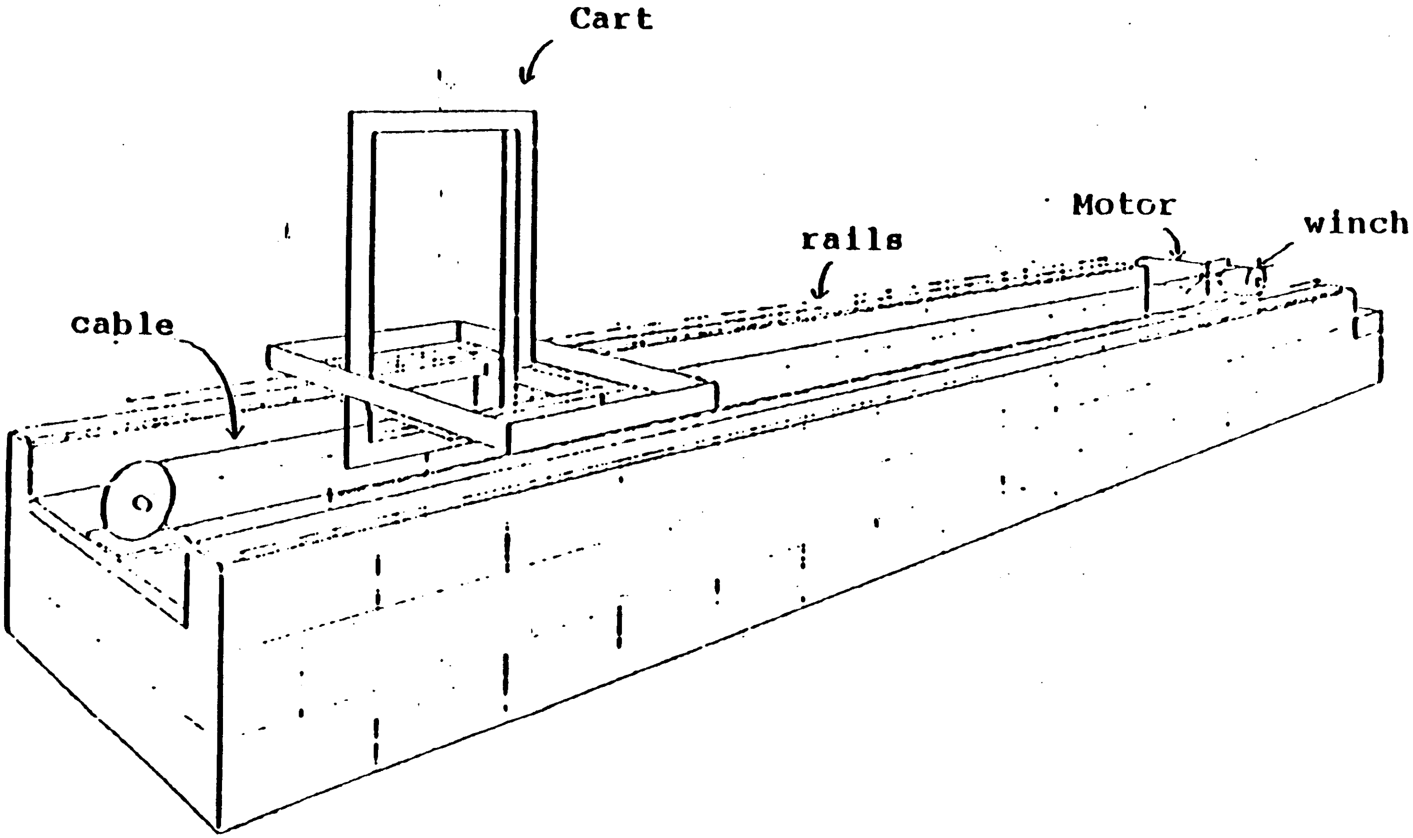


Figure 6. The M.I.T. Sled showing the components which achieve cart motion. The chair is not depicted. (Lichtenberg, 1979)

The aluminum cart is a simple box frame guided along the rails by four pillow blocks with recirculating linear ball bearing bushings. The rails are one inch in diameter and are made of hardened steel. The two rails are 5 meters long, 1.7 meters apart and mounted on top of concrete block walls. One rail is rigidly fixed to its concrete wall, thus properly aligning the cart. The other rail is held more losely on top of its concrete wall. Therefore it is aligned by the ball bushing as the cart moves along the track.

A cable is attached to both sides of the cart and is wound around a pulley at one end of the track and a winch drum at the other. The cable is under 600 pounds of tension to help improve the dynamic response of the cart. The winch drum is directly driven by a 3.5 hp DC permanent magnet torque motor (Inland TTB-5302-100c.) An analog velocity controller (GE PWM Hi-Ac Servo-drive controller Model 3A) controls the motor using pulse-width modulation and tachometer feedback. The controller also serves as a current generator which allows the velocity of the cart to be proportional to low-current voltage signals applied to the controller. A ten-turn potentiometer is mounted on the motor shaft, while an accelerometer is mounted on the chair near the subject's head. These sensors as well as the motor shaft tachometer are used to moniter and control the motion profile of the sled.

The sled is controlled by the DEC PDP-11/34 minicomputer and Digital Lab Peripheral System (LPS). An interactive FORTRAN program, CART, written by A.P. Arrott (1980), provides "real time" remote control of the sled throughout the experiment. The computer program generates velocity commands for the analog controller which executes the given motion profile. Position and velocity feedback are used to provide a safety interlock. In addition, the computer records and stores the physical and physiological signals of interest. The EOG calibration is also controlled by the computer which provides on-line diagnostics of the EOG signals, reporting any warnings or other messages which might be useful to the experimenter.

Helmet

Throughout the experiment the subject's head is restrained in the helmet by a contoured stiff foam liner six inches deep, which extends in front of the ears, leaving on to two inches clearance for the horizontal electrodes. To help eliminate all sources of light leaks, a shroud is placed around the subject's neck and securely attached to the helmet itself. Inside the helmet, a light array is fixed, (approximately five inches from the subject's eyes) from which the EOG calibrations are made. The EOG amplifier is mounted on the side of the helmet. In addition, a fan is mounted to the helmet in order to maintain proper ventilation.

EOG Amplifier

The EOG amplifier consists of a differential isolation amplifier (Analog Devices 284J) at the input followed by a stage of high gain low pass amplifier. The isolation amplifier prevents dangerous currents from being passed through the subject. The low pass frequency of the amplifier is 20 Hz, and it has adjustable gain levels ranging from 10 to 3000.

Light Array

The light array found inside the helmet consists of five LED lights (figure 5). Calibrations of eye movements can be made by having the subject fixate on a given light when it is lit. Both the horizontal and vertical lights are 15 degrees from a center light. Thus a horizontal calibration is made by having the subject look at the light sequence, "right, center, left, center." From this type of calibration a measurement of sensitivity [microvolts/degree] is made. Typical sensitivities ranged from 5 to 20 microvolts/degree for both horizontal and vertical eye movements.

Description of the Experiments

The results presented in this thesis were obtained from three distinct protocols, performed on different subjects. In the first protocol (protocol I) some initial tests were performed. The major characteristics of these experiments were: 1) they were conducted with all room lights turned off; 2) only three profiles were run, each profile repeated three times; 3) All runs were done in the upright lateral (Y-Z) position and only horizontal eye movements were recorded.

The second set of experiments (protocol II) were conducted under the following conditions: 1) all room lights were off; 2) eight separate runs were made in two different orientations, the upright lateral (Y-Z) position, and the fore-aft supine (Z-X) position; 3) in the upright position only horizontal eye movements were recorded, while only vertical eye movements were recorded in the supine positions.

A final group of experiments (protocol III) was performed on the six crew members of Spacelab 1 in conjunction with the 1NS102 preflight/postflight test series being conducted for NASA. The conditions for these tests were: 1) the experiments were conducted with room lights on. The helmet and shroud were to provide total darkness. However there were problems with light leaks. 2) Eight runs were made in the Y-Z and Z-X orientations. However, due to overheating of the motor, all of the runs were not conducted on every subject. In particular, there were problems with the 0.9g profiles at both 0.4 and 0.8 Hz. The orientations, motion profiles, and experiment conditions in each of the three protocols are summarized in tables 1, 2, and 3.

The general protocol for all these experiments was the same. First, the subject was given instructions to "maintain a straight ahead gaze at all times, being sure not to fixate on any real or imaginary point." Also, the subject was asked to count backwards from a thousand by thirteens. This instruction was given for two specific reasons. It was hoped that counting would increase mental alertness, thereby improving the quality of nystagmic response. Secondly, it was used as a diversionary measure to keep the subject's mind off of his eye movements. Between each run, an EOG calibration was made to determine the sensitivity of the eye movements being recorded. A detailed description of the protocol is provided in Appendix A.

TABLE 1

PROTOCOL I

Profile #	Type	Parameters	Duration	# of Cycles
1	Sine	0.06g 0.1Hz	40sec	4
2	Sine	0.2g 0.2Hz	40sec	8
3	Sine	0.9g 0.4Hz	40sec	16

Orientations:	Upright lateral Y-Z only.
Repetitions:	Each run performed three times.
Room Conditions:	All room lights turned off.
# of Subjects:	Three.
Subject Codes:	X1C, X1J, and X1S.
Protocol File:	X1SB4.PCL

TABLE 2

Protocol II

Profile #	Type	Parameters	Duration	# of Cycles
1	Sine	0.6g 0.28Hz	36sec	10
2	Sine	0.05g 0.09Hz	44sec	4
3	Sine	0.2g 0.18Hz	44sec	8
4	Sine	0.1g 0.13Hz	46sec	6
5	Sine	0.9g 0.4Hz	40sec	16
6	Sine	0.2g 0.4Hz	40sec	16
7	Sine	0.6g 0.8Hz	40sec	32
8	Sine	0.1g 0.4Hz	40sec	16

Orientations:	Upright lateral (Y-Z), and fore-aft supine (Z-X).
Repetitions:	Each run was performed once in each orientation.
Room Conditions:	All room lights turned off.
# of Subjects:	Four.
Subject Codes:	X11, X12, X13, and X14.
Protocol File:	X1SBSM.PCL

TABLE 3

Protocol III

Profile #	Type	Parameters	Duration	# of Cycles
1	Sine	0.6g 0.28Hz	43sec	12
2	Sine	0.9g 0.4Hz	40sec	16
3	Sine	0.2g 0.2Hz	40sec	8
4	Sine	0.6g 0.4Hz	40sec	16
5	Sine	0.6g 0.56Hz	39sec	22
6	Sine	0.9g 0.8Hz	40sec	32
7	Sine	0.2g 0.4Hz	40sec	16
8	Sine	0.6g 0.8Hz	40sec	32

Orientations:	Upright lateral (Y-Z) and fore-aft supine (Z-X)
Repetitions:	Each profile was performed once in each orientation.
Room Conditions:	Room lights were on. Darkness provided by helmet and shroud.
# of Subjects:	Six.
Subject Codes:	N1B, N2B, N3B, N4B, N5B, and N6B.
Protocol File:	X1CBT.PCL

RESULTS

Preliminary Experiments

Preliminary experiments were performed on seven subjects. Although these experiments did not yield any useful data for analysis, they did resolve several important issues. First, the instructions given to a subject were found to strongly influence the eye movements obtained. Initially, the instructions were to gaze straight ahead. It appears that most subjects interpreted this to mean "look at a fixed point." Because the room lights were on and the helmet and shroud did not provide complete darkness, it was possible for subjects to look at dimly lit features inside the helmet. Under, these conditions the eyes did not move very much and no evidence of nystagmus or compensatory eye movements was observed.

Instructions to the subject were modified to include the statement, "do not fixate on any point, real or imaginary". In addition, subjects were asked to perform mental arithmetic. This helped to keep the subject alert and kept his mind of his eye movements. The problem of lighting was resolved by reducing the light in the room to the lowest level compatible with safety considerations.

Results with Protocol I

Evidence of horizontal nystagmus was clearly exhibited in subjects during the 0.9g 0.4 Hz profiles. Figure 7 shows that the response

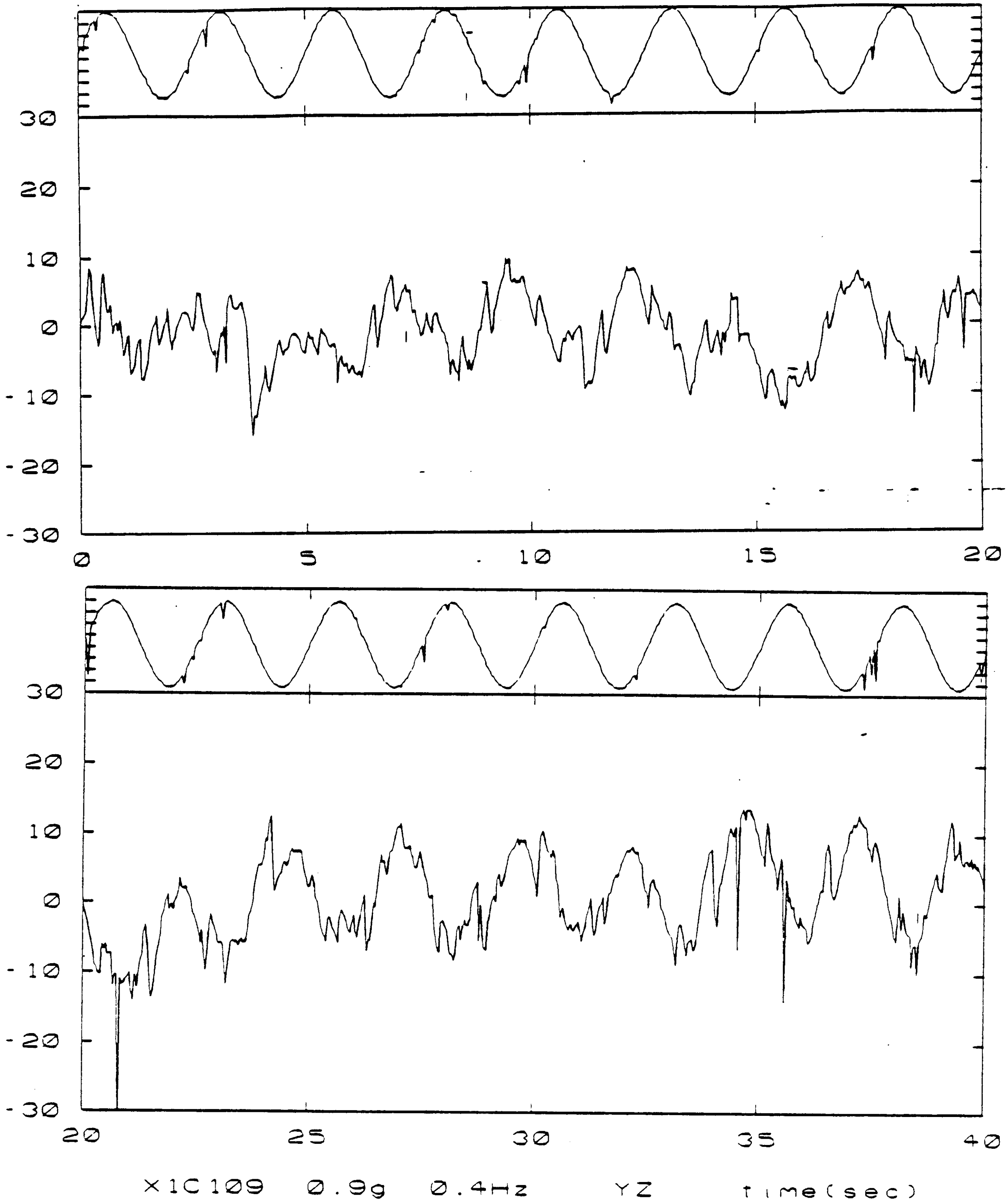


Fig. 7

Horizontal eye position (in degrees) during linear motion. Cart velocity is presented arbitrarily scaled to indicate phase.

becomes distinct at the highest acceleration amplitude. Although there is a definite trend in the response, it is difficult to assess the effects of increasing frequency or acceleration since they are both coupled in this protocol. The average slow phase velocity for the 0.9g 0.4 Hz profiles was 20.4 deg/sec with an average phase lag of -139 deg. (All phase lags discussed in the following sections are with respect to cart velocity.)

The major function of the tests conducted with this protocol was to determine the conditions necessary to obtain horizontal nystagmus. The major conclusions drawn from this protocol were:

1) verified importance of instructions;
2) verified need for complete darkness;
3) demonstrated need for high acceleration to obtain an adequate stimulus.

Plots of selected runs for this and subsequent protocols are presented in Appendix D.

Results with Protocol II

These were the first experiments performed which included tests in the Z-X, longitudinal supine orientation. While clear evidence was again obtained of horizontal nystagmus (figure 8) in the upright orientation, none of these subjects exhibited significant compensatory vertical eye movements in the supine position.

This protocol was designed to include the conditions to be used for similar experiments using the European Space Agency Flight Sled to be

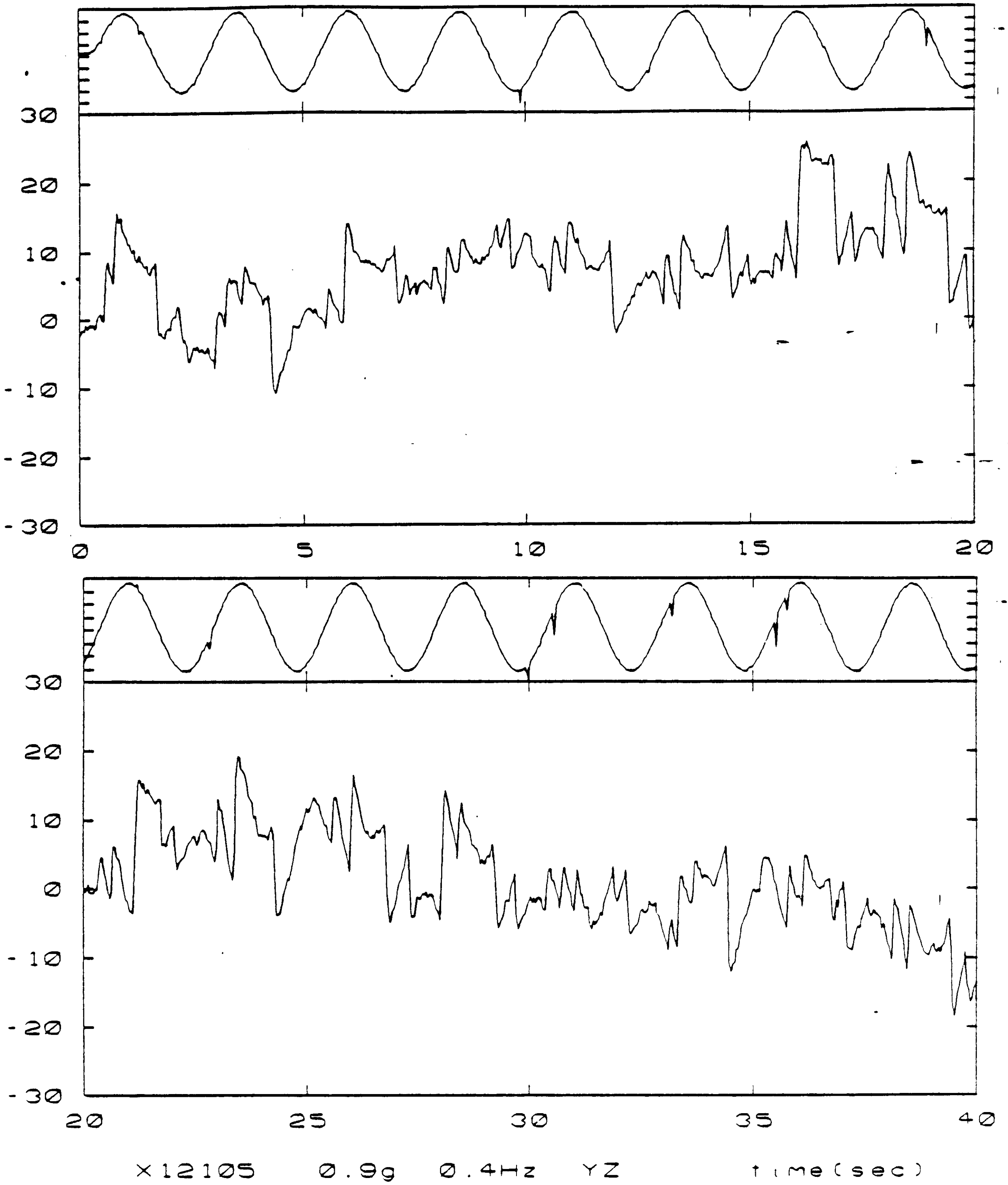


Fig. 8

Horizontal eye position (in degrees) during linear motion. Cart velocity is presented arbitrarily scaled to indicate phase.

flown on the D-1 Mission in 1985. For this reason several low acceleration profiles were included in the protocol. However, the finding from the previous experiments that sufficient acceleration is required was confirmed. From these results, it appears a minimum amplitude of 0.2g is required to obtain compensatory eye movements.

Results with Protocol III (Spacelab Crew Testing)

The majority of eye movements recorded with this protocol show little evidence of nystagmus (figure 9) although distinct compensatory eye movements were obtained in all subjects for at least the higher acceleration amplitudes (0.6g and 0.9g) in the lateral upright orientation. However, two subjects did show signs of nystagmic response in the Y-Z orientation. Vertical compensatory eye movements were observed in only two subjects during several runs in the Z-X orientation (figure 10). A more typical vertical eye movement recored is shown in Figure 11.

The only major difference in experimental conditions between the protocol III tests and the previous ones was that they were performed with the room lights on and the helmet surrounded by a redesigned shroud. The new shroud, while an improvement, still permitted some light leakage. As a result, dim, diffuse light was observed inside the helmet by the subjects.

