

CIRCULARVECTION AND OCULAR COUNTERROLLING IN VISUALLY INDUCED ROLL
- SUPINE AND IN WEIGHTLESSNESS

BY

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S.B. Aeronautical and Astronautical Engineering, M.I.T. (1979)

Submitted in partial fulfillment of the
requirements for the degree of

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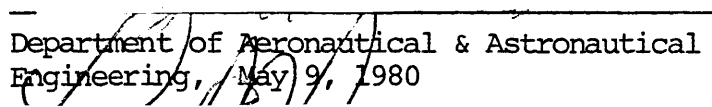
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ABSTRACT

The perception of self motion about the visual axis and the associated ocular counterrolling (OCR) were investigated and documented in several environments. A full visual field of random dots was used to create visually induced roll in a supine position on earth and during zero g parabolic flights. The role of tactile forces as a replacement for otolith cues in limiting sensations of circularvection (CV) was also investigated.

Onset times for CV were shown to be dependent upon visual pattern and to be similar to those found by previous authors in yaw vection. The associated changes were as predicted with the addition of tactile cues increasing onset times and the removal of g forces decreasing them. Vection velocities were unaffected by either tactile cues or the absence of gravity.

Ocular counterrolling and circularvection were shown to have no correlation and appeared to be controlled by independent processes. Binocular vision was shown to produce significantly greater amounts of ocular counterrolling than monocular viewing. In addition, Hering's Law of Equal Innervation was borne out for torsional eye movements by the binocular measurements.

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CHAPTER 1

INTRODUCTION

Circularvection, or the perception of self motion when viewing a fully rotating visual field, is a phenomenon that was studied as early as 1896 by Helmholtz. Functional concern about the problem, however, did not arise again until the 1960's and more so the early '70's. 'Circularvection' pertains to any induced circular motion. It can be generated about yaw, pitch, or roll axes given the proper stimulus, that is, a continuously moving visual field of significant size, contrast and believability to create the illusion that it is the subject who is actually moving (Dichgans and Brandt, 1973; Young et al., 1973). The structure of the semicircular canals, which measure angular accelerations and not steady state motion, must be considered in accounting for the phenomenon (Brandt et al., 1973; Dichgans and Brandt, 1974). Once an initial conflict time has been overcome, one can believe that steady bodily motion exists since it receives no cues to the contrary, and the visual signal is in complete agreement. In this thesis, self motion about the roll axis was studied in an attempt to gain further insights into the cause and effect of the Visually Induced Roll (VIR) illusion.

It is known that when standing, the observation of a rotating visual field produces a sensation of tilt, in the opposite direction to field rotation, of approximately 10 - 15° from gravitational vertical (Dichgans et al., 1972; Held et al., 1975). The visually induced tilt is apparently constrained by veridical input from the otolith

organs resulting in a paradoxical sensation of continuous motion at a constant tilt (Finke and Held, 1978). In the supine position, however, this paradoxical sensation gives way to one of continuous motion about the vertical in a direction opposite to the visual field. Here, the otoliths no longer provide conflicting information about the gravity vector. We are thus able to time this motion, termed circularvection (CV), Visually Induced Roll (VIR), or justvection, and correlate it to actual visual field motion. It is also known that moving visual fields cause many involuntary eye movements (Young, 1972; Young and Henn, 1975). Constant linear motion produces a linear nystagmus, a combination of slow phase tracking motions in the direction of the moving field and fast phase saccades in the opposite direction which reorient the eyes within the orbit and reorient the changing visual field on the retina. This type of eye motion can easily be understood in connection with watching fence posts out the side of a car window, where the eye tracks a single post until it is past and then reorients to catch another. These types of eye movements have been documented in yaw CV by Jen Kuang Huang (1978) and in yaw motion in a rotating chair by Tole (1970) and Guedry (1962).