Despite the absence of the characteristic fast phases of nystagmus, the distinct horizontal compensatory eye movements were amenable to analysis. Since protocol III includes four profiles at an amplitude of

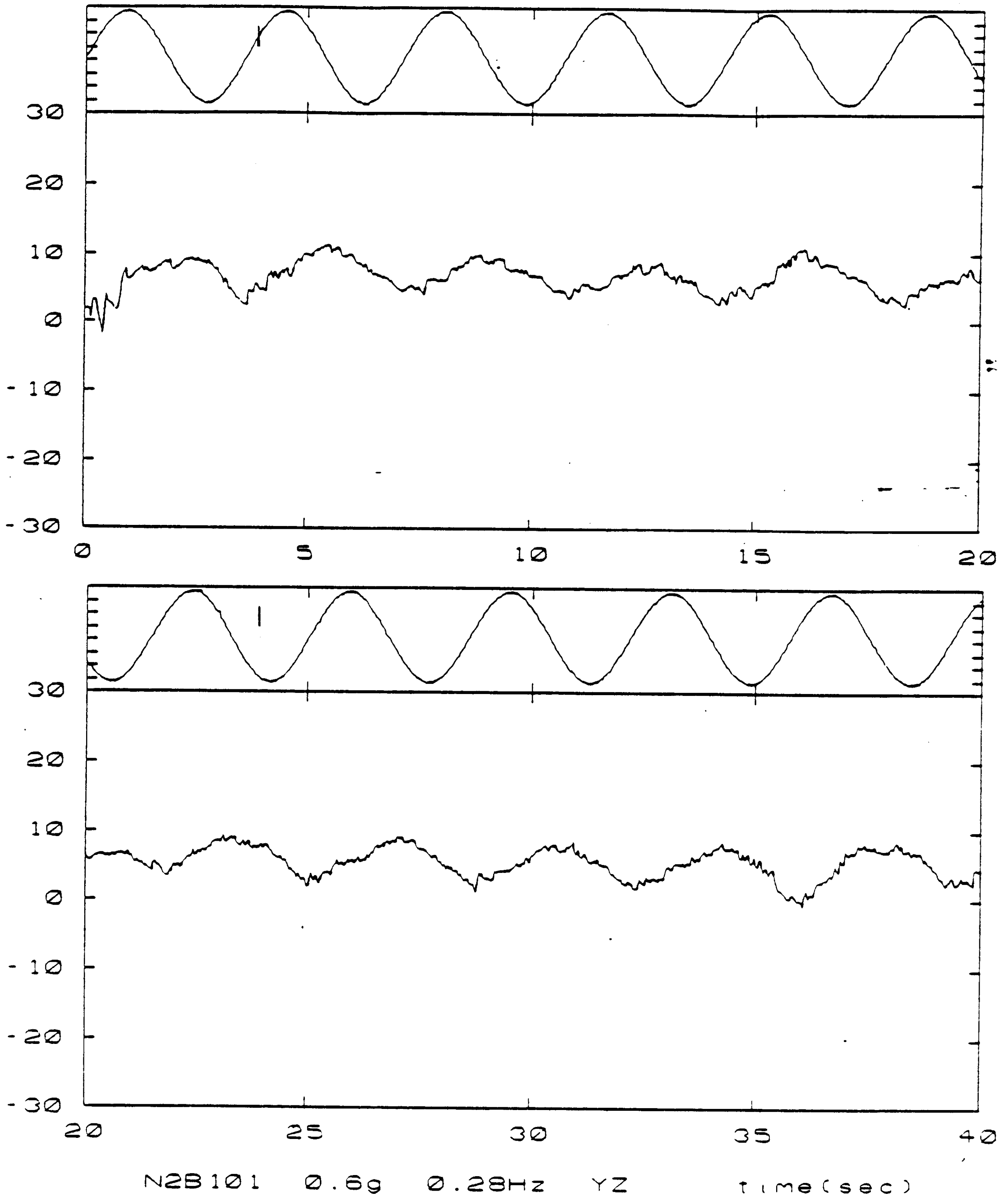


Fig. 9

Horizontal eye position (in degrees) during linear motion. Cart velocity is presented arbitrarily scaled to indicate phase.

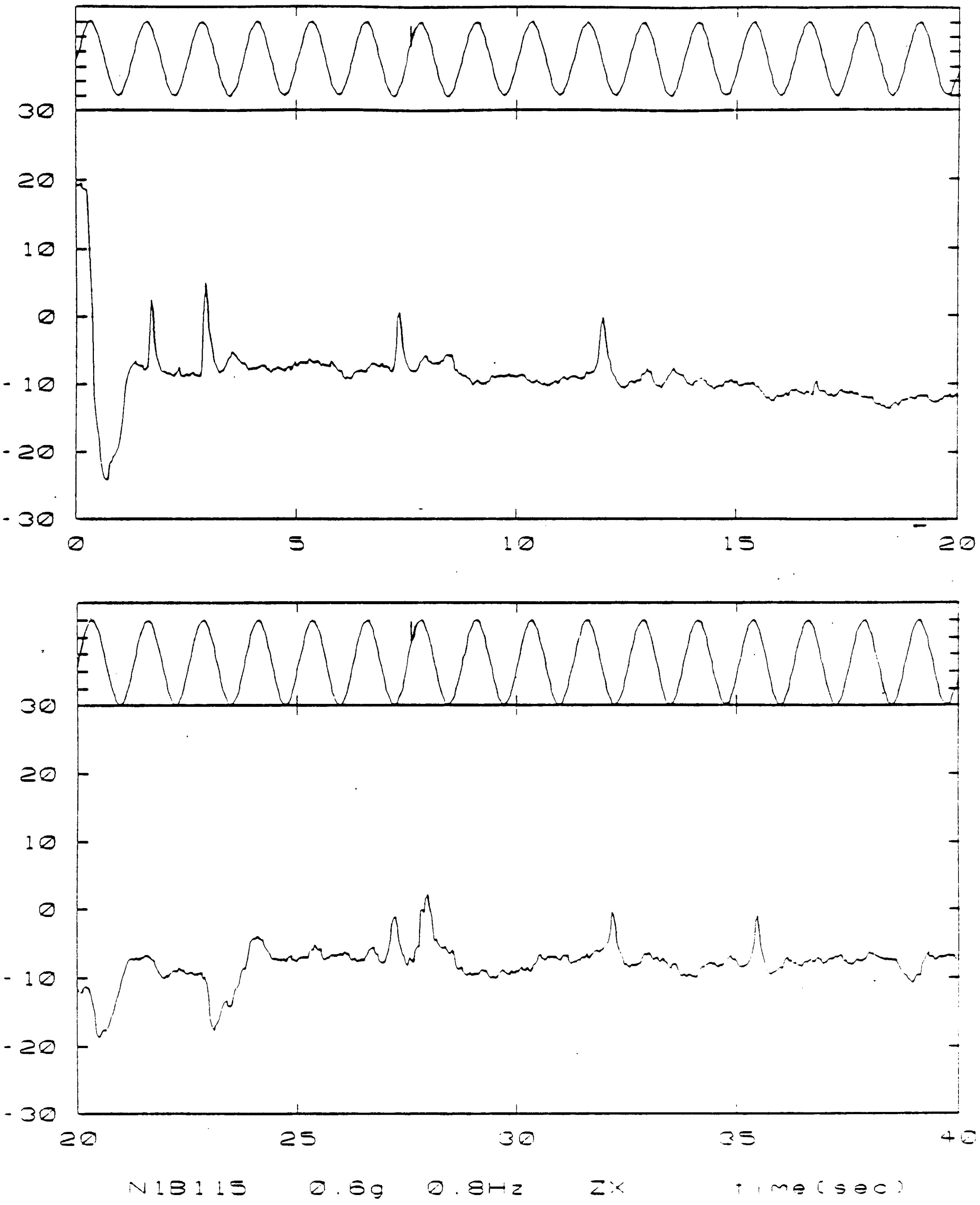


Fig. 10

Vertical eye position (in degrees) during linear motion. Cart velocity is presented arbitrarily scaled to indicate phase.

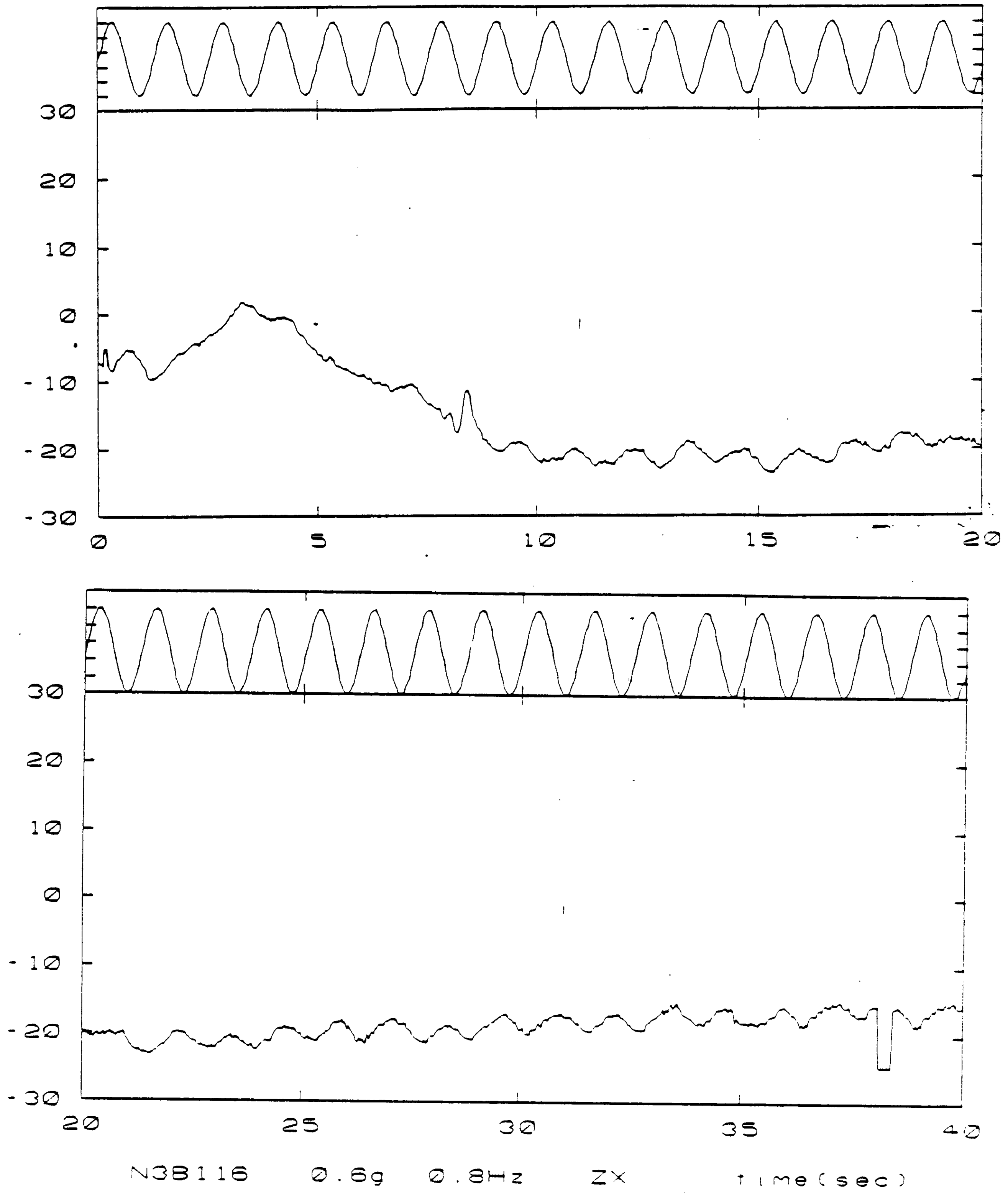


Fig. 11

Vertical eye position (in degrees) during linear motion. Cart velocity is presented arbitrarily scaled to indicate phase.

0.6g while the frequency varies from 0.28 Hz to 0.8 Hz, the frequency dependence of the response can be investigated. Similarly, the protocol includes three profiles at 0.4 Hz with acceleration amplitudes of 0.2g, 0.6g, and 0.9g. From these, amplitude dependence and linearity can be assessed.

If the gain of the response is expressed as the ratio of the amplitude of slow phase eye velocity to the amplitude of cart velocity (deg/sec over m/s), then this gain is observed to increase with increasing frequency for a constant acceleration of 0.6g. The phase lag increases over this same range (figure 12). Beyond these observations, it is difficult to determine the nature of the frequency response without experiments extending over a wider frequency range.

Relating the phase velocity (SPV) to accelerations at a constant frequency reveals that the SPV increases as the acceleration increases (fig 13). Linear regression of this relation gives a slope of 9.8 deg/sec/g.

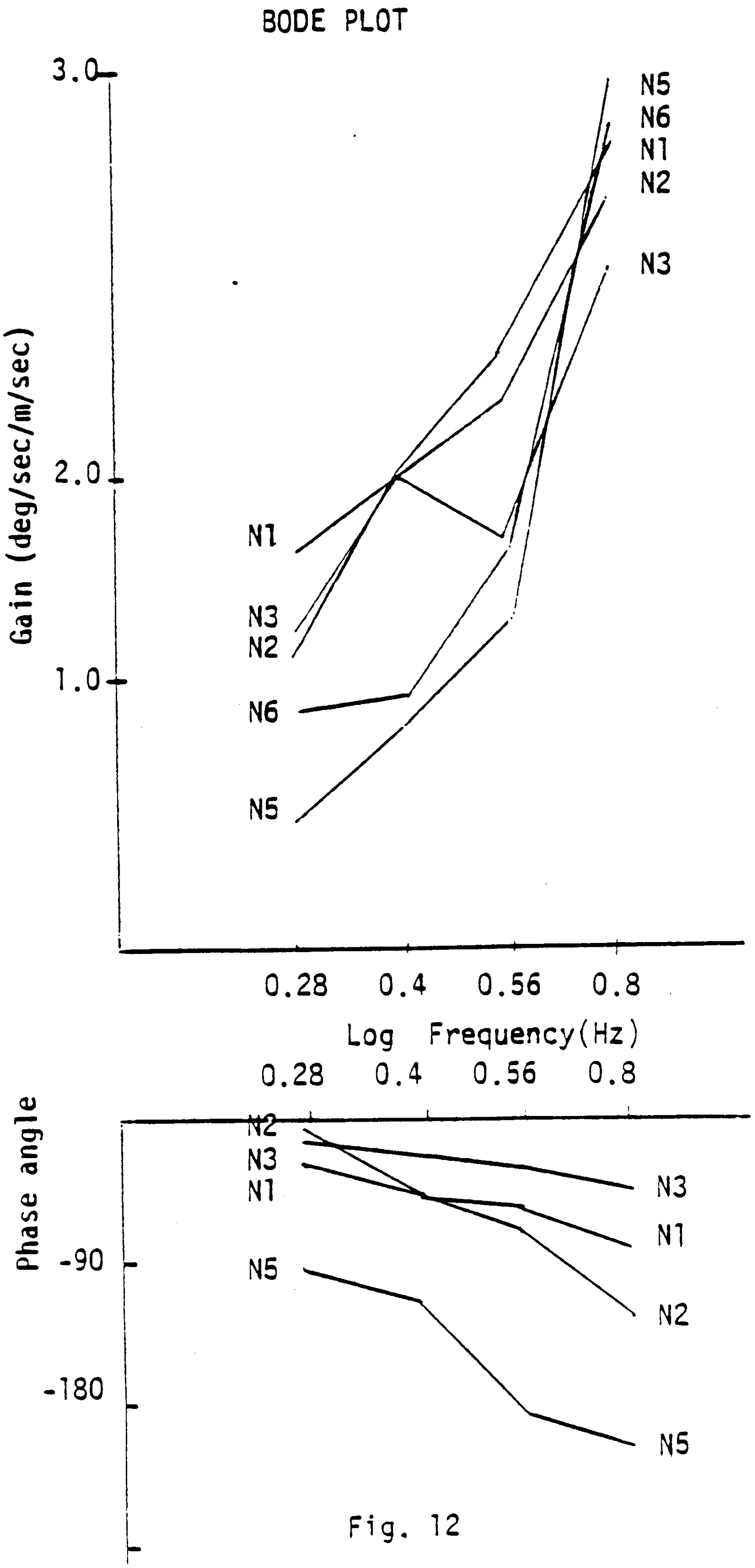

BODE PLOT
3.0
2.0
1.0
Gain (deg/sec/m/sec)
N5
N6
N1
N2
N3
N1
N3
N2
N6
N5
0.28
0.4
0.56
0.8
Log Frequency(Hz)
0.28
0.4
0.56
0.8
Phase angle
-90
-180
N2
N3
N1
N5
N3
N1
N2
N5

Fig. 12

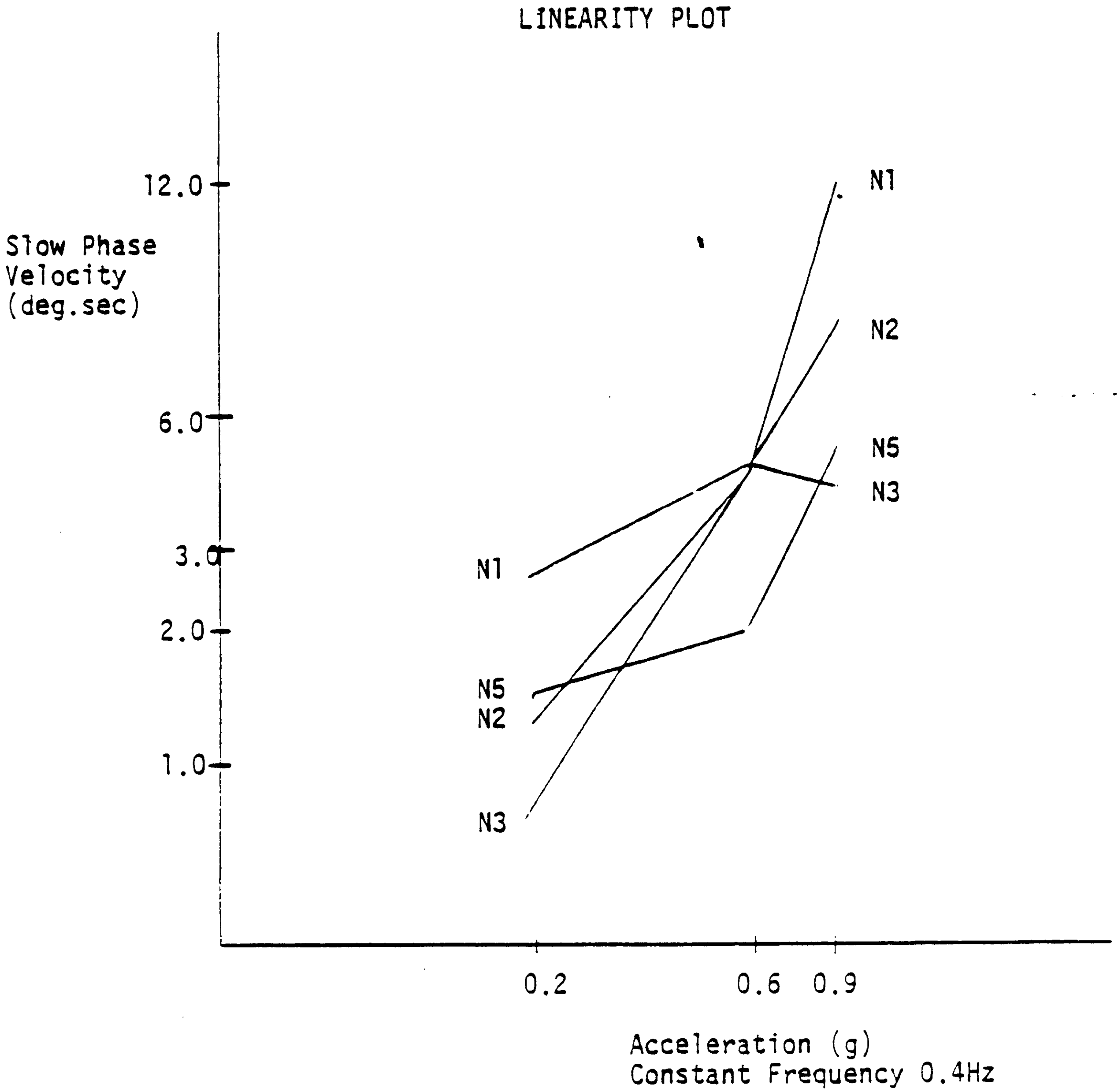

LINEARITY PLOT
12.0
6.0
3.0
2.0
1.0
Slow Phase
Velocity
(deg.sec)
N1
N2
N5
N3
N1
N5
N2
N3
0.2
0.6
0.9
Acceleration (g)
Constant Frequency 0.4Hz

Fig. 13

DISCUSSION

Horizontal nystagmus and compensatory eye movements can be readily elicited given an adequate stimulus (greater that 0.2g at 0.2Hz). Vertical eye movements, on the other hand, were not present in most of the subjects tested.

Although there is not much direct correspondence (i.e. several identical profiles) between Protocols I, II and Protocol III, examination of the time series plots clearly illustrates that there is a remarkable difference in responses obtained under the two lighting conditions. Tests conducted with all room lights off produced highly nystagmic responses while either compensatory eye movements (smooth movements) or greatly reduced nystagmic responses are mainly seen when there was diffuse light present. This result underlines the necessity of conducting the experiments in total darkness. If this condition cannot be attained using the helmet and shroud,then provisions should be made to conduct these tests with room lights turned off. There is also a noticable difference in the magnitude of the slow phase velocity under the two different lighting conditions. In general the magnitudes of the slow phase velocity are higher for those tests conducted in complete darkness.

Subject responses obtained under conditions of diffuse lighting exhibit, among themselves, two distinct responses. Three of the subjects consistantly exhibited smooth compensatory eye movements with few, if any, saccades. Two of the remaining three subjects exhibited a clear nystagmus but of greatly reduced slow phase velocity when compared with the nystagmus observed under conditions of complete darkness.

Figure 14 displays the gain and phase relationship for comparable profiles in Protocol I, Protocol III, and the results of Niven et al. Gain is the amplitude ratio of slow phase eye velocity (deg/sec to m/sec) and is represented as vector magnitude. The phase angle of slow phase eye velocity is referenced to cart velocity and is depicted as an angle about the origin. All data included were obtained at a frequency of 0.4 Hz while the acceleration amplitude was 0.58g, 0.6g, or 0.9g.

The most distinctive feature of this plot is that for subjects who exhibit a nystagmic response (Niven et al., Protocol I, and the nystagmic responses from Protocol III) the phase angles are between -120 and -140 degrees. In contrast, the Protocol III subjects with smooth compensatory responses have phase angles between -40 and -50 degrees - decidedly phase advanced of the nystagmic responses. Responses obtained with Protocol III included both 0.6g and 0.9g amplitudes at 0.4Hz. For both the nystagmic and smooth responses the trends of higher gain and increasing phase lag with higher amplitude of acceleration are apparent.

Overall, the nystagmic responses at this frequency show good aggreement with Niven et al. while the smooth compensatory responses are significantly different. However, where comparable, the frequency responses observed in this study are only in partial agreement with Niven et al. Both studies indicate an increasing phase lag between 0.2 and 0.8Hz. In the present study the gain was observed to increase with frequency whereas Niven et al. found a constant gain over the same

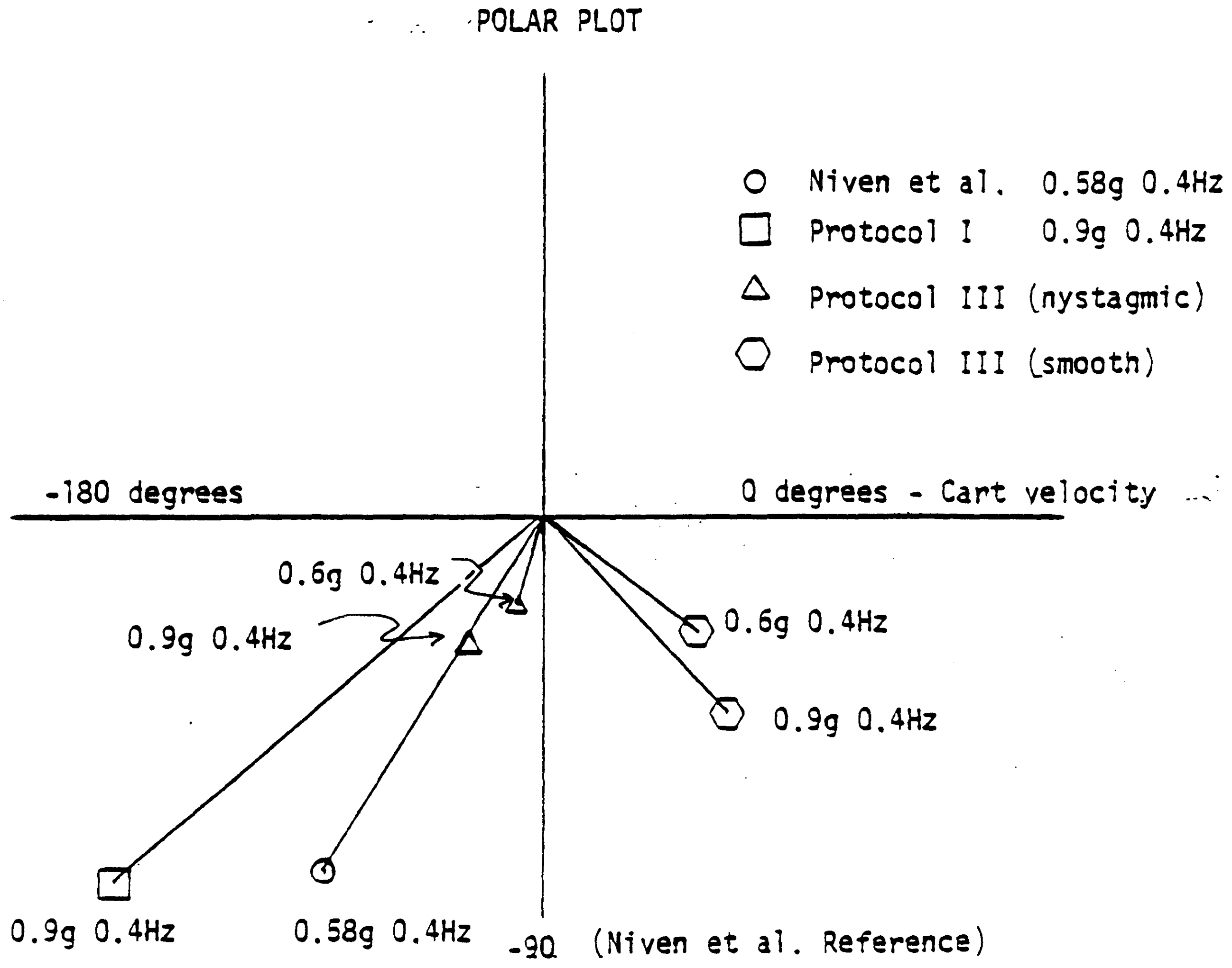


Fig. 14 Polar Plot

frequency range.

In comparing the results of Niven et al with those of the present study, there is an additional consideration of data analysis which may contribute to differences. Niven et al. found the peak SPV by measuring the maximum slope of the eye movement recordings for each cycle, and taking the mean of these measurements. The data analysis techniques used for this thesis took the nystagmic response and removed all of the saccades using a detection algorithm developed by Massoumnia (1983). The cumulative eye position record that resulted was differentiated with a 9 point digital filter to obtain the slow phase velocity (Massoumnia, 1983). A sinusoidal fit for the amplitude and phase of the SPV was then made (Arrott, 1982). It is felt that this method more accurately reflects the slow phase velocity than the maximization procedure of Niven et al.

SUMMARY

During linear acceleration in the dark, evidence of horizontal nystagmus can consistantly be obtained, while vertical nystagmus only appears in a small fraction of the population. In order to elicit a horizontal nystagmic response the amplitude of the stimulus should be above 0.2g. It would appear that even small amounts of diffuse light can transform a highly nystagmic response to smooth, compensatory eye movements. Over the limited frequency range of testing possible on the sled, the repsonse dynamics are not clearly discernable. However, a clear trend of rising gain and increasing phase lag was observed over the range 0.2 - 0.8 Hz. Measurements at a frequency of 0.4 Hz indicated good amplitude linearity with respect to acceleration over the range 0.2g - 0.9g.

SUGGESTIONS FOR FUTURE RESEARCH

In order to completely test the linearity of the otolith-ocular reflex, more tests should be conducted. If possible the frequency band should be expanded in order to determine the specific behavior of the otoliths. The MIT Sled Facility is somewhat limiting in this respect because of track length and motor torque limitations. Since horizontal nystagmus is more easily elicited, more studies should be done to completely understand the function of the system in the Y-Z orientation. Once this analysis is completed, then more energy could be spent examining the affects of the other orientations. The Y-X acceleration with the subject lying supine would be particularly interesting to examine. Theoretically one would expect to see horizontal nystagmus since the visual field that the subject would be viewing is moving along this axis. Also this result would confirm the findings of Niven et al. If this is the case, it would be interesting to compare the responses of the Y-X acceleration to the Y-Z acceleration to see if the gain and phase are similar.

For the 1NS102 ground based experiments, it is recommended that only the Y-Z lateral upright position be tested. Since vertical nystagmus is not consistantly exhibited in all subjects, and testing time is limited, the Z-X fore-aft supine tests should be discontinued.

Finally, an independent test should be made to determine the effects of electrode/skin artifacts. If these artifacts significantly change the nature of the eye recordings being made, then an alternate measurement technique may need to be employed. Of particular concern in this area is the possible movement of the skin, especially near the horizontal recording electrodes, during large amplitude stimuli. If present, this type of movement could introduce spurious, albeit correlated, signals that obscure the eye movements which are actually taking place.

BIBLIOGRAPHY

Arrott, A.P. "Torsional Eye Movements in Response to Linear Accelerations", S.M. Thesis, MIT,1982.

Balliet R, Nakayama K. Training of Voluntary Torsion. Insvet Ophthalmol Visual Sci 1978;17:303-14

Bles, W. and Kapteyn, T. S. (1973) Seperate Recording of the Movements of the Human Eye During Parallel Swing Tests. Actaotolaryngol 75:6-9.

Lichtenberg, B. K., "Ocular Counterrolling Induced by Linear Acceleration, Sc.D. Thesis, MIT, 1979.

Lichtenberg, B. K., Young, L. R., and Arrott, A. P. (1982) Human Ocular Counterrolling Induced by Varying Linear Accelerations. Experimental Brain Res 48: 127-136.

Massoumnia, M., "Detection of Fast Phase of Nystagmus Using Digital Filtering", S.M. Thesis, MIT, 1983.

McCabe, B. F. (1964) Nystagmus Response of the Otolith Organs. Laryngscope V. 76.

Niven, J. I., Hixson, W. C., and Correia, M. J. (1966) Elicitation of Horizontal Nystagmus by Periodic Linear Acceleration. Acta Otolar. 62:429-441.

Oman, Charles M. (1982) "Space Motion Sickness and Vestibular Experiments in Spacelab", SAE Technical Paper 820833.

Tole, J.R., Background and Procedures for Electro-oculography. Harvard/MIT Biomedical Engineering Center. 1979.

Spacelab Mission I Experiment Descriptions, NASA, 1982.

Vidic, T.R., "Clinical Test for Abnormal Human Response to Linear Acceleration", S.B. Thesis, MIT, 1976.

Weiss, J.A., "Motion Artifacts in Surface Electrodes," S.B. Thesis, MIT, 1976.

Young, L.R., Effects of Linear Acceleration on Vetibular Nystagmus. Progress Report, NASA Grant NGR 22-009-156.

Young, L.R., (1972) "Cross-coupling Between Effects of Linear and Angular Acceleration on Vestibular Nystagmus", Bibl. Ophthalm. 82:116-121.

Young, L.R. Human Orientation in Space. AIAA Dryden Lecture in Research, 1982.

Young, L.R. and Meiry, J.L., (1969) "A Revised Dynamic Otolith Model", AMRL-TR-66-209; Aerospace Medicine 39:606-608.

Appendix A: Detailed Protocol

F07-SB Experiment

Crew Baseline Testing

MIT

April 19-21, 1983

Test Protocol

1. Sled Preparation
2. Helmet Preparation
3. Subject Preparation

1. Sled Preparation

1.1 SLED: Place chair in proper axis.

1.2 HELMET: Mate helmet and cables to chair.

1.3 HELMET: Attach EOG amplifier and leads.

1.4 SLED: Start sled and computer systems.

1.5 SLED: Load Protocol file X1CBT.PCL.

1.6 SLED: Set computer options.

1.7 SLED: Enable sequential data storage.

1.8 SLED: Perform stationary sled safety test.

1.9 SLED: Perform empty sled motion test.

2. Helmet Preparation

2.1 Helmet: Check function of the following:
- light array
- fan
- masking noise
- communication system

2.2 HELMET: Check to see that everything on the helmet is secure.

3. Subject Preparation

3.1 SUBJECT: Apply five electrodes to subject

3.2 SUBJECT: Check electrodes with impedance meter.

3.3 SUBJECT/HELMET: Place subject in chair and adjust helmet height.

3.4 SUBJECT/SLED: Adjust foot rests.

3.5 SUBJECT: Attach body restraint straps and secure subject.

3.6 SUBJECT: Check level of masking noise and communication system.

3.7 SUBJECT/HELMET: Attach EOG leads to electrodes.

3.8 SUBJECT: Give subject panic button and demonstrate.

3.9 SUBJECT: Give subject instructions for the test.

3.10 HELMET: Lower helmet.

3.11 SLED: Zero offset and perform.
manual EOG calibration.

3.12 HELMET: Turn on fan and masking noise.

3.13 HELMET: Attach shroud.

3.14 SUBJECT: Obtain subject's comments on light leaks.

F07-SB Timeline

TIME(min:sec)	ITEM TO BE COMPLETED
00:00	Begin Experiment F07-SB
05:00	Subject Secured in Sled
07:00	Zero the offset
08:00	Do EOG calibration
09:00	Run Profile #1
09:30	Do EOG calibration
10:30	Run Profile #2
11:00	Do EOG calibration
12:00	Run Profile #3
12:30	Do EOG calibration
13:30	Run Profile #4
14:00	Do EOG calibration
15:00	Run Profile #5
15:30	Do EOG calibration
16:30	Run Profile #6
17:00	Do EOG calibration
18:00	Run Profile #7
18:30	Do EOG calibration
19:30	Run Profile #8
20:00	Do EOG calibration
26:00	Change orientation of the sled
29:00	Subject secured in chair
31:00	Zero Offset

32:00	Do EOG calibration
33:00	Run Profile #1
33:30	Do EOG calibration
34:30	Run Profile #2
35:00	Do EOG calibration
36:00	Run Profile #3
36:30	Do EOG calibration
37:30	Run Profile #4
38:00	Do EOG calibration
38:30	Run Profile #5
39:00	Do EOG calibration
40:00	Run Profile #6
40:30	Do EOG calibration
41:30	Run Profile #7
42:00	Do EOG calibration
43:00	Run Profile #8
43:30	Do EOG calibration
48:00	Subject out of sled
49:00	Secure sled
50:00	End of Experiment F07-SB

Appendix B: Electrode Study

In the process of conducting the initial experiments for this thesis, several questions concerning the electrodes were raised. The first concern was whether or not the offset potential between the electrodes was within the range for proper EOG amplifier performance. The offset potential is the difference between the potentials at the skin-electrode interface and the junction potentials that exist at the metal-electrode interface of the electrodes (Weiss 1981). Secondly, how long should the electrodes be allowed to "settle" or reach a steady state? Thirdly, how important is the use of alcohol as a skin preparation?

Since the corneo-retinal potential is in the range of 0.2-1.0 mv, the offset pontential between any two electrodes is very important. The EOG amplifier was designed for optimal performance for offset potentials of less than 125 mv. The stability of the electodes is also very important, especially when scheduling subjects within strict time constraints. Therefore it is useful to know how long the electrodes need to be on the subject before reliable recordings can be made. Finally, if the use of alcohol has no bearing on electode performance, then its use can be discontinued.

In this study, three different electrodes were examined: Harco 157 Infant ECG Electrodes (Hewlett-Packard Part No. 14389(H157)), Medi-Trace Pellet Electrodes (MED1901 FB08042), and Marquette Electronics ECG Electrodes (Part No. 9430-300). In order to study the offset potentials of the electrodes, 7-9 electrodes were placed on the author's forehead. After 30 minutes were allowed for the electrodes to settle down, the potentials between the various pairs of electrodes were made. A summary of the data gathered as well as histograms are shown in Table B1 and Figure B1, B2, and B3. All offset potentials are absolute values.

To determine the settling time of the electrodes, recordings of offset potentials between two electrodes were made over a period of 15 minutes. (Figure B4.)

Offset potentials and settling times were measured with and without the use of alcohol to study its effects. (Figure B5)

Conclusions

The Harco and Meditrace Elecrodes have small offset potentials ranging up to only 40mv. The offset potential of the Marquette Electrodes are generally higher, with a maximum of approximately 65mv. However all three electrodes are within the desired range for proper EOG amplifier performance. The Harco and Meditrace Electrodes also settle down more quickly than the Marquette's. The Harco Electrodes settle down after ten to fifteen minutes while the Meditrace are stabilized after ten minutes. The Marqeutte Electrodes take at least twenty minutes to settle down. More importantly, the difference in offset potentials from the initial placement and twenty minutes later is more than 20mv for the Marquette Electrodes. Even if the offset potentials are changing with time, you would like the changes to be small over short periods of time, so that the recordings made during an hour session are fairly consistant. While conducting this study, several of the ~~Harco~~ Med, trace Electrodes were found to have very high offset potentials (greater than the 125mv that the EOG amplifier can record). Therefore, it suggested that they not be used for these experiments. Finally, it appears that the use of alcohol should be continued. The offset potentials recorded when alcohol was not used are too high to be tolerated.

Table B1

Type of Electrode	#samples	#electrodes	Mean(mv)	Range(mv)
Harco 157(alcohol)	57	16	11.22	0.3-26.5
Medi-Trace (alcohol)*	51	16	10.94	0.4-38.5
Marquette (alcohol)	42	14	20.19	0.5-64.4
Medi-Trace (no alcohol)**	60	18	19.66	0.2-76.4

*One electrode had offset potential greater than 125mv.

**Two electrodes had offset potentials greater than 125mv.

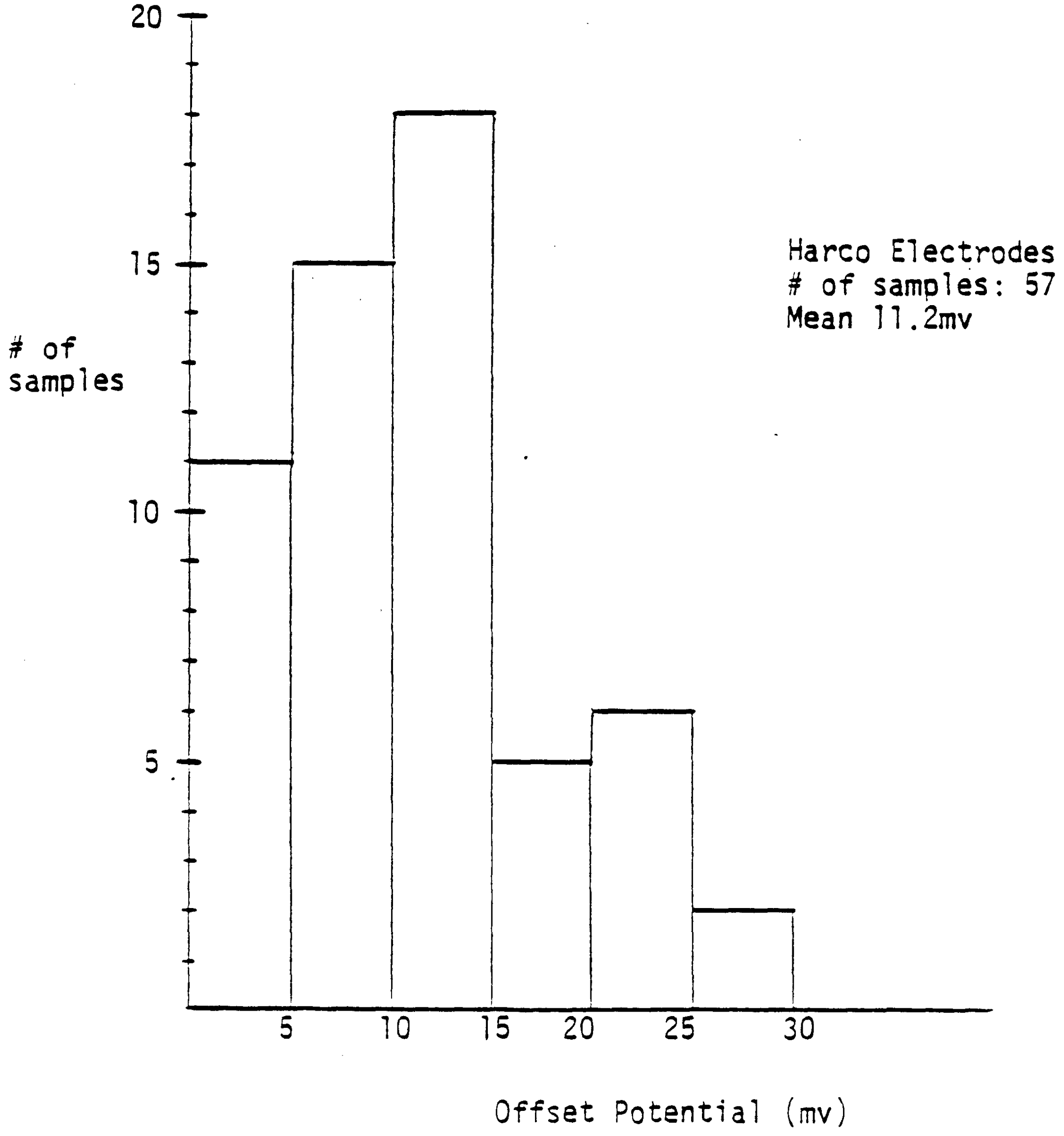
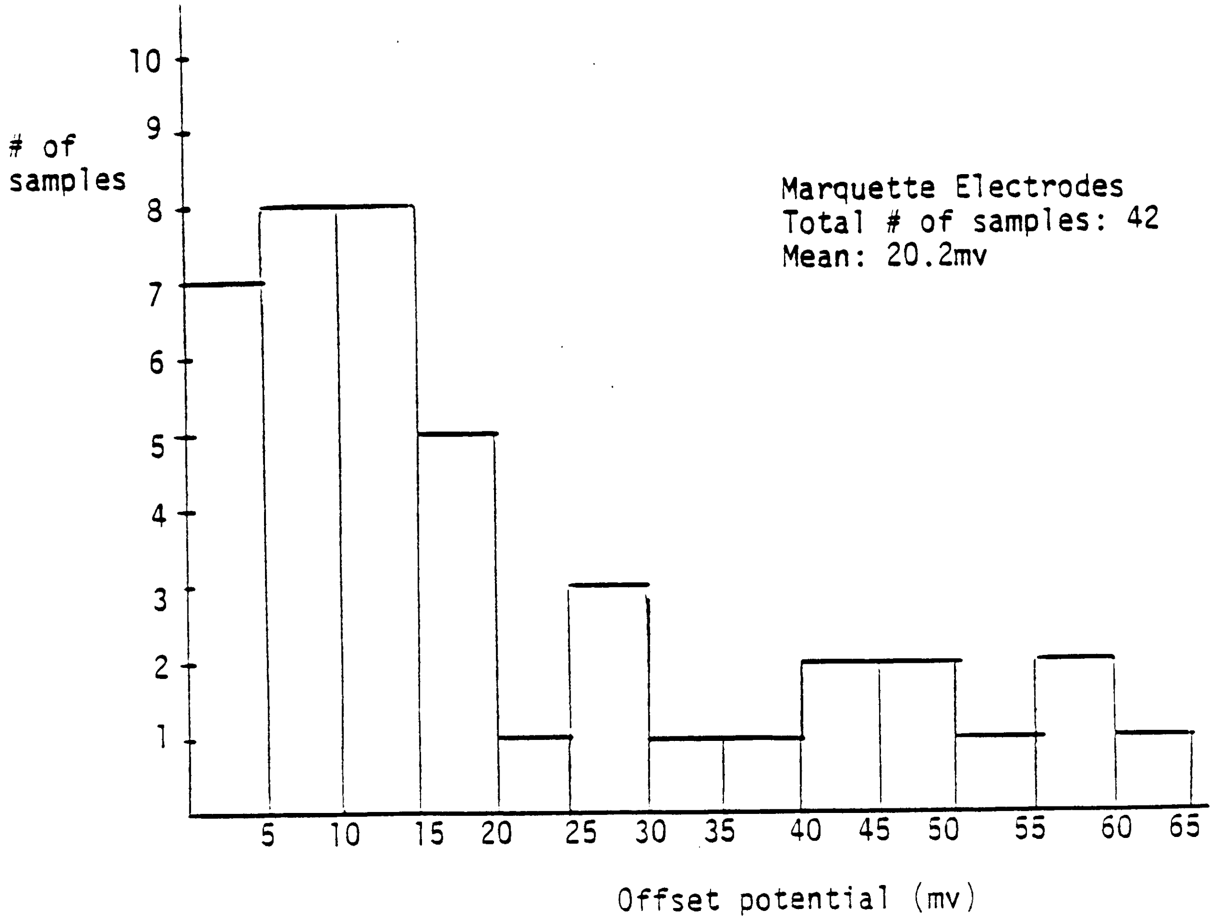

20
15
10
5
# of samples
5
10
15
20
25
30
Offset Potential (mv)
Harco Electrodes
# of samples: 57
Mean 11.2mv

Fig. B1



10
9
# of samples
8
7
6
5
4
3
2
1
Marquette Electrodes
Total # of samples: 42
Mean: 20.2mv
5
10
15
20
25
30
35
40
45
50
55
60
65
Offset potential (mv)