In viewing a field which rotates about the line of sight, it is noted that the eye again performs a nystagmus motion - this time in a rotary direction. The eye appears to follow the visual field in a slow phase rotation, attempting to keep the visual field fixed on the retina, and performs a rotary saccade back to again position the eye in the orbit (Edelman, 1979). These torsional eye movements have been termed ocular torsion or ocular counterrolling (OCR) in the literature. Although

OCR is commonly used to refer to the static torsional movements acting compensatory to the rotated gravito-inertial force (GIF), the term OCR will be used in this thesis to reflect all torsional eye movements, since it is clear that any positive roll of the eye must be accompanied by a counterrolling motion.

The study of the correlation between these two phenomena, i.e. CV and OCR in VIR, and their physical importance are the main objectives of this thesis. The effects of various visual patterns, types of vision and other influences on vection are also addressed, as well as the interplay of gravity and tactile cues on OCR and CV.

CHAPTER 2

BACKGROUND

2.1 Ocular Counterrolling

A method of OCR recording was attempted as early as 1889 by Orchansky. Methods attempted since that time have included: after-images, contact lenses, sutures on the conjunctiva, attachment of mirrors, sheets of metal, polarized lenses and objects extending on stalks to the eye. Each new technique, often claiming higher accuracy, found a new result. As a result, static OCR, induced by varying GIF, went through periods of acceptance and rejection, with final proof not fully realized until the early 1960's. A full review of all the past techniques, however, is not called for nor offered here. It can be found in the MIT Sc.D. Thesis of Byron Lichtenberg (1979), whose method of OCR measurement was adopted for this work. The mechanics have been changed only by the fact that we have moved to binocular recording. The method is straightforward: 35 mm photography of the eye is enlarged 50 times on an X-Y plotting screen. Two iral landmarks are selected with 4 repeats of each landmark entered for assurance of accuracy, and an angle obtained in reference to a fiduciary affixed to the skull via a dental biteboard. Standard deviations calculated on the four repeats of the iral landmarks range from 0.2 to 0.8 degrees, with the lower range being obtained at the expense of time and money on the Hermes Senior Film Analyzer (HSFA), the device used to determine the iral coordinates. The actual calculations of eye angle and plots of such are

done by digital computer through programs established during the work of Lichtenberg.

The major drawbacks of the present OCR measurement system are as follows:

1) Cost and time: The system involves slow and patient frame-by-frame analysis on an expensive analyzer that is logged into a PDP-8 computer. Analysis rates of 20 frames/hour appear to be unsurpassable with losses in accuracy occurring if scanning is rushed any faster. With data acquisition occurring at 3 frames/sec, and 126 frames per data set with numerous subjects being recorded, the result is many hours of tedious labor. Cost of the system and scanner alone runs on the order of \$1.25 per frame, with computer computation and film developing costs causing that figure to be nearly doubled. The process from data acquisition to a plotted output can take a minimum of one week, with the norm running closer to one month when any volume of data is required.

2) Sampling rate: Although it appears possible that future improvements will push the sampling rate to 5 frames/sec, it remains at 3 frames/sec. The flash electronics are unable to operate much above the 3 frame/sec rate presently employed. This slight improvement, however, may not be enough to see exactly all the high frequency components of OCR. Torsional nystagmus, as generated by a rotating visual field, appears to have a high frequency component that cannot be fully understood or modelled until the dynamics can be extracted from traces of eye position curves. The sampling theorem would dictate that many of the torsional saccades are missed and that it is impossible to even

measure slow phase velocities. Measurements made by Edelman (1979), using a video system, indicate that even a 60 Hz sampling rate is questionable in obtaining the frequency response of the system.

3) Accuracy: The system appears to work well for measuring the angular displacements induced with a rotating visual field, but it may not have the resolution to accurately determine deviations of less than 1° . It is valid to ask whether this is needed in any case. As reported by Miller (1962) and later authors, there appears to be an amount of noise in the eye positioning system. Exact repetition of conditions in varying the GIF does not necessarily produce the same amount of OCR, even in the same subject on the same day. This noise, presumably not introduced by the measurement system, is on the order of $1-2^\circ$. Therefore, as long as the measurement system is better than the noise factor, the underlying results will be obtained through the averaging methods involved in most types of analyses. It is therefore felt that of the three drawbacks listed, only the first two are of real concern.