Fig. B2

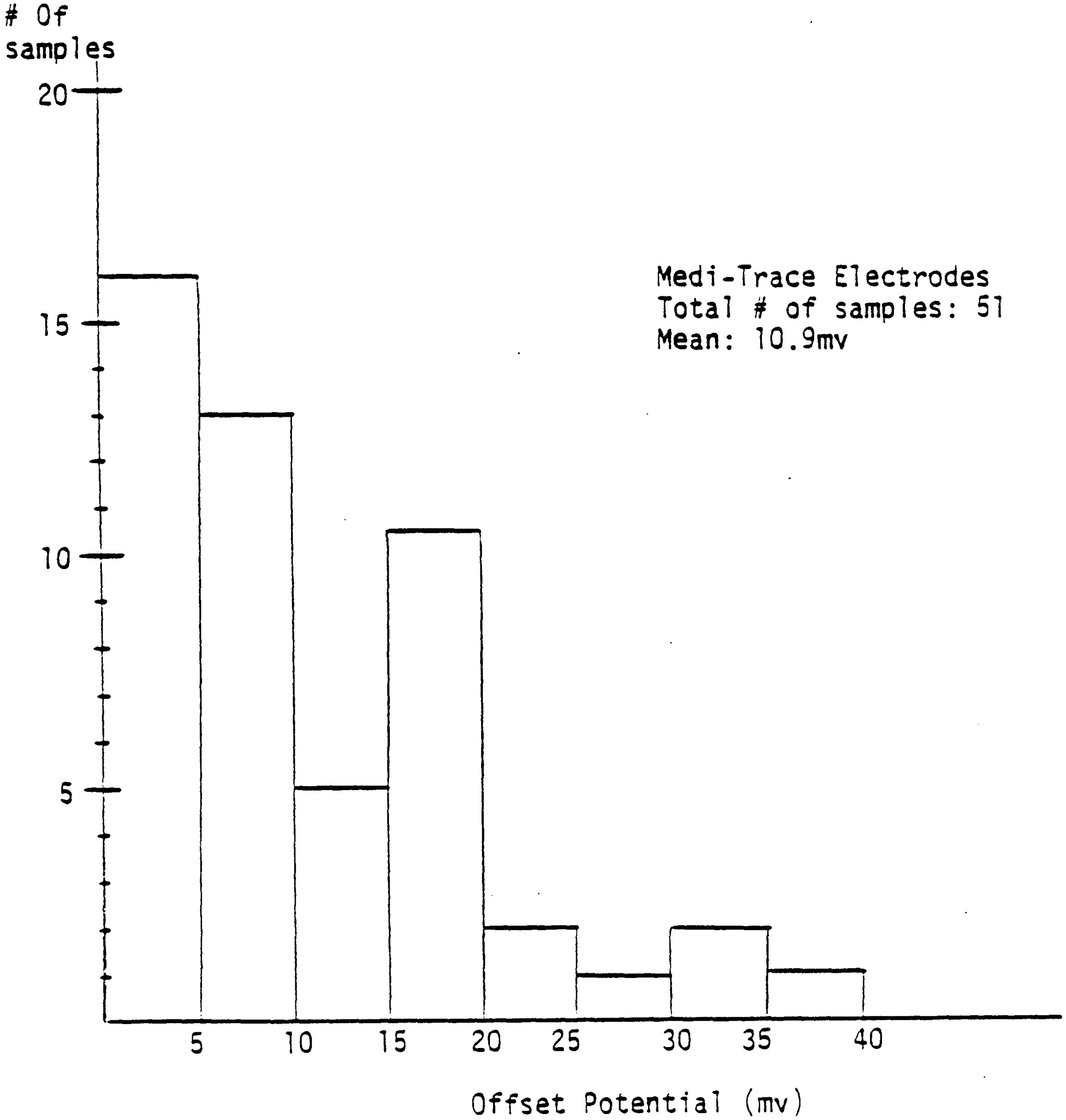
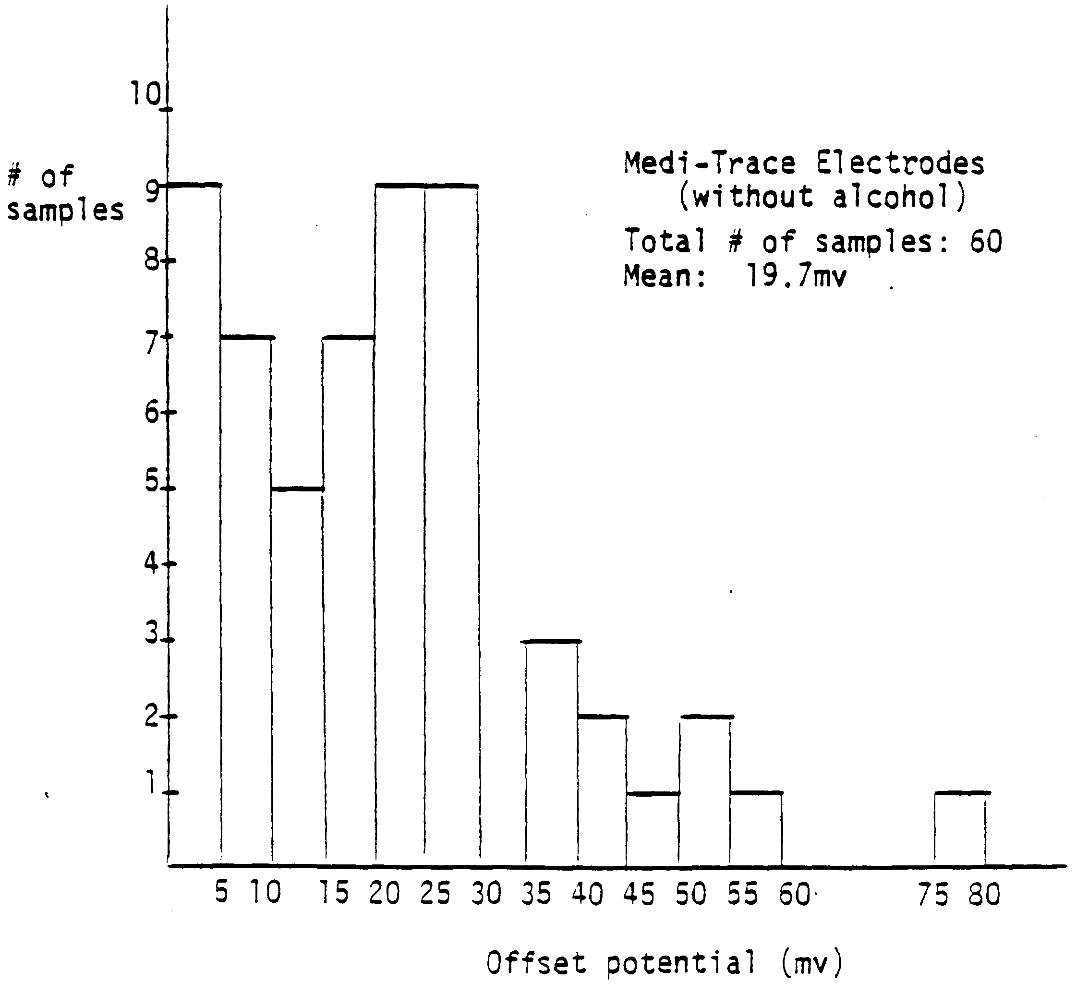

Of
samples
20
15
10
5
Medi-Trace Electrodes
Total # of samples: 51
Mean: 10.9mv
5
10
15
20
25
30
35
40
Offset Potential (mv)

Fig. B3



# of samples
10
9
8
7
6
5
4
3
2
1
5 10 15 20 25 30 35 40 45 50 55 60 75 80
Offset potential (mv)
Medi-Trace Electrodes
(without alcohol)
Total # of samples: 60
Mean: 19.7mv

Fig. B4

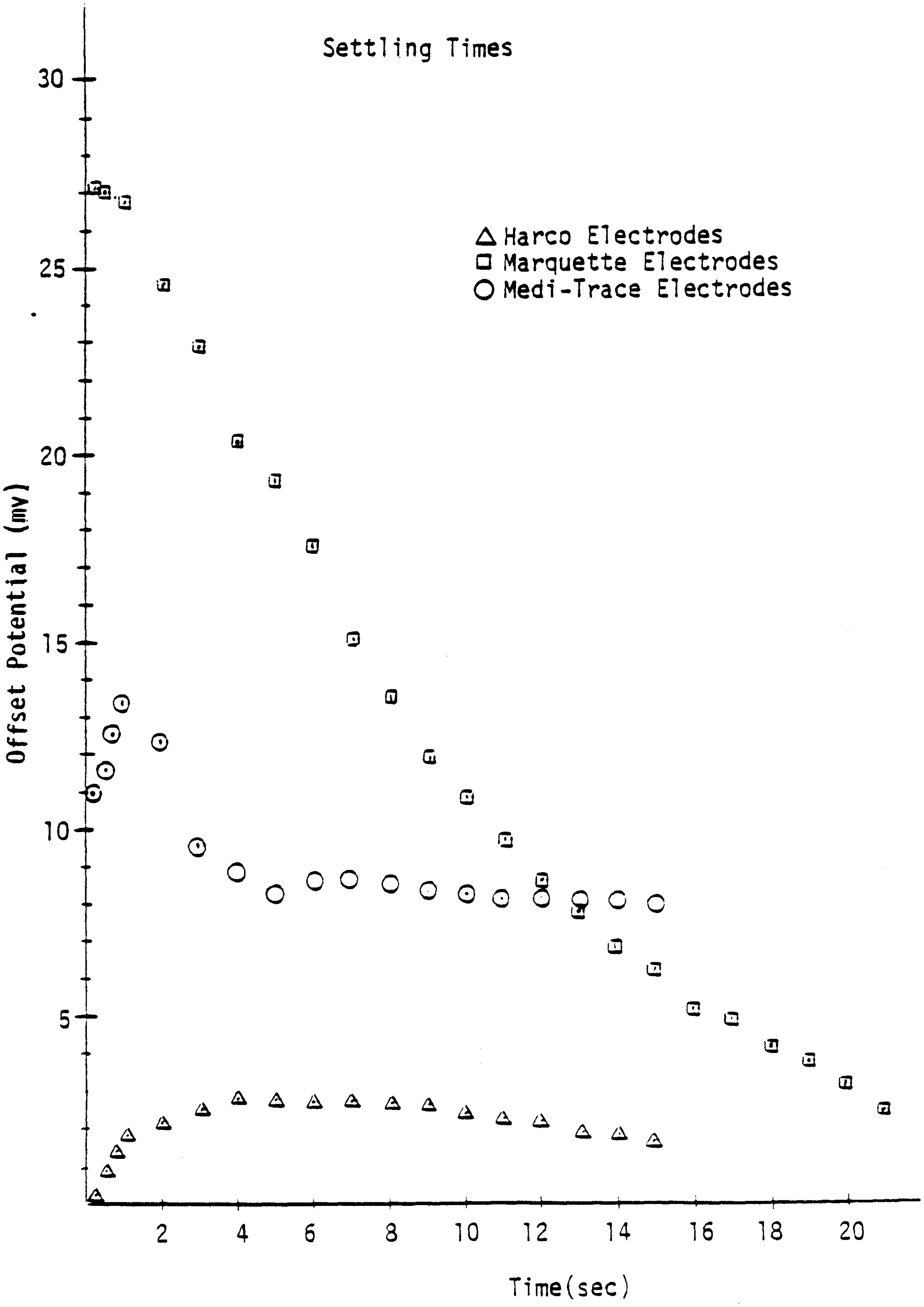

Settling Times
30
25
20
15
10
5
Offset Potential (mv)
△ Harco Electrodes
□ Marquette Electrodes
○ Medi-Trace Electrodes
2
4
6
8
10
12
14
16
18
20
Time(sec)

Fig. B5 .

Appendix C: Individual Test Results

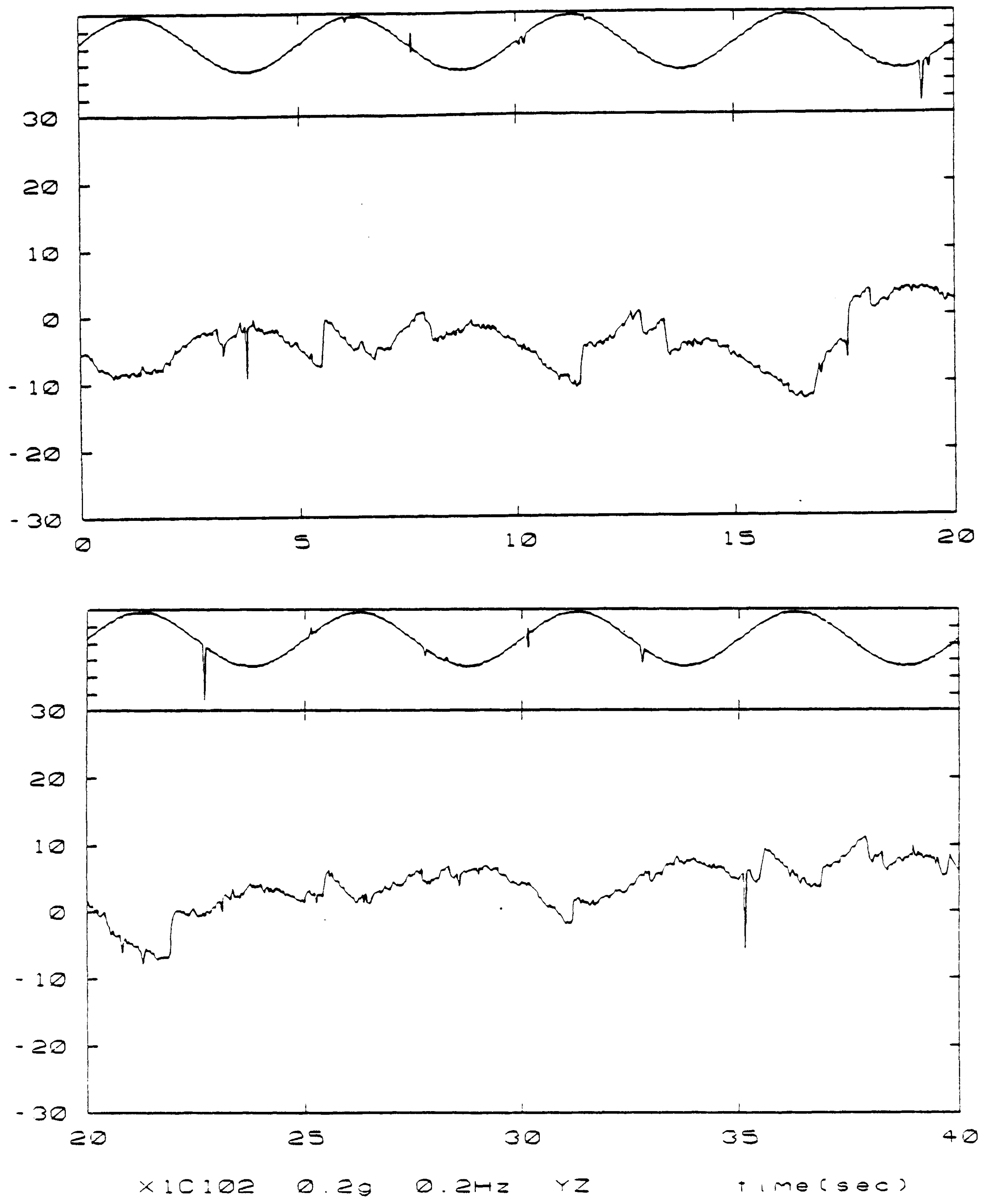
The following pages contain the eye position records from selected tests as well as summaries of those tests.

Summary of Results

subject: X1C
protocol: I (X1SB4)
Orientation: YZ
Eyes: Horizontal

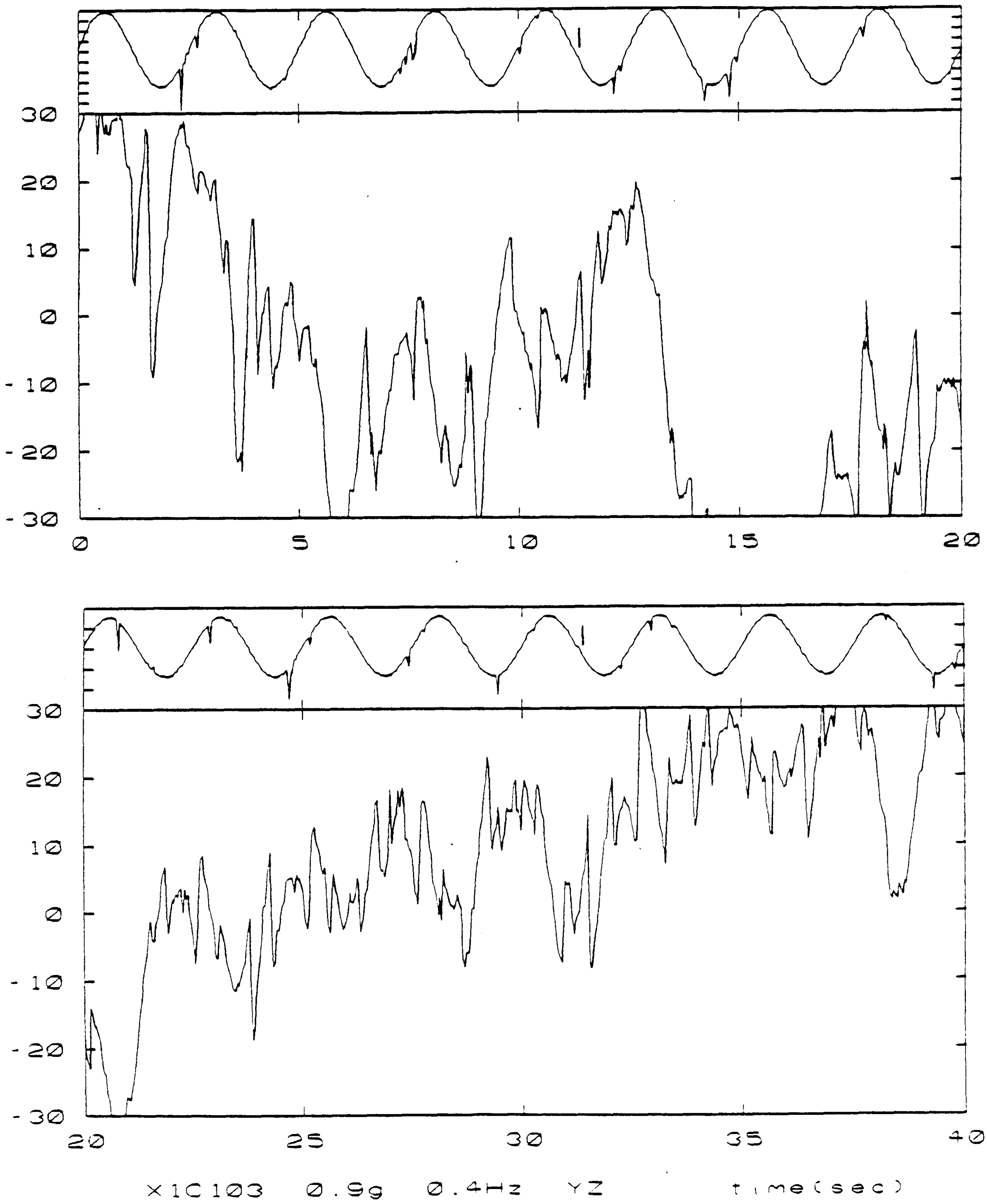
data code	stimulus		response		coherence
	amplitude [g]	frequency [Hz]	amplitude [deg/sec]	phase [deg]	[%]
X1C101	0.06	0.1	0.90	-148	6
X1C104	0.06	0.1	0.94	-41	0.5
X1C107	0.06	0.1	0.24	-18	0.03
X1C102	0.2	0.2	2.54	-119	3
X1C105	0.2	0.2	3.09	-104	1.1
X1C108	0.2	0.2	1.48	-70	0.7
X1C103	0.9	0.4	39.45	-157	25
X1C106	0.9	0.4	30.95	-134	63
X1C109	0.9	0.4	26.26	-131	37

VAX/VMS *** PEMPLOT 18-MAY-1983 03:01:27.28 RES2:[P3441.ARROTT.SPACELAB]X1C102A.PLT;2 ARROTT *** VAX/VMS

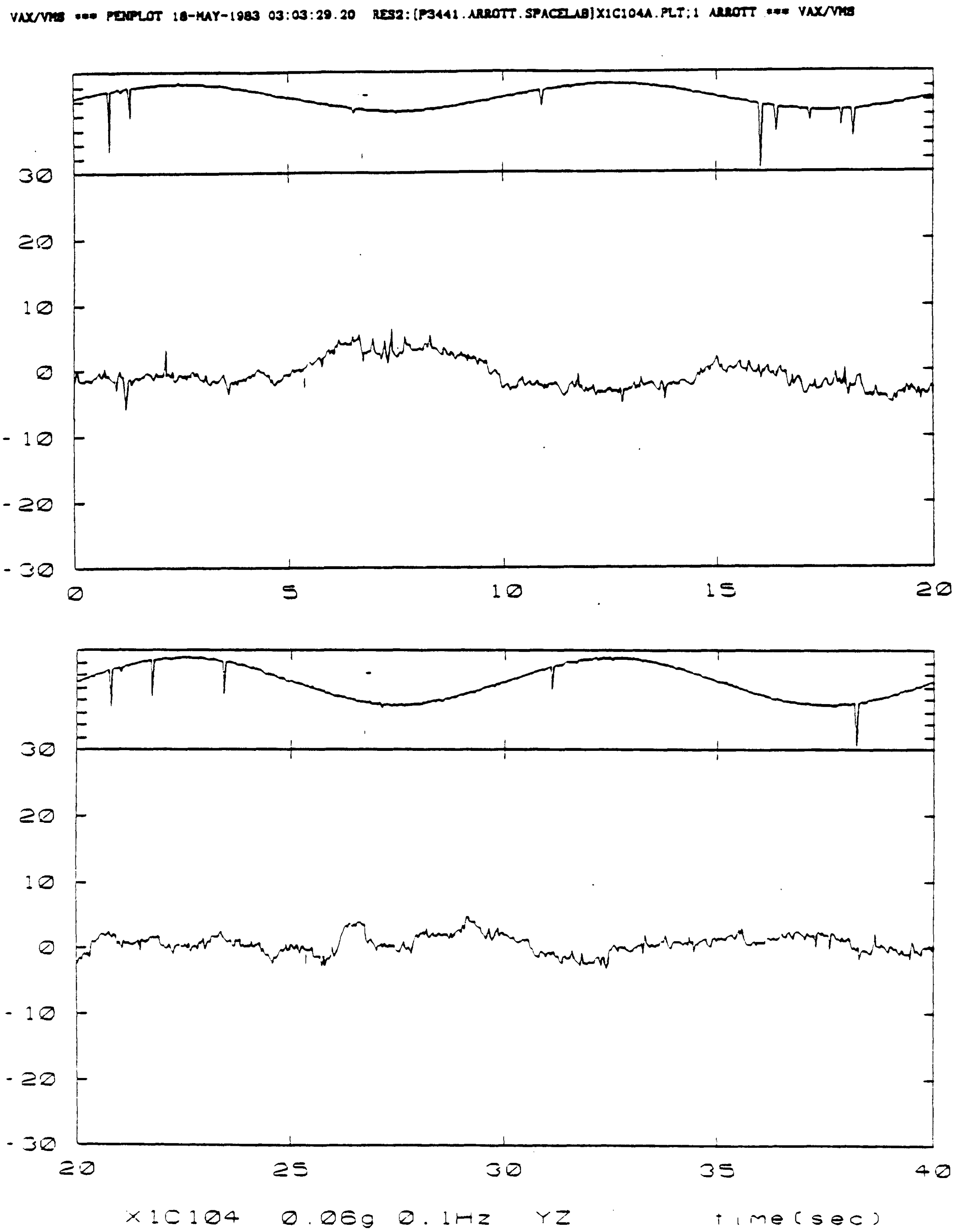


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 18-MAY-1983 03:02:28.59 RES2:[P3441.ARROTT.SPACELAB]X1C103A.PLT;1 ARROTT *** VAX/VMS

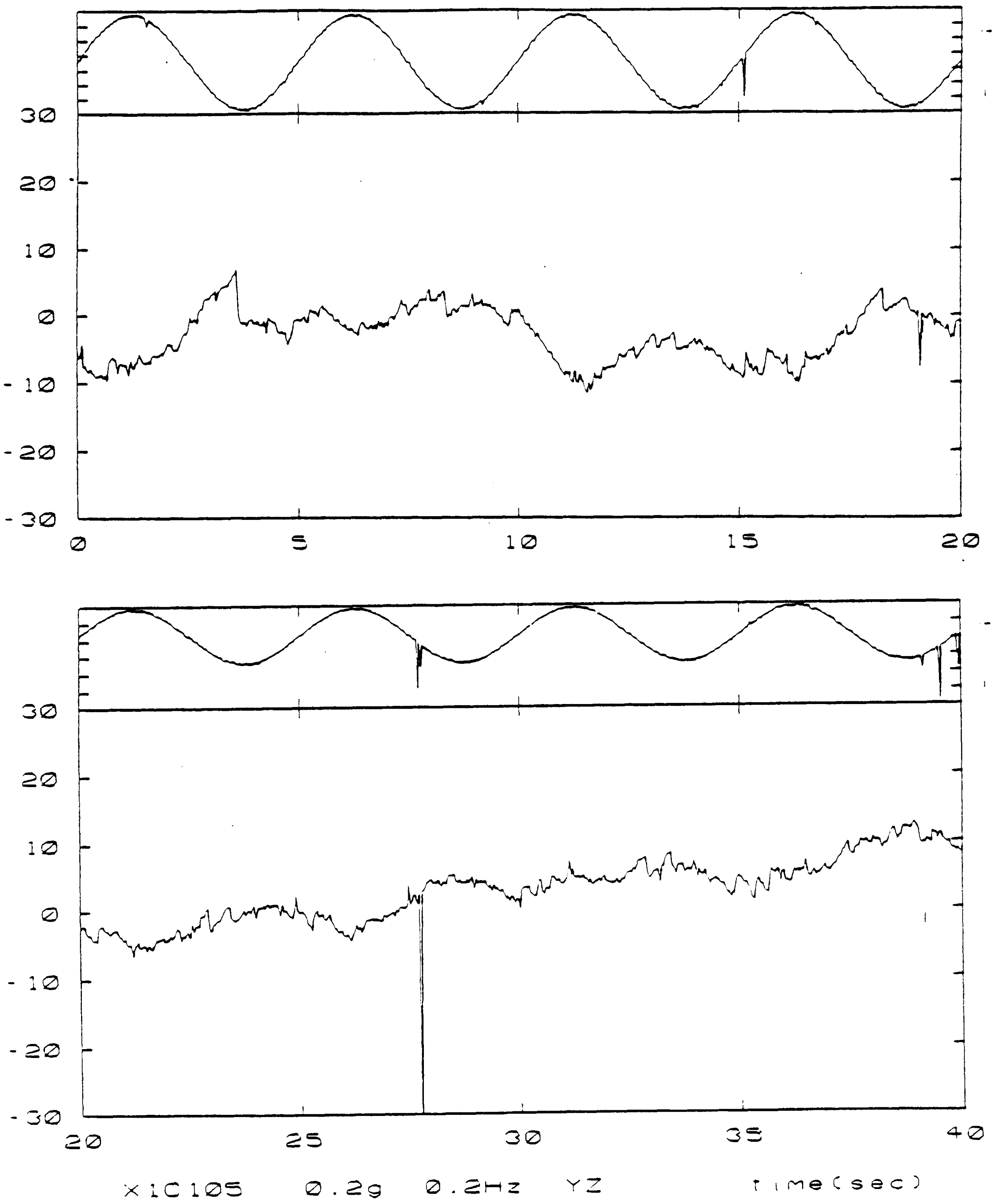


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.