2.2 Circularvection

The termvection or CV was first used in 1930 by Fischer and Kornmüller and by Tschermak when referring to the perception of self angular motion created by viewing a rotating visual field. This 'illusion' can be generated around all three body axes; pitch, roll and yaw, given the proper stimulus (Young and Oman, 1975). Not until the 1960's and '70's, however, was any physical importance placed on the role of CV and OCR. Even today, the amount of reliable information on the interaction of CV and OCR is limited. A considerable amount of work has been done in yaw CV, that is, motion around the vertical body axis. It has been documented (Dichgans, Young, Huang, Zacharias, to name a few) to generate nystagmus motion in the eyes, and to show adaptation characteristics similar to those created in self angular rotation. The close relationship between thevection sensation and the generated nystagmus, however, is still under question. For example, Brandt et al. (1973) state "vection is basically independent of the direction of eye movements". This was demonstrated in yaw CV by presenting a small central pattern moving in one direction and a peripheral field moving in the opposite direction. Circularvection was dependent on the peripheral field while nystagmus was dependent on the central. In rollvection, however, this independence has not been shown.

In fact, a previous work reports the opposite conclusion. Finke and Held (1978) report that ocular torsion, as they call and measure it, is a function of the viewer's state, with more torsion occurring in State 2. They have defined states as: State 1 - Observer experiences

self motion opposite in direction to the observed field; State 2 - Observer feels no self motion and only sees the moving visual field. Their method of OCR measurement, however, can be questioned. They use an after-image technique of flashing a bright bar of light on the subject's eye, and have him align a pointer along the after-image created. It is presumed that this can accurately reflect the amount of ocular torsion induced by the rotating visual field. Fluor (1974) has concluded that this technique leads to a large uncertainty and there is some evidence that after-images induce perceptual phenomenon (Aubert-Muller effects) which may cause faulty compensatory eye movements. In addition, this method presumes a steady and slow rolling movement of the eye and is unable to measure or even account for the rapid torsional saccades seen in this investigation. The results obtained by Finke and Held are therefore open to further study and thus provide some of the motivation for this present investigation.

The limited number of works studying circularvection about the line of sight - roll circularvection - is one of the reasons for the lack of clear knowledge on the subject. Beyond the work just mentioned by Finke and Held (1978), no work has studied CV and OCR in a supine position. It has been studied in an upright or standing position, where the feeling of self motion at a constant tilt becomes quite paradoxical. When standing erect, the otolith organ is thought to mediate the system and prevent the sensation of continuous motion. If continuous motion were accepted, it would necessarily have to be accompanied by a sinusoidally varying utricular otolith cue (Dichgans et al, 1972; Held et al, 1975). This perception of tilt can also be mediated by affecting the effectiveness

of the otoliths to discern vertical by placing them out of their optimal horizontal plane (Howard and Templeton, 1966; Young, 1974).

It is clear that the complex visual vestibular interaction is not fully understood. To this end, several studies have looked to understand which "division" of the visual system interacts with the vestibular system. As reported in Perception (Held et al., 1978), "The retinal periphery as opposed to the center of the visual field dominates the perception of stationarity as well as CV (Brandt et al., 1973), roll vection (Dichgans and Brandt, 1974; Held et al., 1975) and linearvection (Lestienne et al., 1977)." Specifically, in studying CV about the yaw axis, Brandt et al (1973) state, "stimulation of the central visual field up to 30° in diameter almost never leads to CV, whereas exposure of the same stimulus to the retinal periphery may be quite effective. Conversely, masking the central field up to 60° in diameter doesn't impair CV and diminishes the apparent self motion velocity only slightly with the mask subtending 120°." This statement was also under investigation in this study since it appears to be in contradiction with studies by Finke and Held (1978), Wolfe and Held (1978) and Merker and Held (1977), who used visual fields of 122°, 100°, and 130° respectively to generate OCR and CV. These three studies found the illusion to be quite satisfactory even with the limited visual angle. Brandt himself used a visual field subtending only 132° in a research project on "Foreground and Background in Dynamic Spacialization" (1975) and found this to be an acceptable visual stimulus.

One other question appears in trying to find the optimal rotation speed and pattern to induce CV about the line of sight. Three papers of

Held et al mentioned previously used rotation speeds of 40°/sec, 27°/sec and 20°/sec respectively. Brandt et al. (1975), on the other hand, used a rotation speed of 50°/sec. All found saturated vection, where the observer perceives self motion and sees no motion on of the visual field. The patterns used were similar. The first three used a pattern of 'visual noise', small irregular white speckles on a black background. The Brandt study was aimed at finding the optimum pattern. His choices were randomly distributed contrasts ranging from 1 to 72% coverage with each single contrast composing 1/4% of the total area. He reports "visually induced self motion is saturated when about 30% of the visual field is moving." The importance of this finding beyond the phenomenological level is questionable. Brandt's work finds the background and periphery to be of greatest importance in spatial orientation. Why?

Wolfe and Held state that OCR or ocular torsion, as they call it, is mediated by a different process than CV. Finke and Held complement this by stating that ocular torsion is driven by self perception of tilt and that this is independent of the "competing inputs provided by the vestibular system". This finding, however, is questioned in the light of the methods used. The OCR method, as described earlier, was quite subjective and limited in accuracy. The measurement of subjective tilt was used in both a standing and a supine position. Yet it is documented that supine viewing of a rotating visual field causes continuous self motion about the visual axis (Dichgans et al, 1972; Young and Oman, 1975). This tilt angle measured, therefore, has little or no reference to the experienced motion. In contrast to the finding of Finke and Held, Merker and Held report that OCR induced by head tilt and field rotation

sums in a predictable fashion, indicating that the process is indeed vestibularly driven in part.

In another vein, the question is posed, "What is the reasoning for the static OCR observed by Miller (1962) and others?" Has it evolved as a method of keeping the visual image fixed on the retina? It can't possibly account for full head rotation, but the eye appears to be able to counterroll equivalent to small head rotations that would be common in everyday survival movements. But are the OCR movements seen in VIR driven by the same mechanism? The central nervous system (CNS), viewing a visual field rotating in a clockwise (CW) direction, could interpret the visual information as indicating that the observer was falling counterclockwise (CCW) or to the left. This action would elicit, in turn, a counterrolling of the eye in a CW direction, opposite to the direction of supposed fall or tilt, and in the same direction as the rotating visual field.

Most of the discrepancies and questions in the literature will be addressed in one form or another in this thesis. The OCR measurement system was improved upon in hopes of getting higher resolution and a faster sampling rate and at the same time eliminating the subjective measures commonly used. The work was done on subjects in 1 g, 2 g, and zero g environments, with more work proposed for all conditions in hopes of exactly sorting out the gravitational influences and thus otolith influences on CV and OCR. Conditions were kept as constant as possible, but refinements were made as problems came up or improvements were suggested. The overall objective was to fully document the phenomenon as observed and to attempt to postulate reasoning for the underlying causes.

2.3 Motivation

The question may well be asked - 'Why bother studying the phenomena of CV and OCR in VIR?' What is it going to tell us that we don't already know? Studied strictly by itself, probably not all that much, but seen in the light of many other research projects dealing with this and similar phenomena, it is hoped that we may gain a better understanding of the vestibular system and man's ability to utilize it.

The visually induced roll experiment is an integral part of a Vestibular Experiments Package proposed to NASA in 1976 by Professor L.R. Young and coinvestigators of the Man Vehicle Laboratory/Center for Space Research at MIT and by the D.C.I.E.M. in Canada. The package was selected for flight onboard the ninth Shuttle mission - the first scientific and life sciences mission. The seven experiment package is designed to cover several aspects of man's adaptation to weightlessness, with the overall scientific question being: "How does a fully developed sensory-motor system, which receives partially redundant information from several sensory mechanisms, reorganize to account for the loss of usable information from one channel because of environmental variation?"

The seven experiments, out of 100 total experiments being flown, are to be repeated several times, or are continuously recorded throughout the mission, in order to obtain the desired adaptation information. The experiments are:

1. Measurement of perceived velocity during linear acceleration on the Space Sled.

2. Measurement of eye deviation and ocular counterrolling during acceleration on the sled.
3. The perception of self motion and ocular counterrolling induced by a rotating visual field.
4. Awareness of body image and spatial localization.
5. The timing of lower leg muscular activity during "hopping" and during constant velocity and constant acceleration "falls".
6. Susceptibility to motion sickness.
7. Pre- and post-flight vestibular tests.