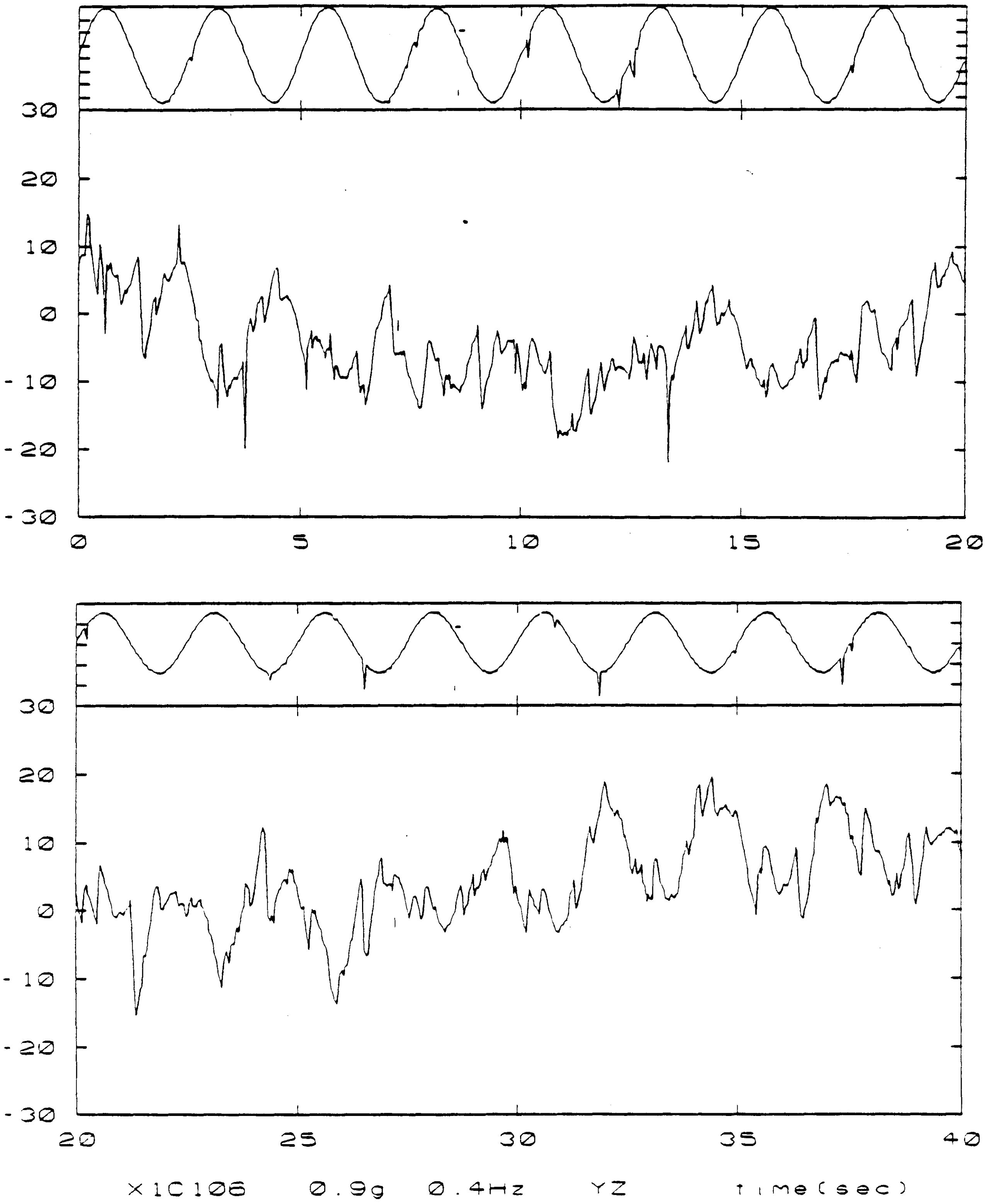
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 18-MAY-1983 03:04:34.61 RES2:[P3441.ARROTT.SPACELAB]X1C105A.PLT;1 ARROTT *** VAX/VMS

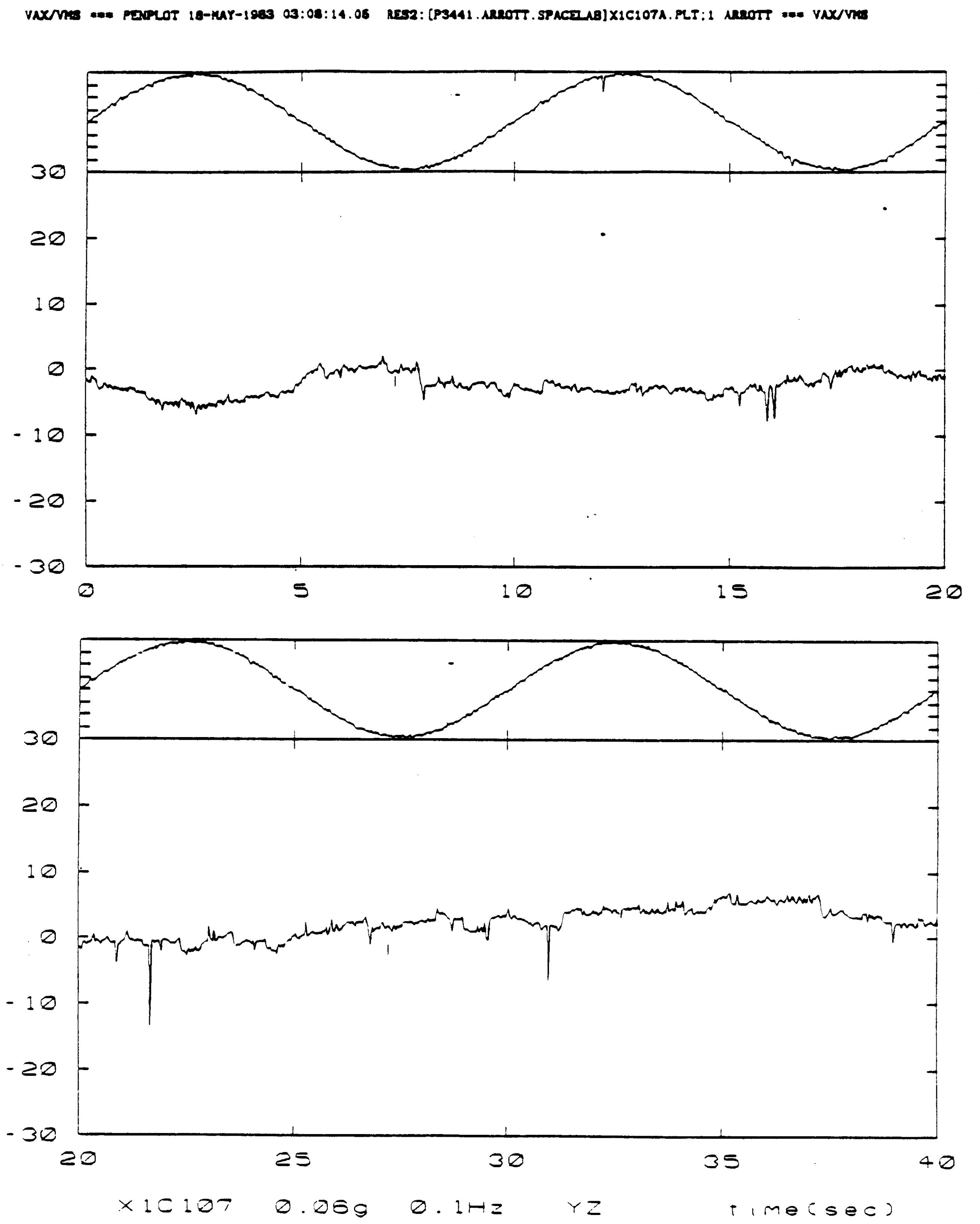


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS === PENPLOT 18-MAY-1983 03:05:34.87 RES2:[P3441.ARROTT.SPACELAB]X1C106A.PLT;1 ARROTT === VAX/VMS

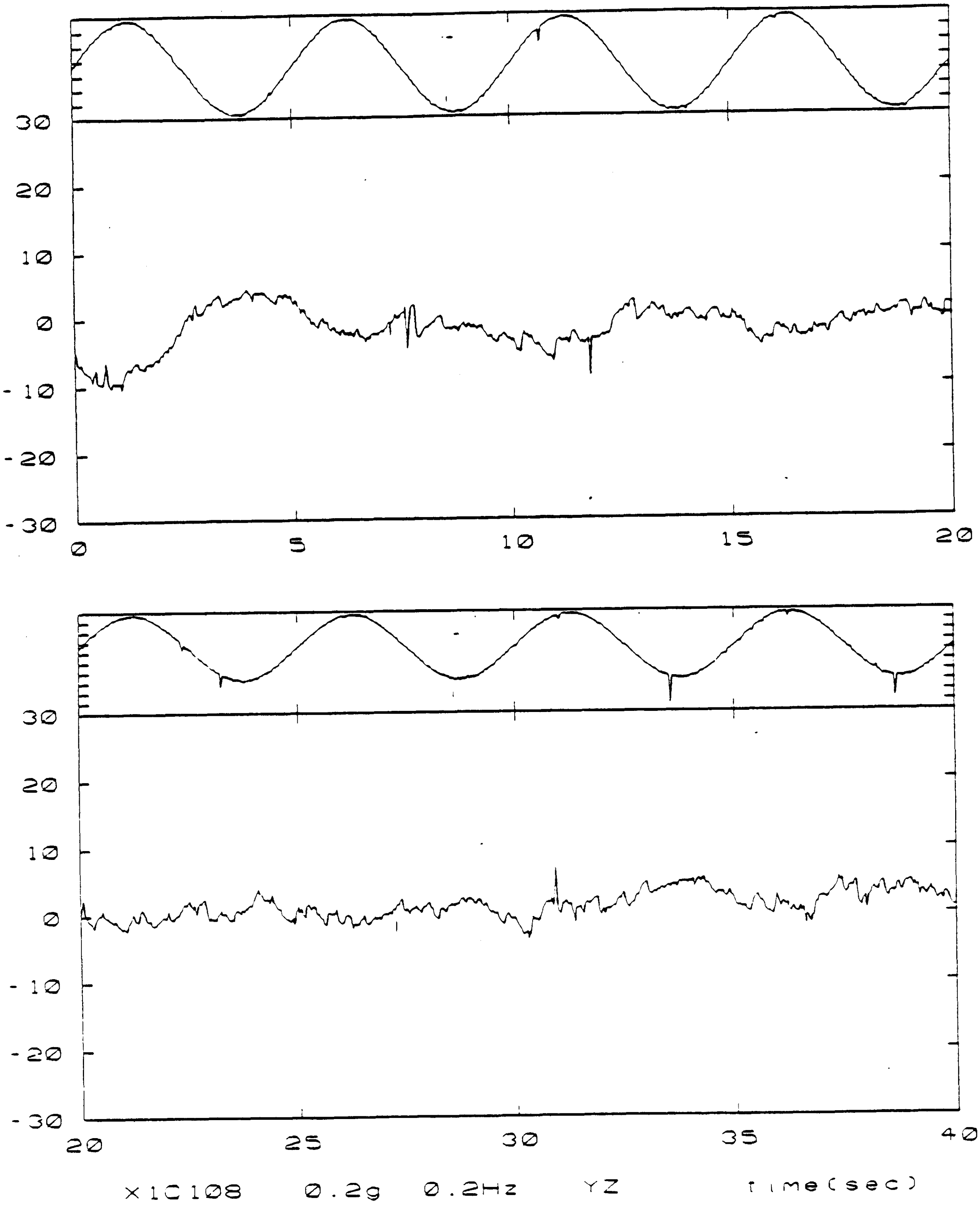


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.



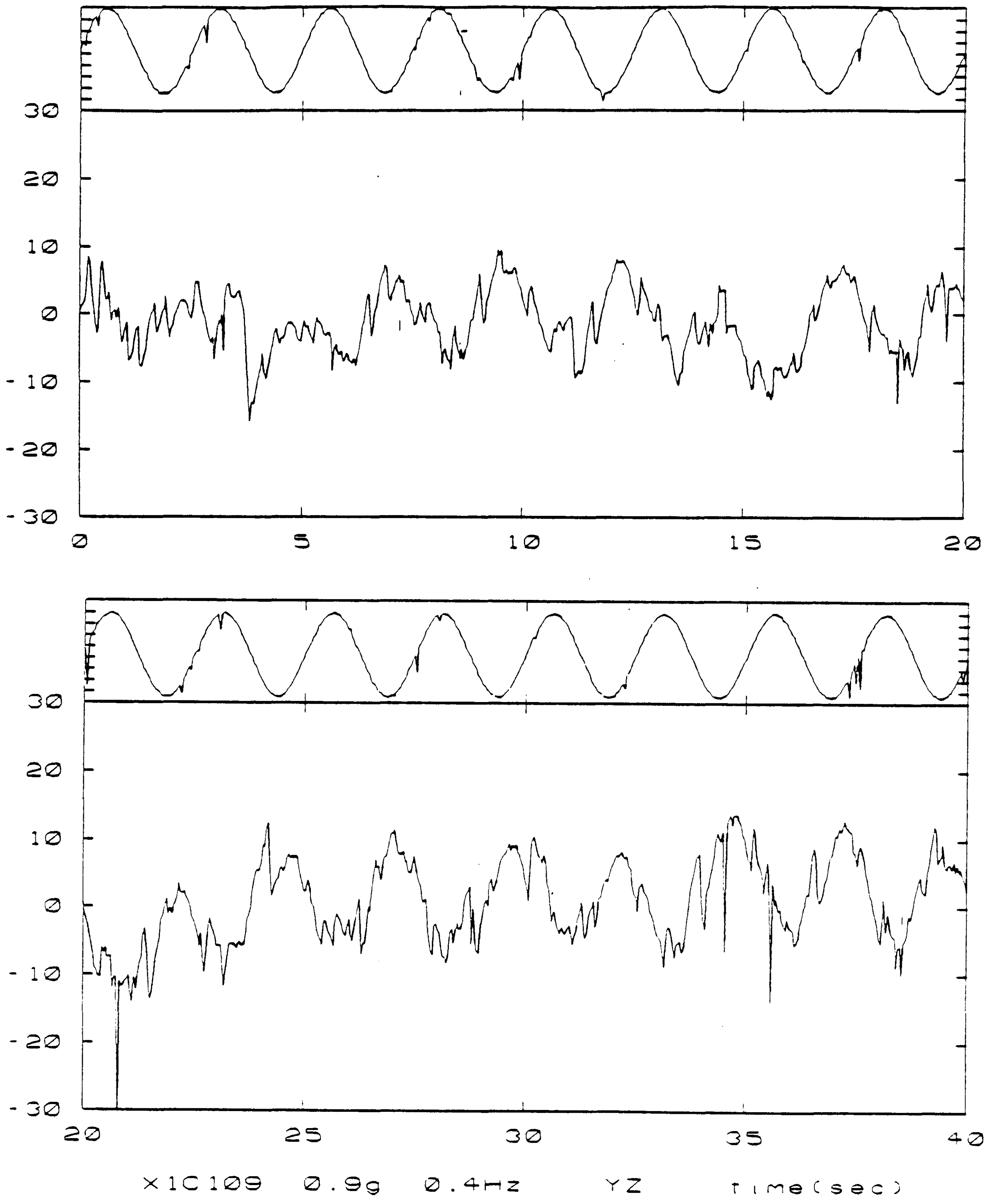
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS === PENPLOT 18-MAY-1983 03:11:14.11 RES2:[P3441.ARROTT.SPACELAB]X1C108A.PLT;1 ARROTT === VAX/VMS



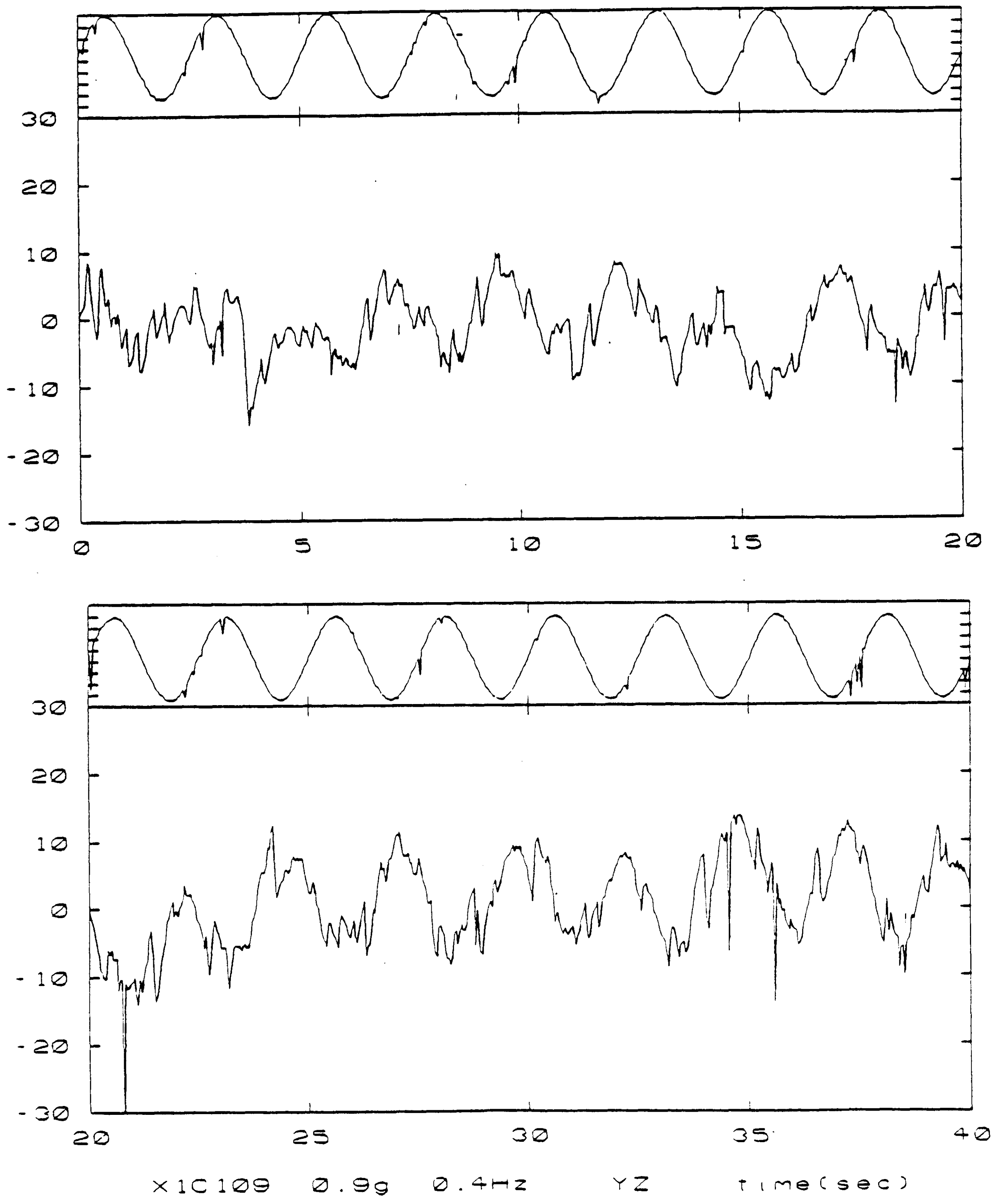
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 18-MAY-1983 03:13:06.75 RES2:[P3441.ARROTT.SPACELAB]X1C109A.PLT;1 ARROTT *** VAX/VMS



Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 18-MAY-1983 03:13:08.75 RES2:[P3441.ARROTT.SPACELAB]X1C109A.PLT;1 ARROTT *** VAX/VMS