Experiment number 3 provided the impetus for this thesis. The objectives of experiment 3 are two-fold: (1) to quantify the latency and magnitude of the sensation of VIR, and (2) to measure the OCR associated with VIR. The hypothesis is that in zero g, the latency of onset of CV will decrease, the feelings of vection will be stronger, ocular counterrolling more prevalent and the subjective measurement of rotation speed closer to the actual visual field speed. In all, it is hoped that by watching the adaptation of man to weightlessness over a seven day period, some valuable information can be gained on man's use of his vestibular signals. Again, the question can be asked, why?

One reason is the continuing quest for knowledge. Man is always in search of the unknown, and is continuously questioning his surroundings and experiences. Why does man get seasick? Carsick? Planesick? Or most recently, spacesick? The motions induced in these activities are surely not more severe than running through a jungle, swinging on a vine or wrestling, yet have you heard of a single incident of motion

sickness caused by running? It is only since man has created alternate means of transportation that any such symptoms have been recorded. Strictly speaking, there is little known about man before he could travel, at least by sea or camel. But there is no evidence of animals getting motion sick in their own environment. Motion sickness can, however, be generated in nearly all species when they are exposed to external, unanticipated motion. The vestibular system is a very well adapted system that has evolved over the course of evolutionary history. And on this time scale, man's venture into these alternate transportation or motion devices has come in a short span, much too short to allow for any evolutionary changes or adaptations. Most people are able to overcome the feelings of sickness in cars and everyday activities simply by experience and prediction. It is the unexpected motions that tend to disturb the vestibular system and cause nausea. First time air travelers are much more prone to air sickness than are trained pilots.

In the most recent mode of transportation, space travel, there have been numerous reports of motion or space sickness in both Russian and American missions (Table 1). As can be seen from the table, not all travelers get sick. There were no reports of nausea of any type on the early Gemini and Mercury missions. Several explanations are available. The vehicles were small and the astronauts strapped down for the most part. Work loads were high and all were experienced test pilots with a great deal of experience with similar sensations. As vehicles got larger, - Apollo, Skylab and Soyuz - the number of incidents increased, as did the number of inexperienced pilots. Scientists began

SPACE SICKNESS IN MANNED SPACE FLIGHT PROGRAMS

as Compiled by C.M. Oman, MIT.

UNITED STATES

<u>PROGRAM</u>	<u>NUMBER OF CREWMEN</u>	<u>MOTION SICKNESS INCIDENCE</u>
MERCURY	6	0
GEMINI	16	0
APOLLO:		
COMMAND MODULE	33	11
LUNAR SURFACE	12	0
SKYLAB	9	5
SOVIET UNION		
VOSTOK	6	1
VOSKHOD	5	3
SOYUZ AND SOYUZ/SALUT	55	22

TABLE 1. Incidence of reported Space Sickness

to fly as experiments became more involved and required more technical expertise.

It was found in the longer duration missions that the motion sickness symptoms (elicited as pallor, sweating, dry mouth, yawning, nausea, retching, or vomiting) went away after five to seven days, and thus hampered only the early part of the mission. Considering, however, that the nominal mission for the Shuttle - the mode of space transportation for the near future - will be seven days, space sickness will be of extreme consequence, especially in an emergency. Light nausea can cut a crewmember's workload ability in half, if not more, and in the event that a pilot was sick, landing could be altogether out of the question. With individual maneuvering units in the planning stages, the picture could get much worse.

What are the solutions? Anti-motion sickness drugs appear to be a quick, easy answer, but they have several drawbacks at present. They are not universally effective, just as everyone is not equally susceptible. They also have side effects, as do many drugs, which vary with the individual, the day, and the drug. Drugs are not exactly satisfactory because they are trying to affect a system that is not fully understood. Therefore, the only solution is to attempt to understand the vestibular system, how it works and passes information on to the brain, and, in turn, how the brain processes and uses this information to balance, move and carry on normal bodily activities.

It is obvious that the brain is capable of adapting to weightlessness within a week, or immediately in some cases, but what are the mechanisms used to effect this change? Without going into great detail

about the mechanics or exact transmission characteristics of the vestibular system, some understanding is needed to see how gravity could affect the system. The vestibular system is composed of two essentially redundant systems, each located in the inner ear (Figure 1). The semicircular canals (SCC), oriented orthogonally to each other, sense angular accelerations in all planes (Wilson and Melvill Jones, 1979). The system should be essentially independent of gravity and only referenced to inertial space. The SCC system, which includes transfer paths and the CNS, has been modeled as a second order feedback system with two important time constants (Young and Oman, 1969) (Figure 2). The first is the latency time for sensing a step in acceleration, on the order of $1/25$ or 0.04 sec. The second time constant, which applies to the full canal-CNS vestibular system, can be thought of as the time required for the initial sensation of acceleration to die out, even in a continuous spin condition. It's value is approximately two times longer than the time constant for the semicircular canals themselves, and is under debate, but has been approximated at 10-20 sec. Here a value of $1/0.0625$ or 16 sec has been given. This second time constant should play an important role in the latency of onset of vection times experienced in VIR. However, as Young and Oman (1969) state, "While the form of the model is based on what is known about the dynamic characteristics of the canals, the models are of the non-rational parameter type. The mathematics is not intended to reflect any exact physical mechanism in more than a general way."