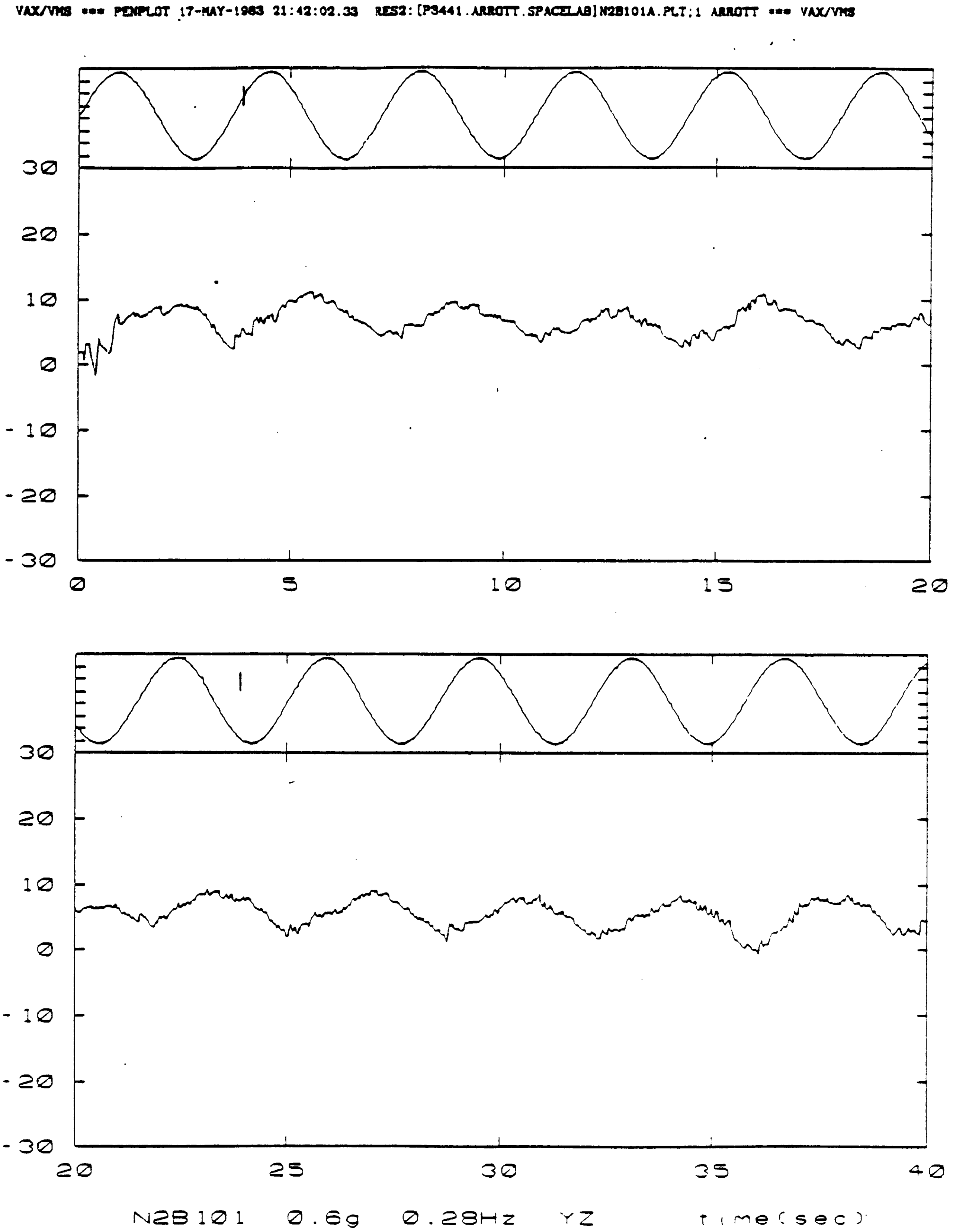


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

Summary of Results

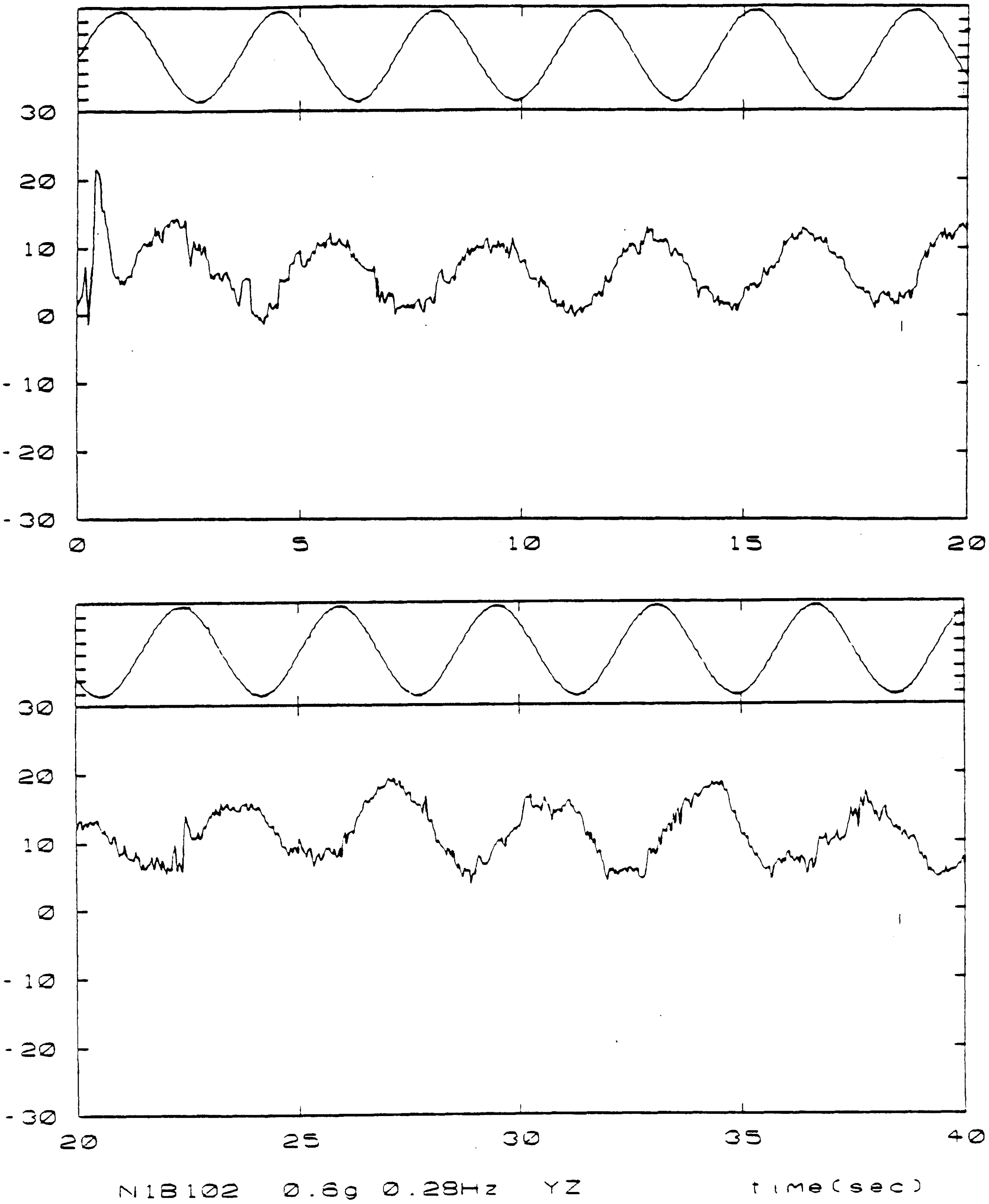
subject· N1
protocol III (X1CBT)
Orientation· YZ
Eyes· Horizontal

data code	stimulus		response		coherence
	amplitude [g]	frequency [Hz]	amplitude [deg/sec]	phase [deg]	[%]
N1B104	0.2	0.2	2.51	-87	0.8
N1B108	0.2	0.4	2.66	-95	0.6
N1B102	0.6	0.28	5.23	-28	5
N1B105	0.6	0.4	4.69	-50	3
N1B106	0.6	0.56	4.99	-67	5
N1B109	0.6	0.8	7.19	-79	8
N1B103	0.9	0.4	11.81	-52	19



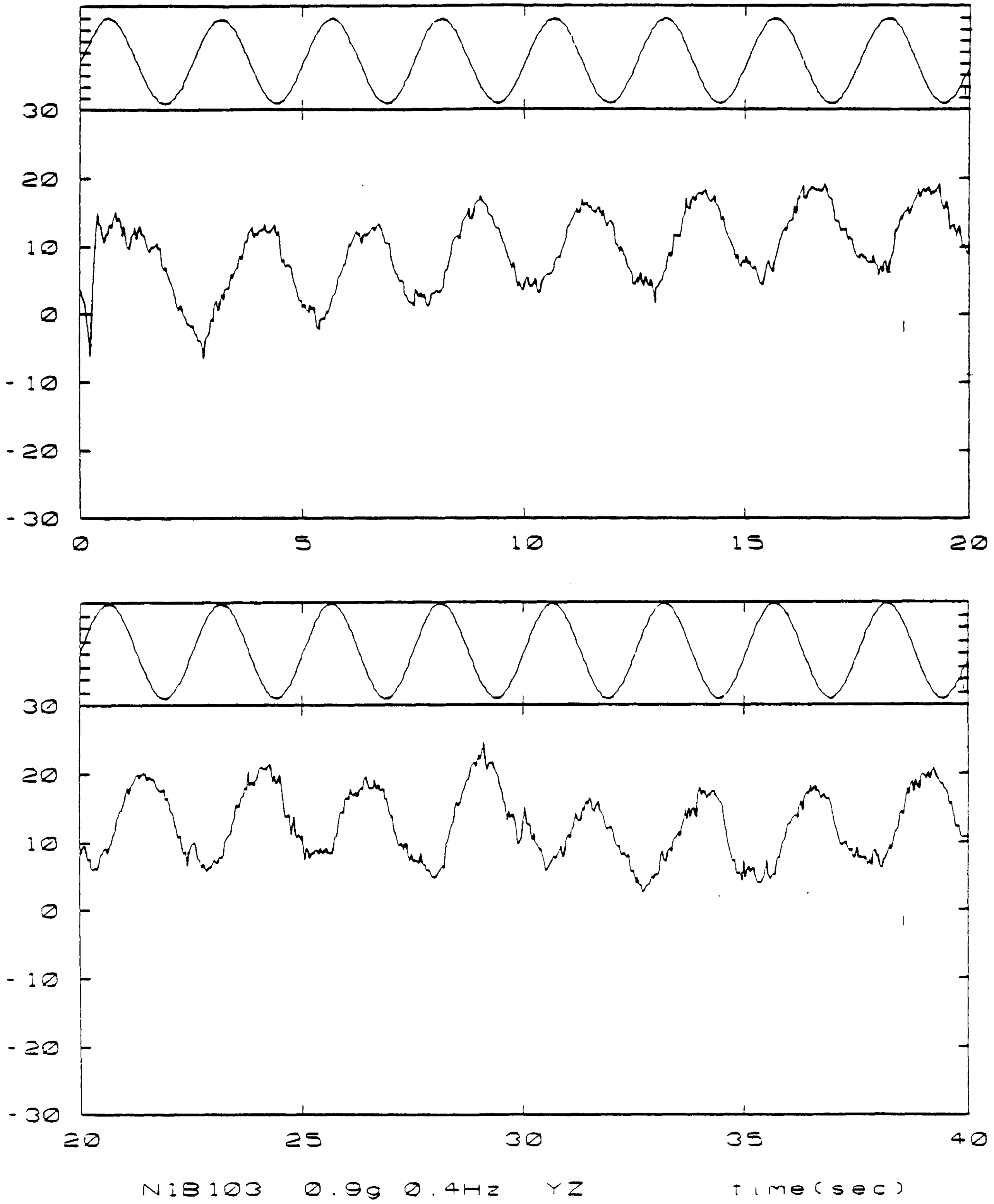
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:27:07.39 RES2:[P3441.ARROTT.SPACELAB]N1B102A.PLT;1 ARROTT *** VAX/VMS



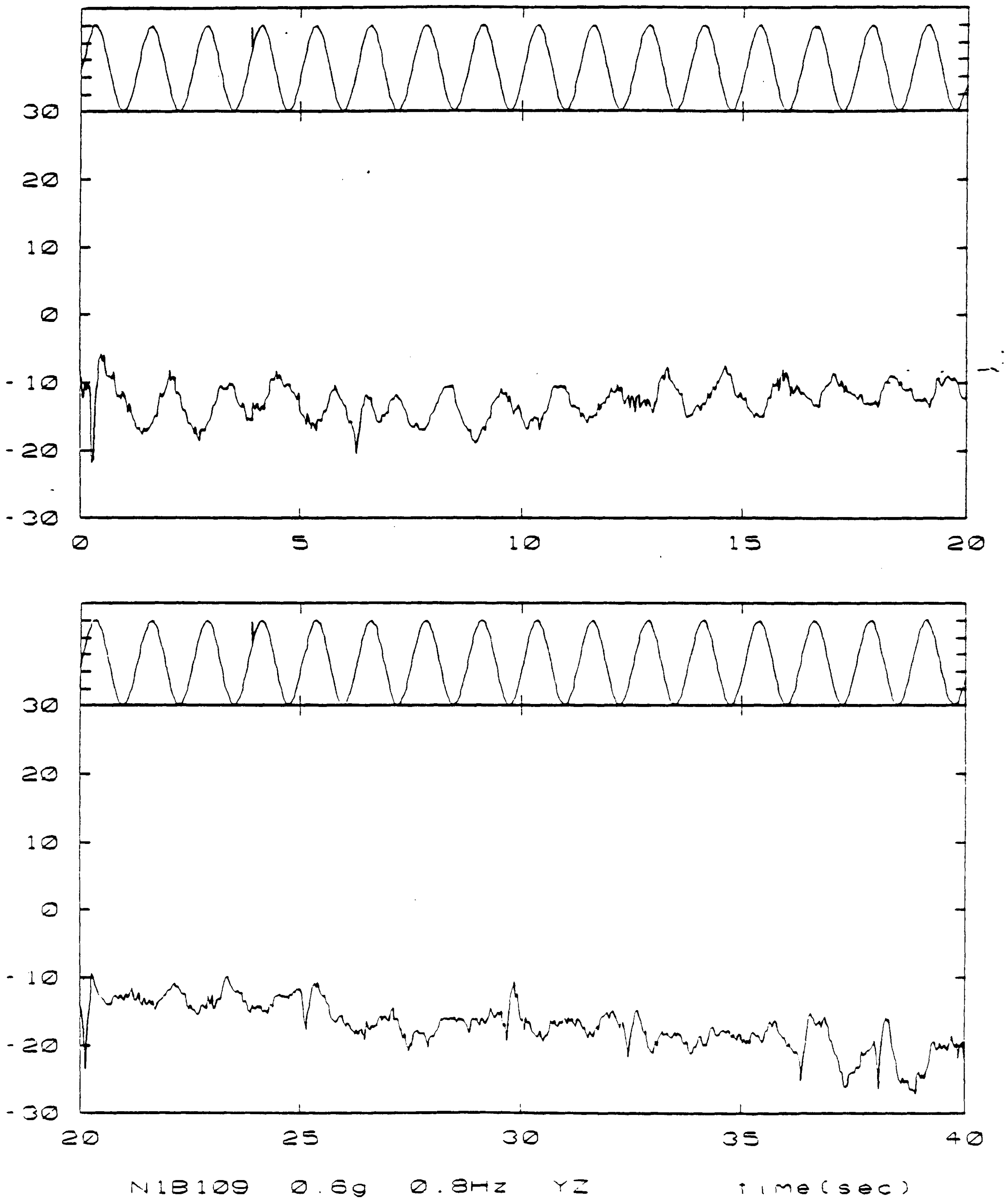
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:31:00.81 RES2:[P3441.ARROTT.SPACELAB]N1B103A.PLT;1 ARROTT *** VAX/VMS



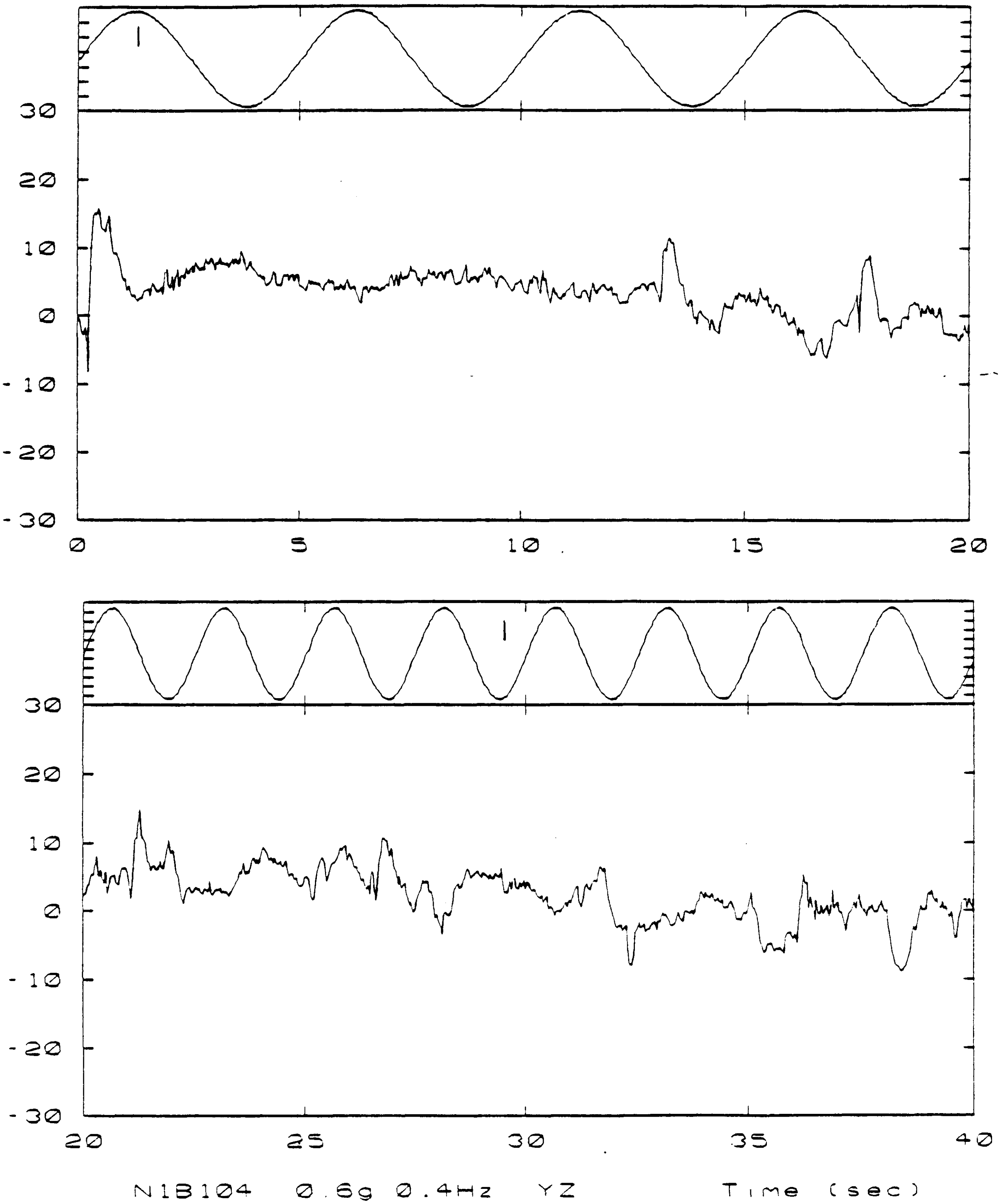
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS === PENPLOT 17-MAY-1983 21:39:14.68 RES2:[P3441.ARROTT.SPACELAB]N1B109A.PLT;1 ARROTT === VAX/VMS



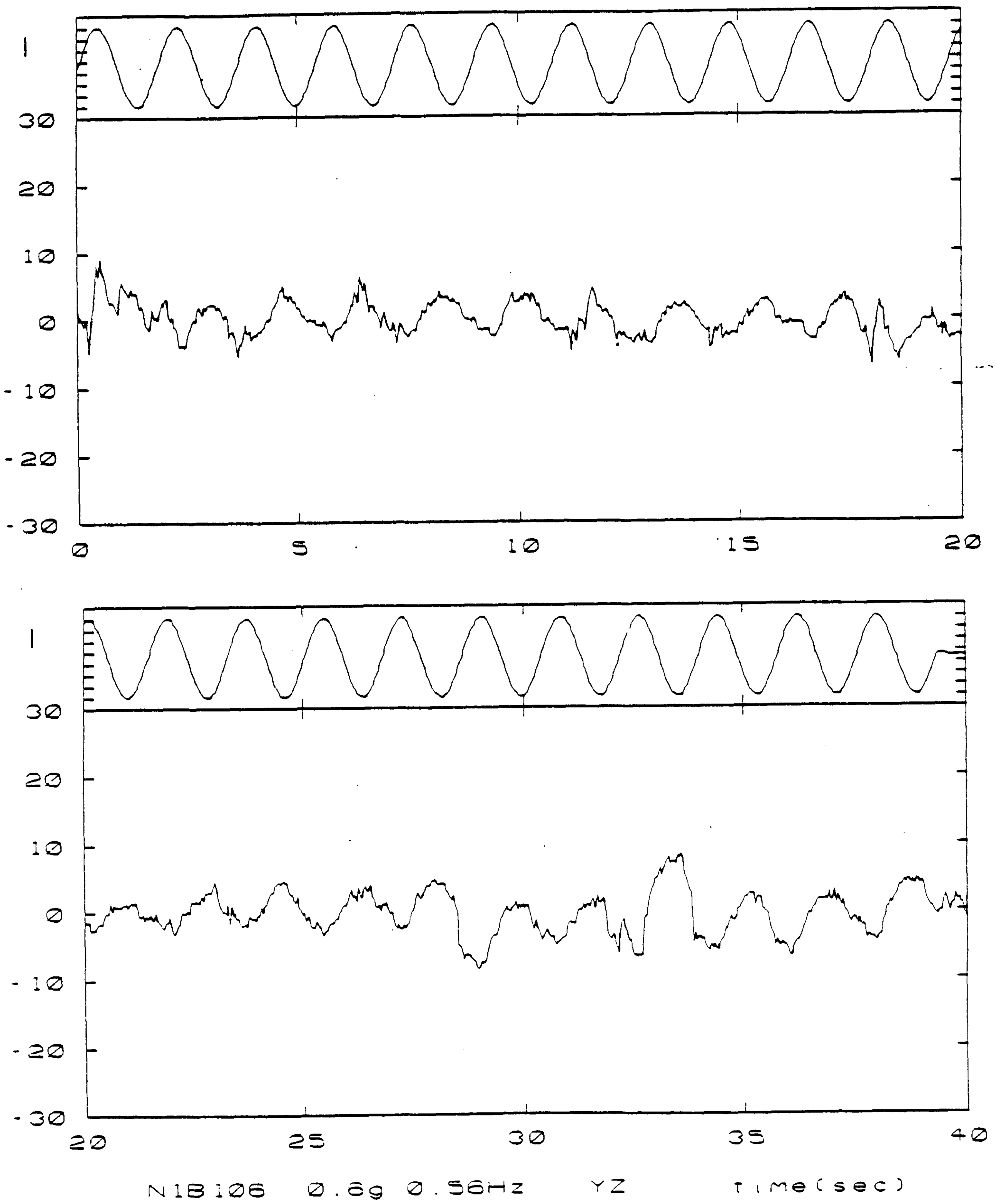
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:32:43.57 RES2:[P3441.ARROTT.SPACELAB]N1B104A.PLT;1 ARROTT *** VAX/VMS



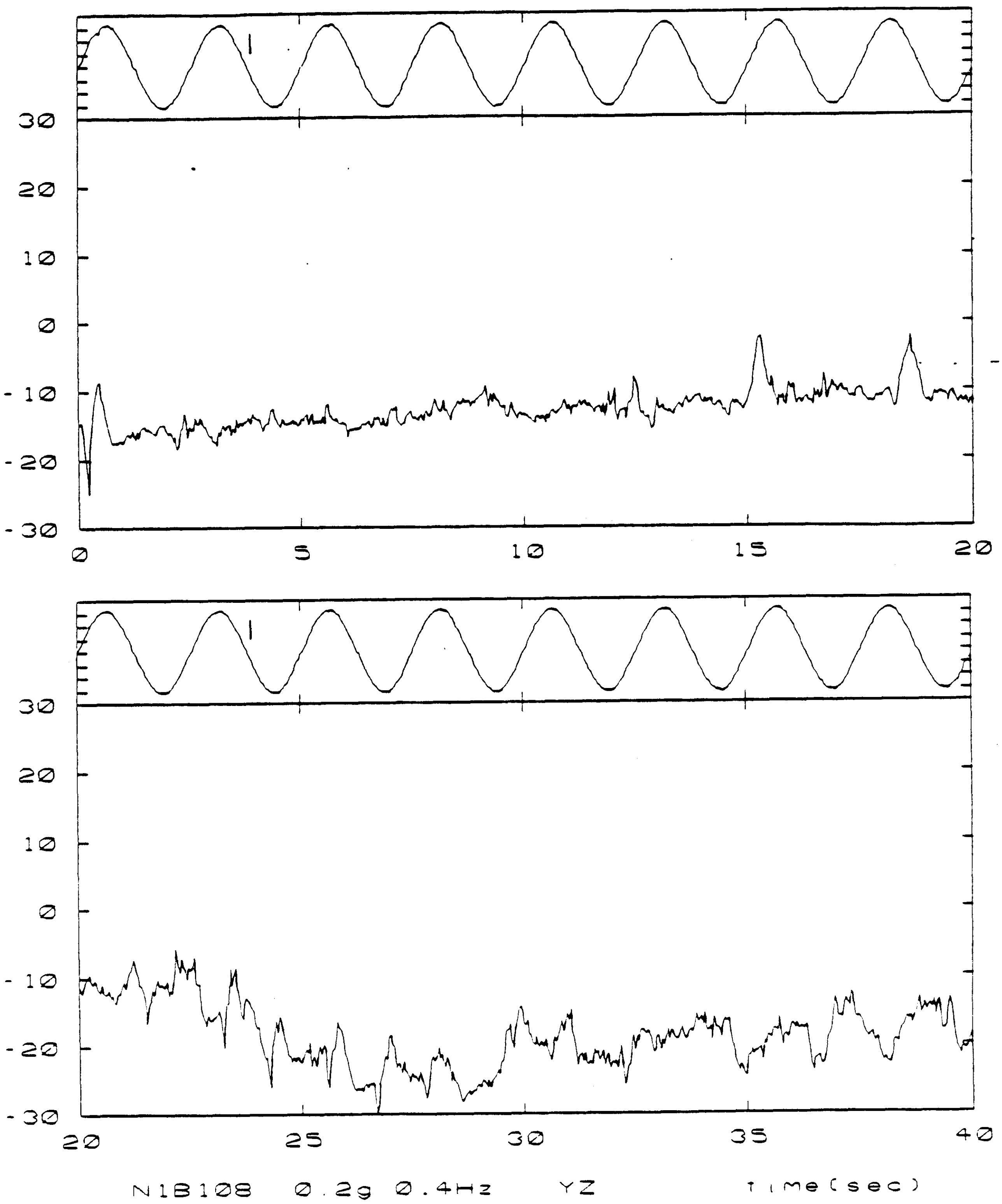
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:35:41.94 RES2:[P3441.ARROTT.SPACELAB]N1B106A.PLT:1 ARROTT *** VAX/VMS



Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:37:18.11 RES2:[P3441.ARROTT.SPACELAB]N1B108A.PLT;1 ARROTT *** VAX/VMS

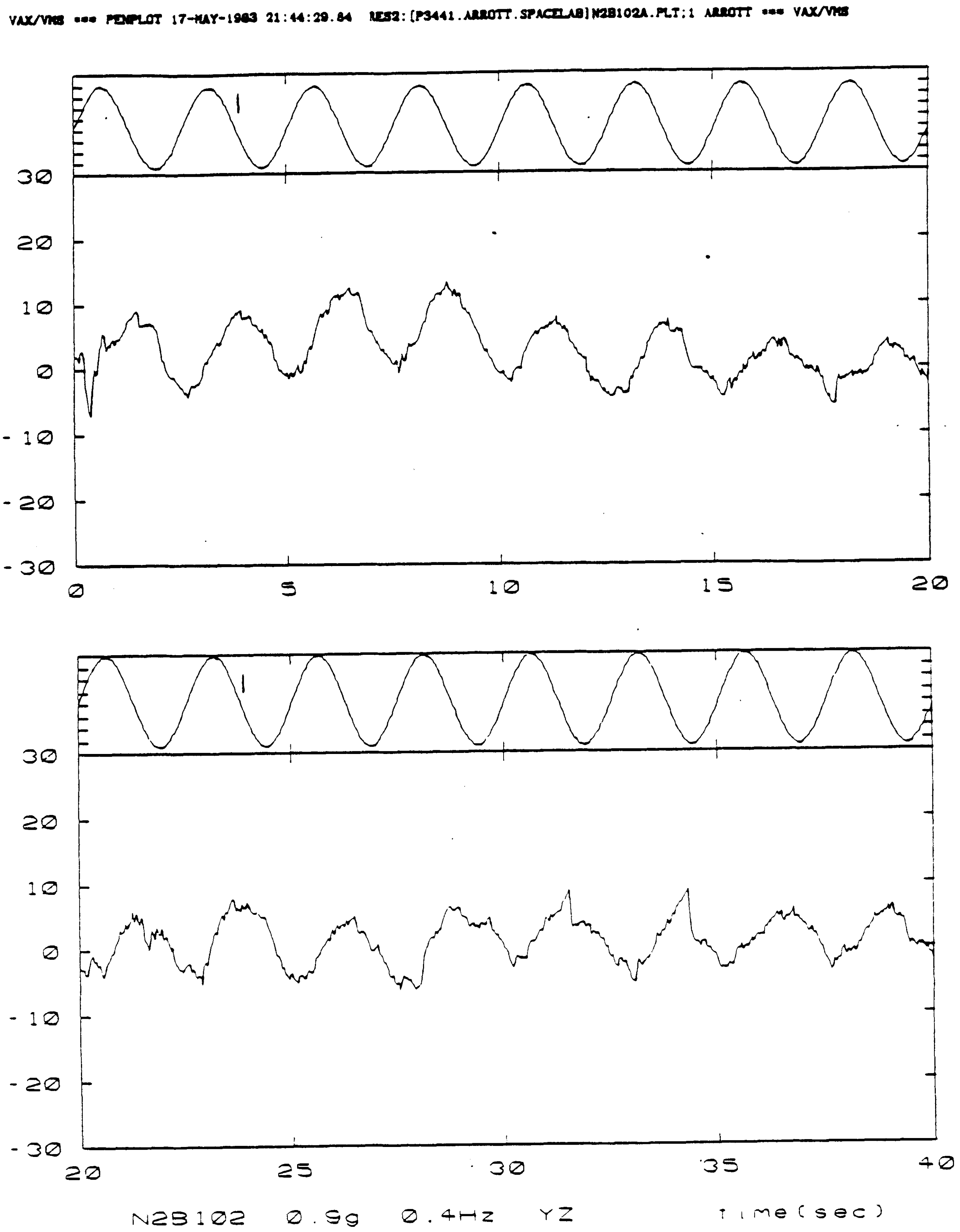


Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

Summary of Results

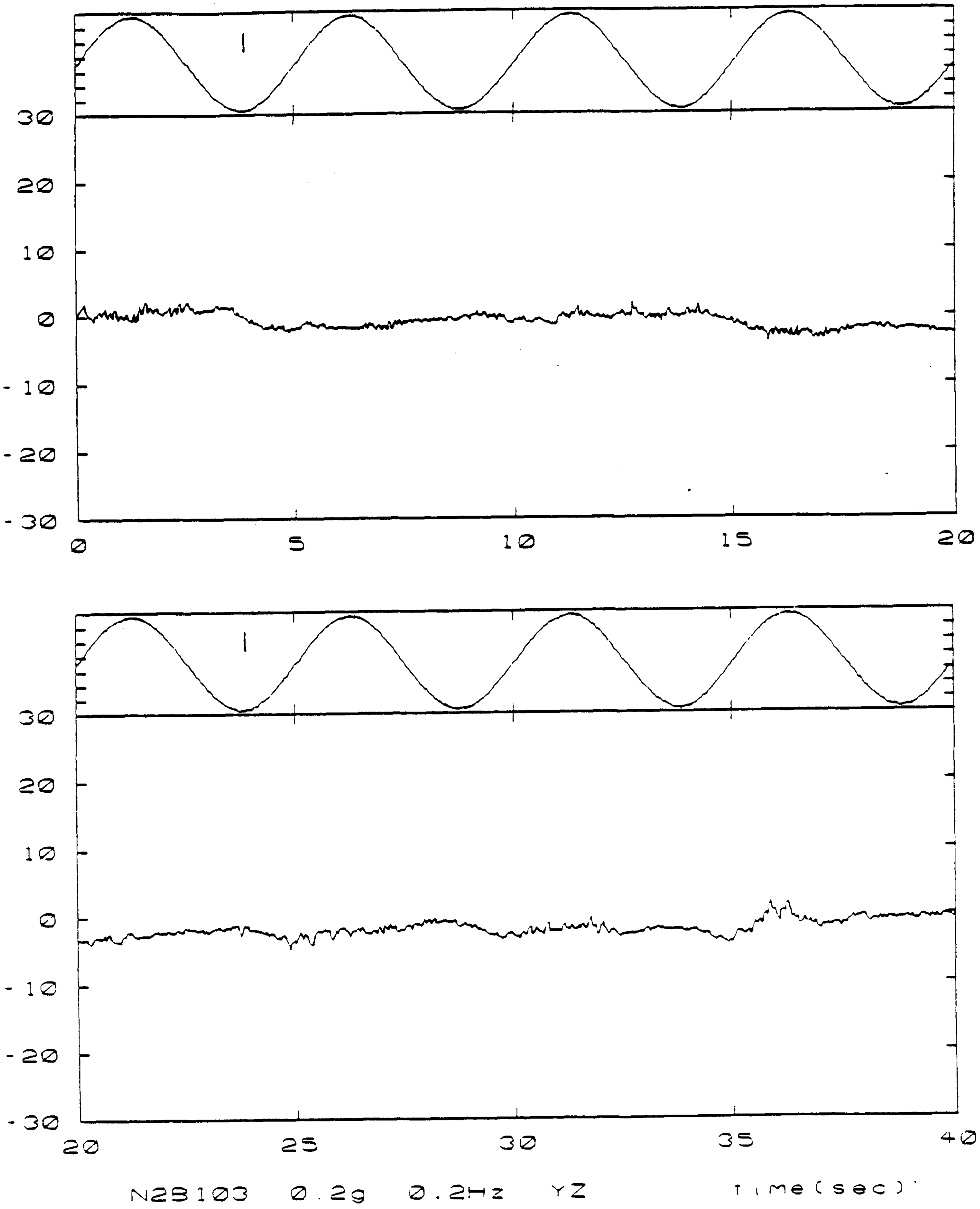
subject: N2
protocol: III (X1CBT)
Orientation: YZ
Eyes: Horizontal

data code	stimulus		response		coherence
	amplitude [g]	frequency [Hz]	amplitude [deg/sec]	phase [deg]	[%]
N2B103	0.2	0.2	0.40	6	0.1
N2B107	0.2	0.4	1.21	-188	1.2
N2B101	0.6	0.28	3.74	-7	8
N2B104	0.6	0.4	4.66	-45	10
N2B105	0.6	0.56	4.30	-54	7
N2B108	0.6	0.8	6.00	-91	12
N2B102	0.9	0.4	9.80	-54	27
N2B106	0.9	0.8	13.75	-93	45



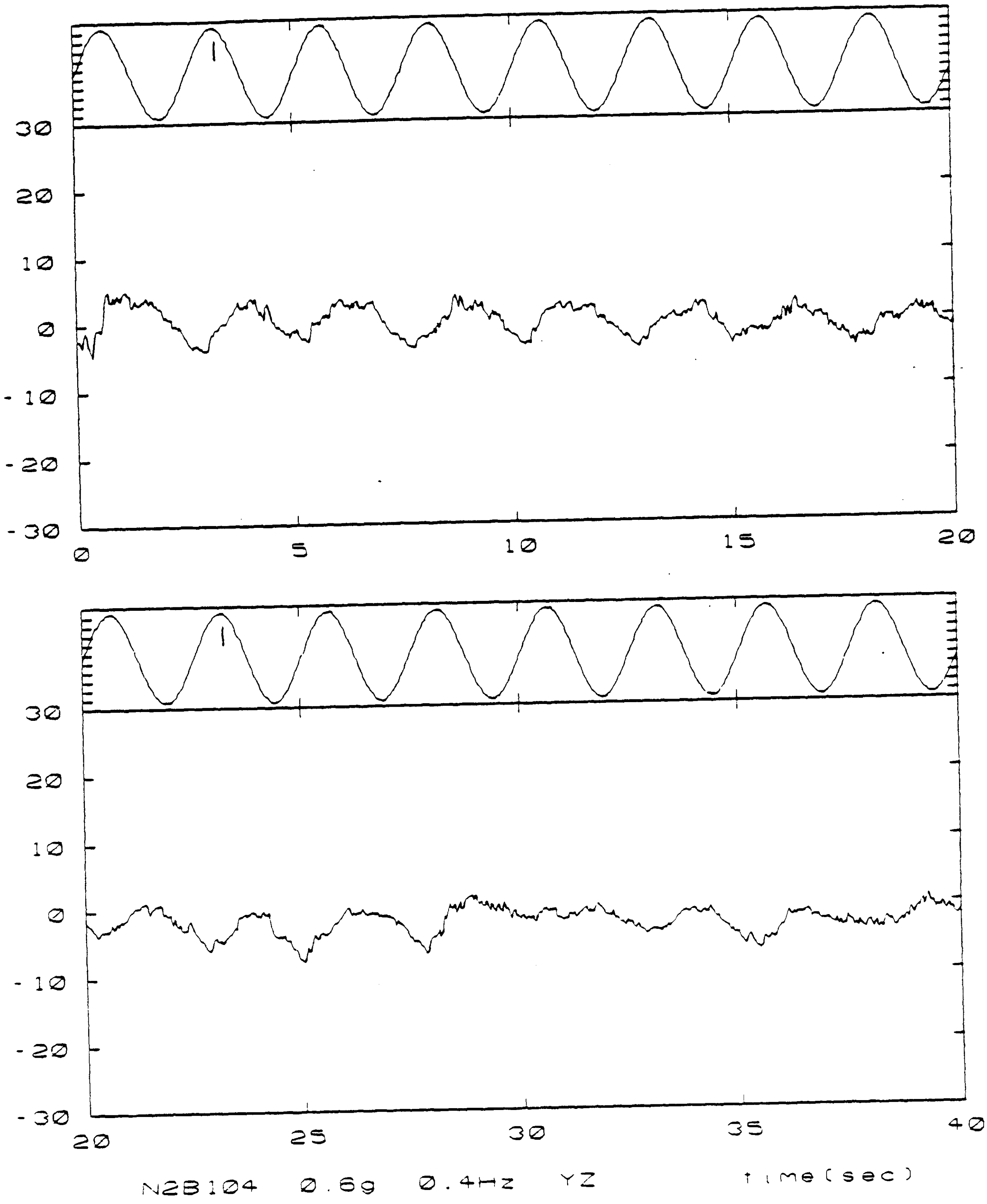
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 17-MAY-1983 21:46:02.96 RES2:[P3441.ARROTT.SPACELAB]N2B103A.PLT;1 ARROTT *** VAX/VMS



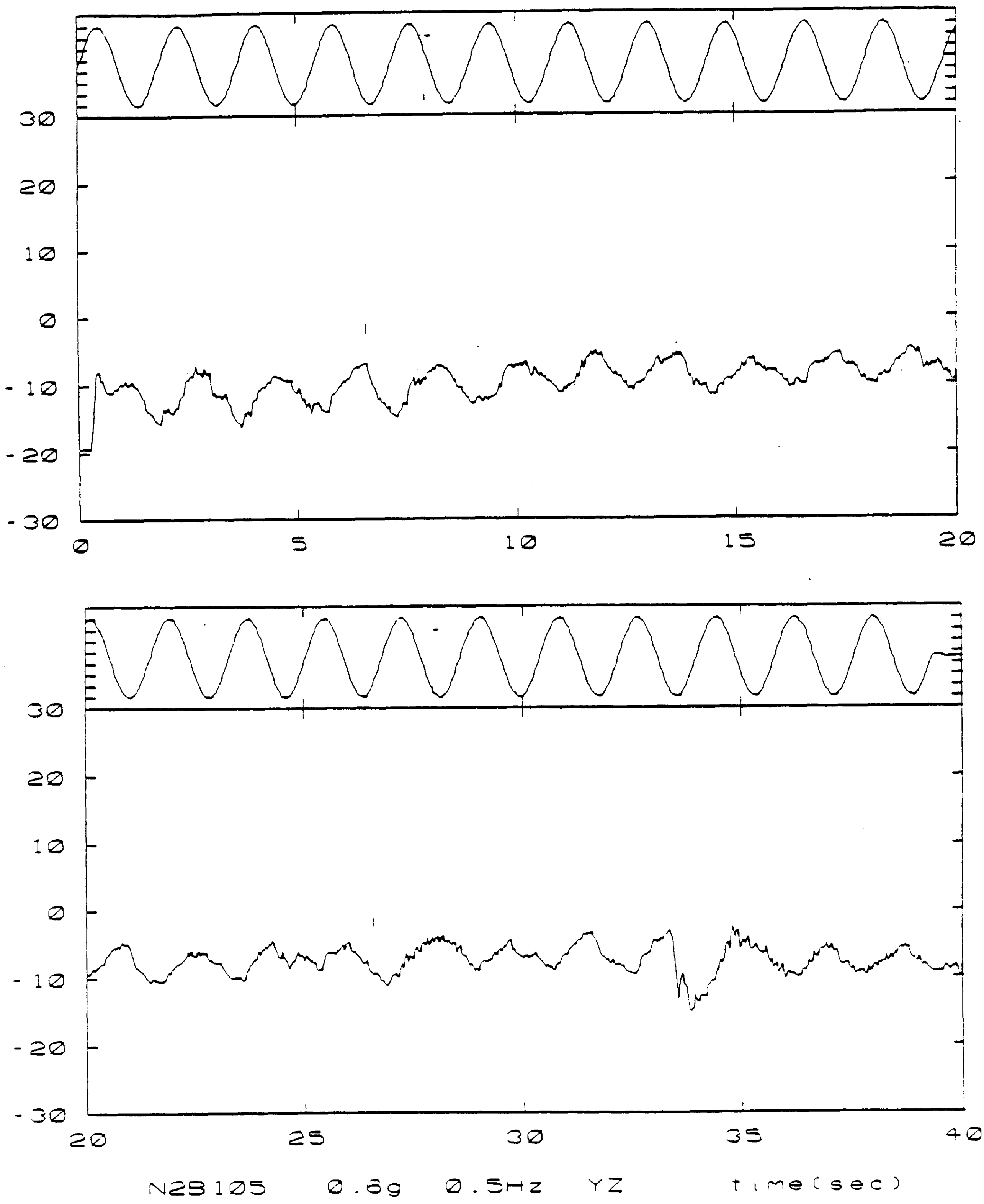
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

```
VAX/VMS *** PENPLOT 17-MAY-1983 21:47:47.33  RES2:[P3441.ARROTT.SPACELAB]N2B104A.PLT;1 ARROTT *** VAX/VMS
```



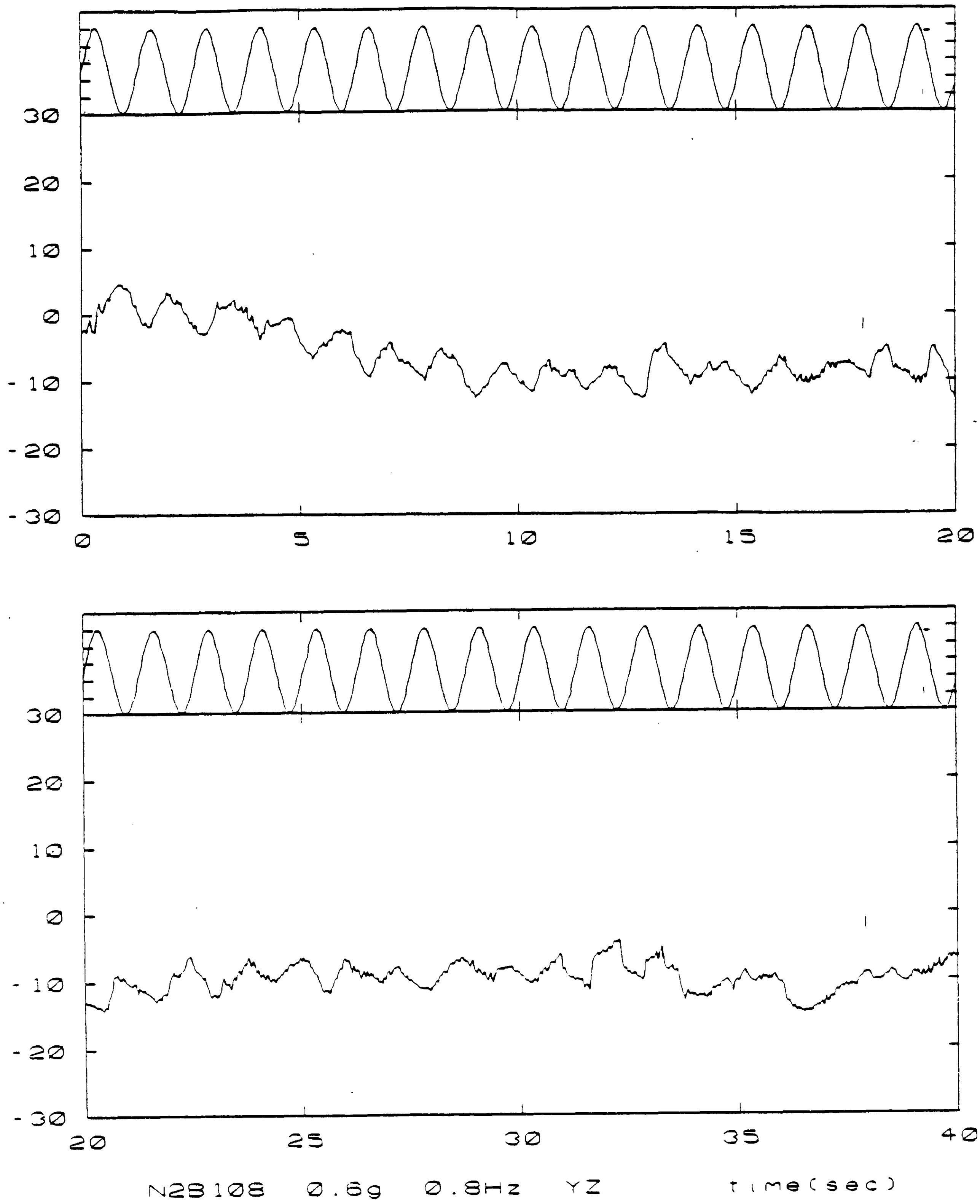
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

VAX/VMS *** PENPLOT 18-MAY-1983 02:44:02.67 RES2:[P3441.ARROTT.SPACELAB]N2B106A.PLT;1 ARROTT *** VAX/VMS



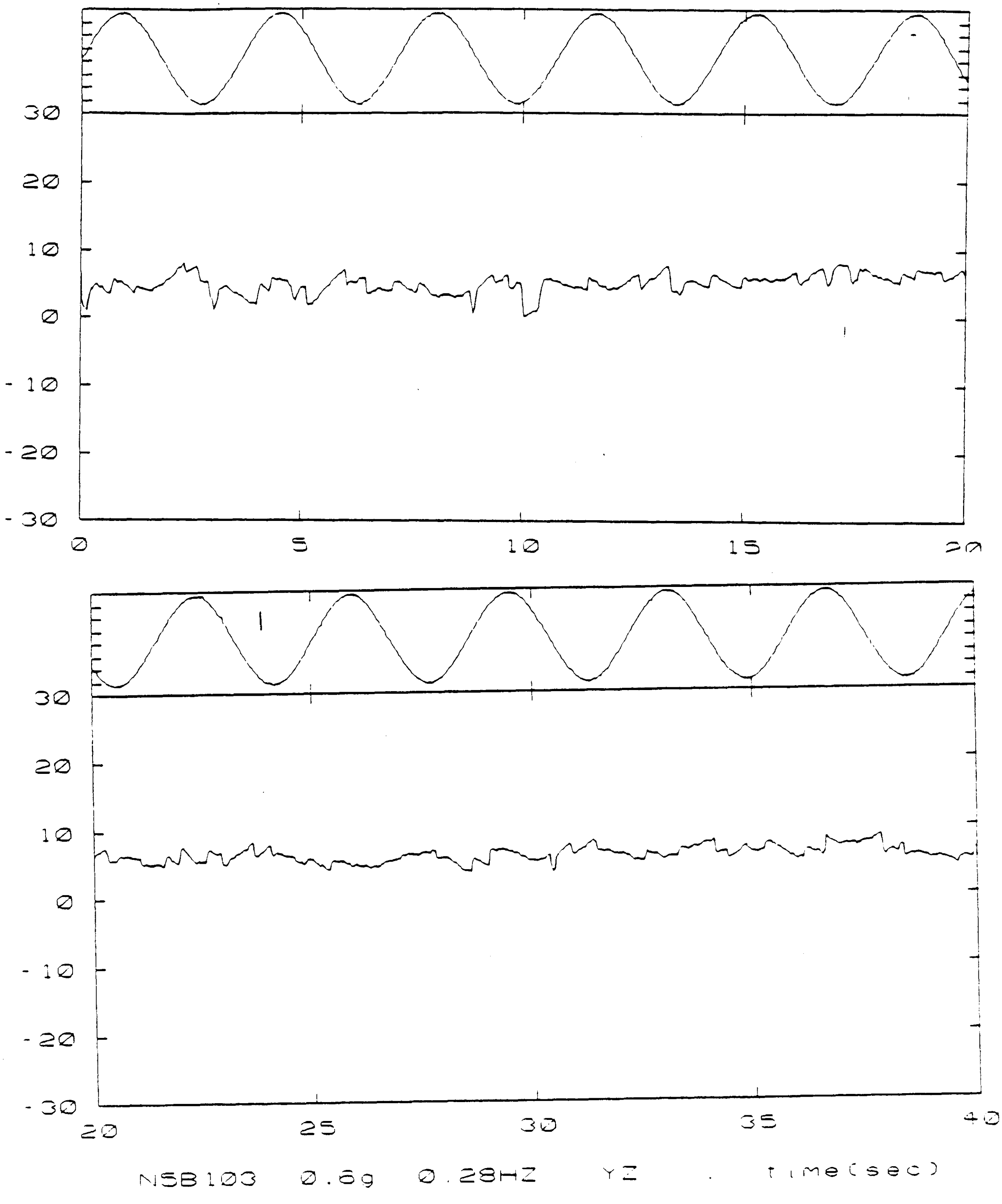
Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

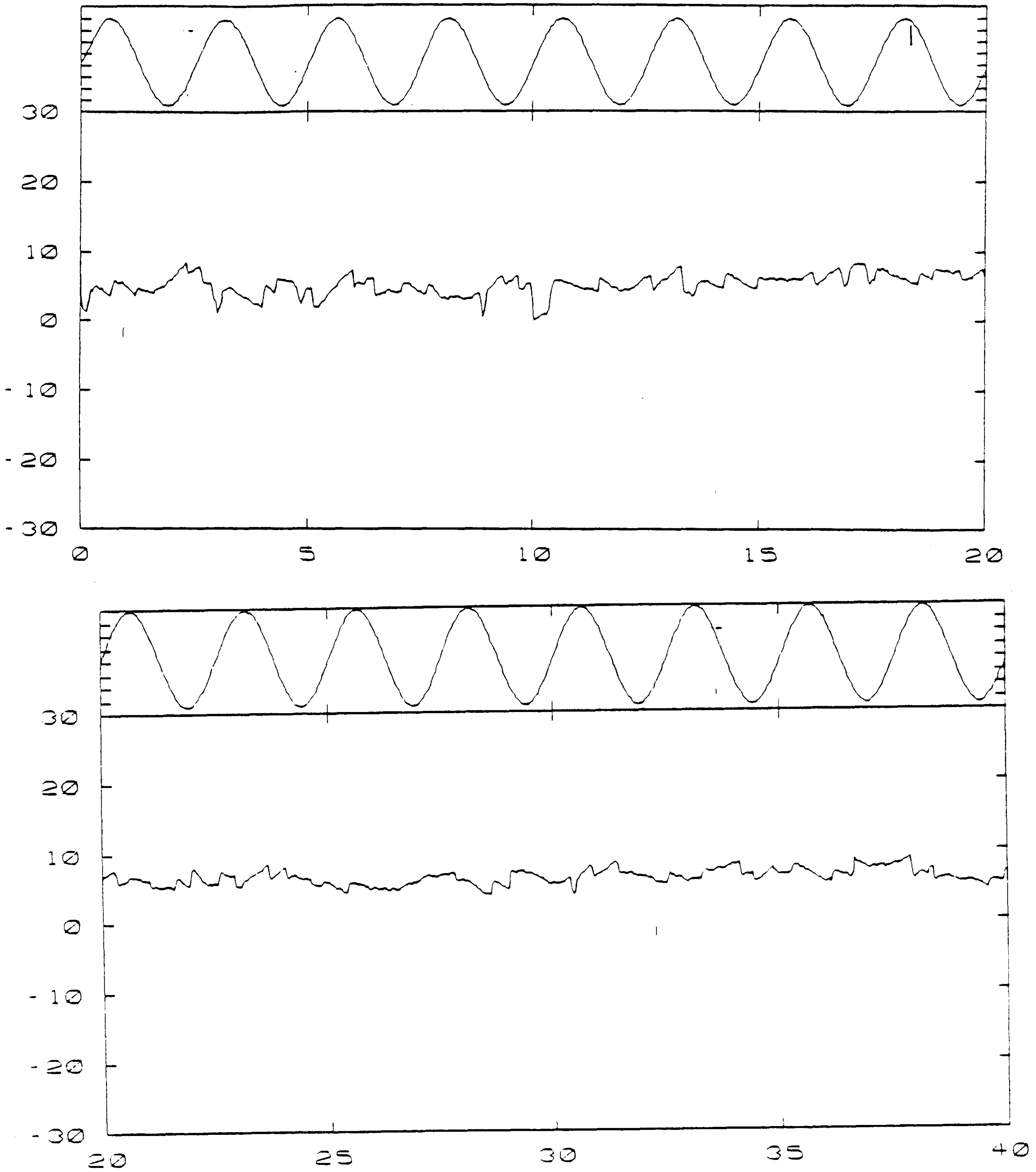
VAX/VMS *** PENPLOT 17-MAY-1983 21:57:47.59 RES2:[P3441.ARROTT.SPACELAB]N2B108A.PLT;1 ARROTT *** VAX/VMS



Horizontal eye position (in degrees) during linear motion. Cart velocity trace is presented arbitrarily scaled to indicate phase relationship.

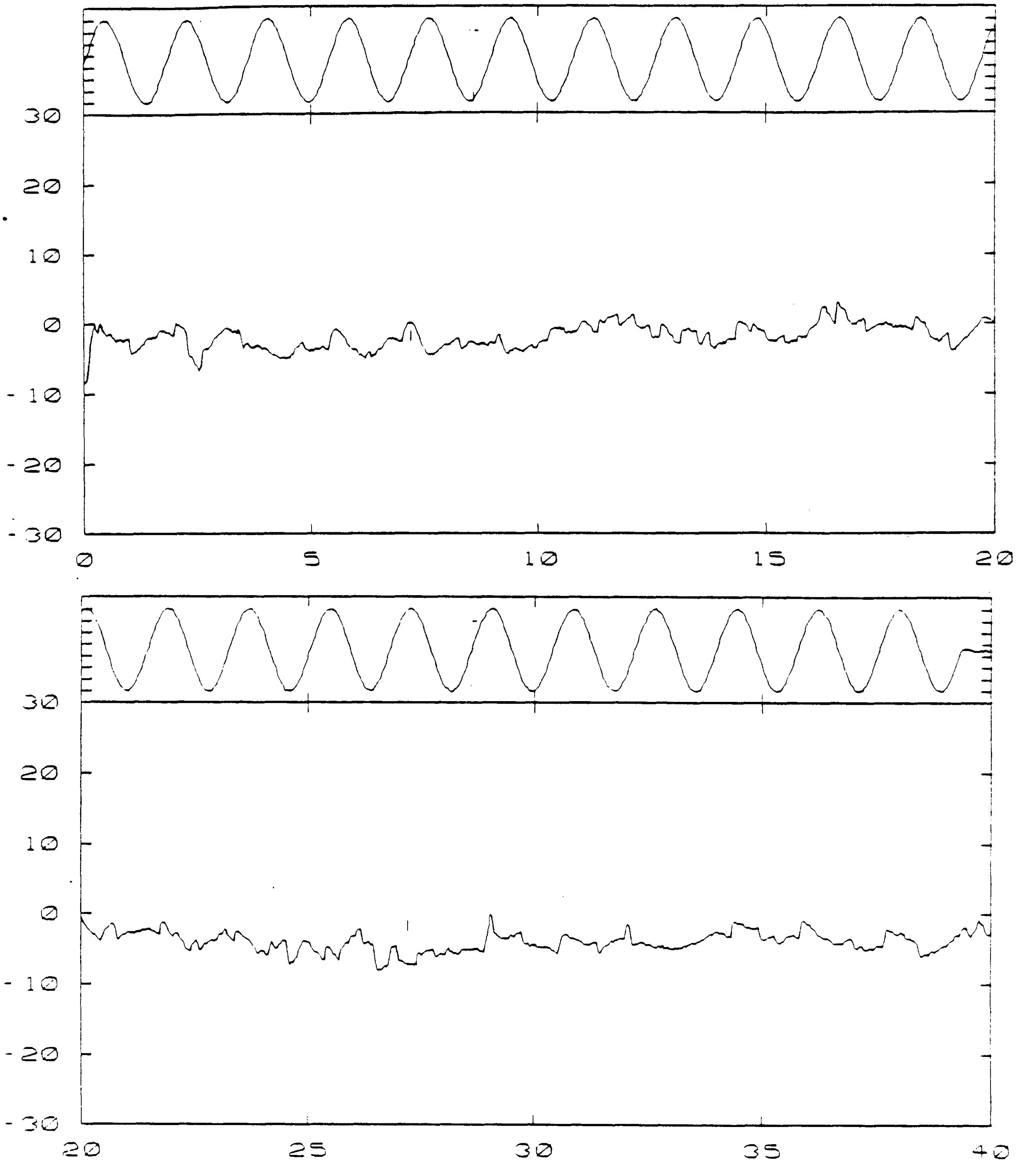
VAX/VMS *** PENPLOT 17-MAY-1983 22:22:53.82 RES2:[P3441.ARROTT.SPACELAB]N5B103A.PLT;1 ARROTT *** VAX/VMS



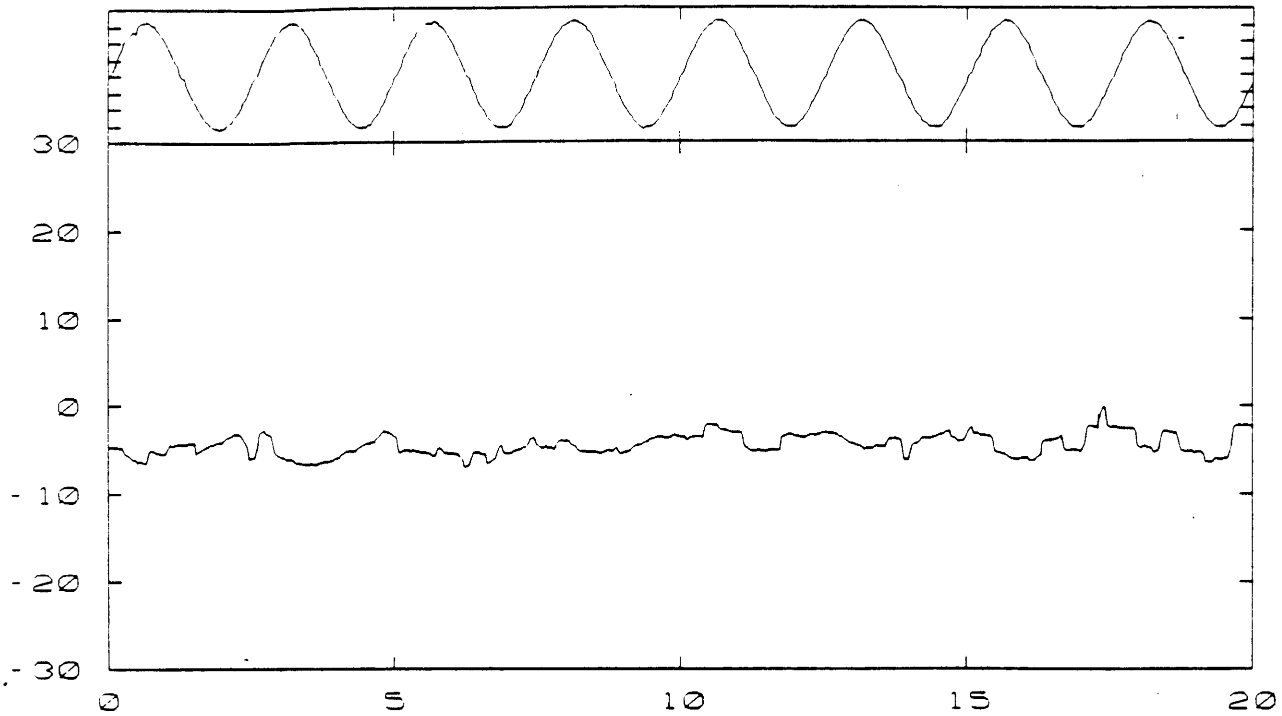


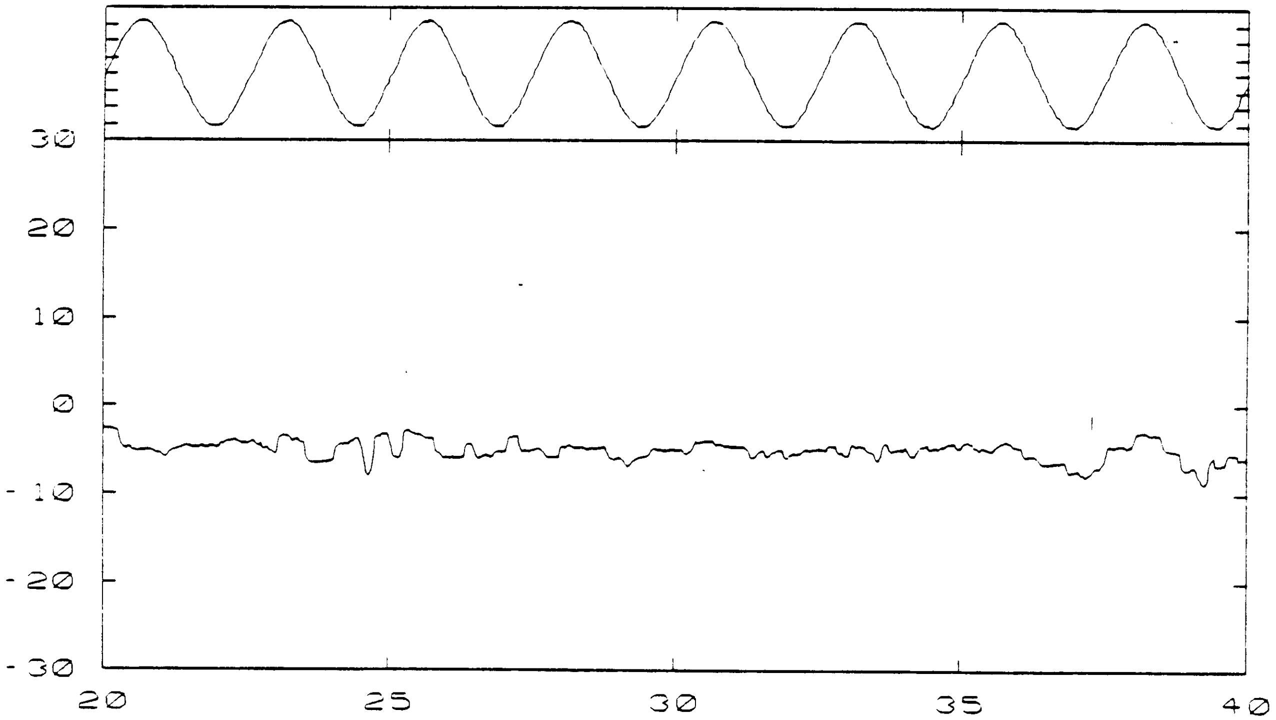
N5B104 0.9g 0.4Hz YZ time(sec)

VAX/VMS *** PENPLOT 18-MAY-1983 01:24:46.70 RES2:[P3441.ARROTT.SPACELAB]N5B107A.PLT;1 ARROTT *** VAX/VMS



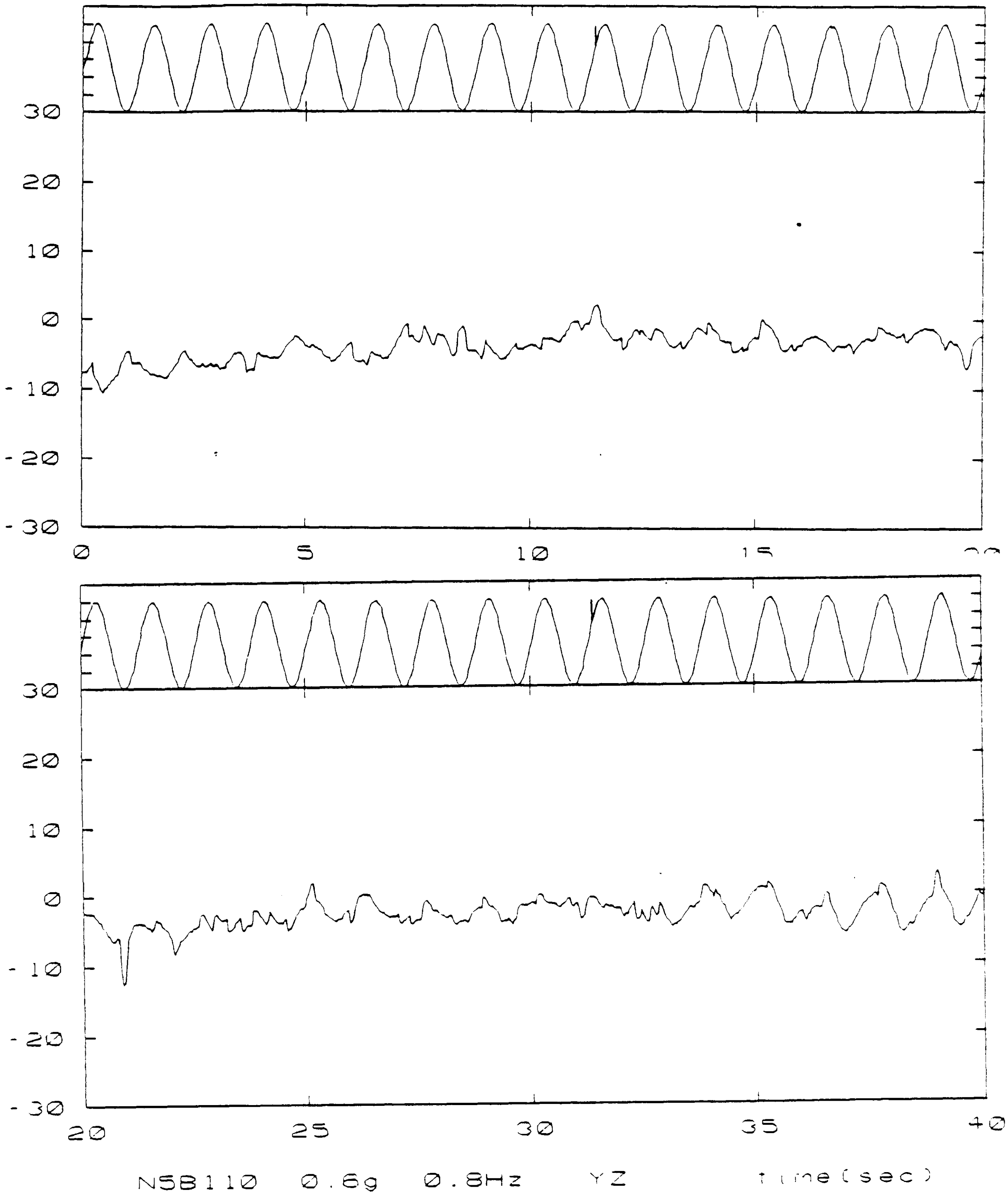
N5B107 0.6g 0.56Hz YZ time(sec)





N5B109 0.2g 0.4Hz Y-Z time(sec)

VAX/VMS *** PENPLOT 18-MAY-1983 01:30:25.14 RES2:[P3441.ARROTT.SPACELAB]N5B110A.PLT;1 ARROTT *** VAX/VMS



N5B110 0.6g 0.8Hz YZ time(sec)

VAX/VMS *** PENPLOT 18-MAY-1983 02:30:08.88 RES2:[P3441.ARROTT.SPACELAB]X12106A.PLT;1 ARROTT *** VAX/VMS