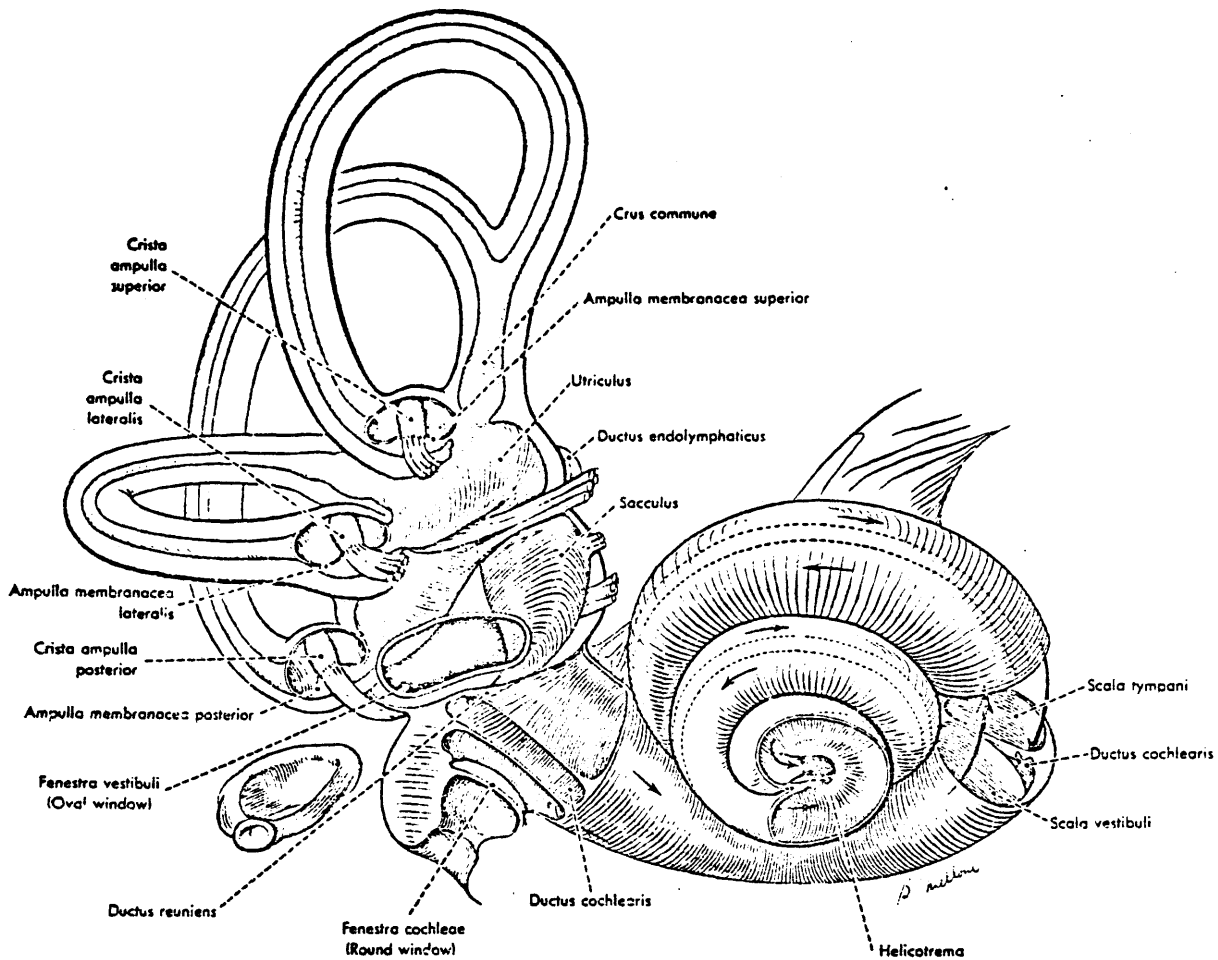


FIGURE 1. The Vestibular System and Inner Ear

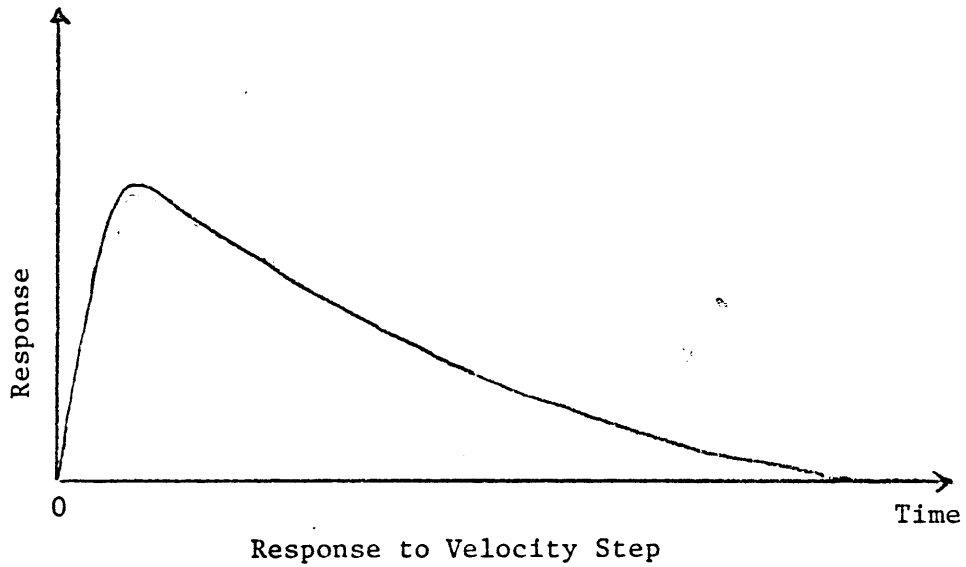
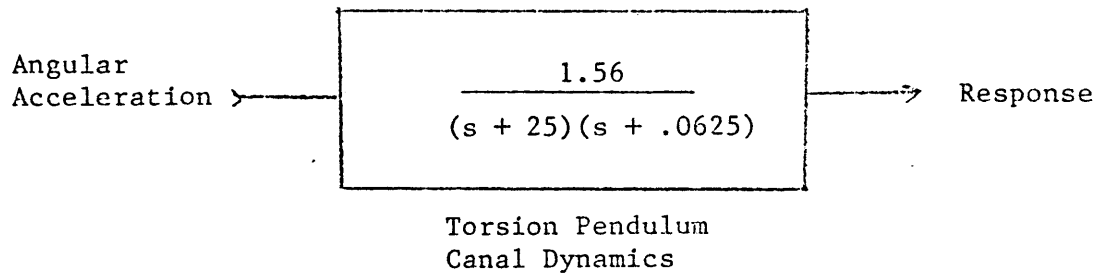
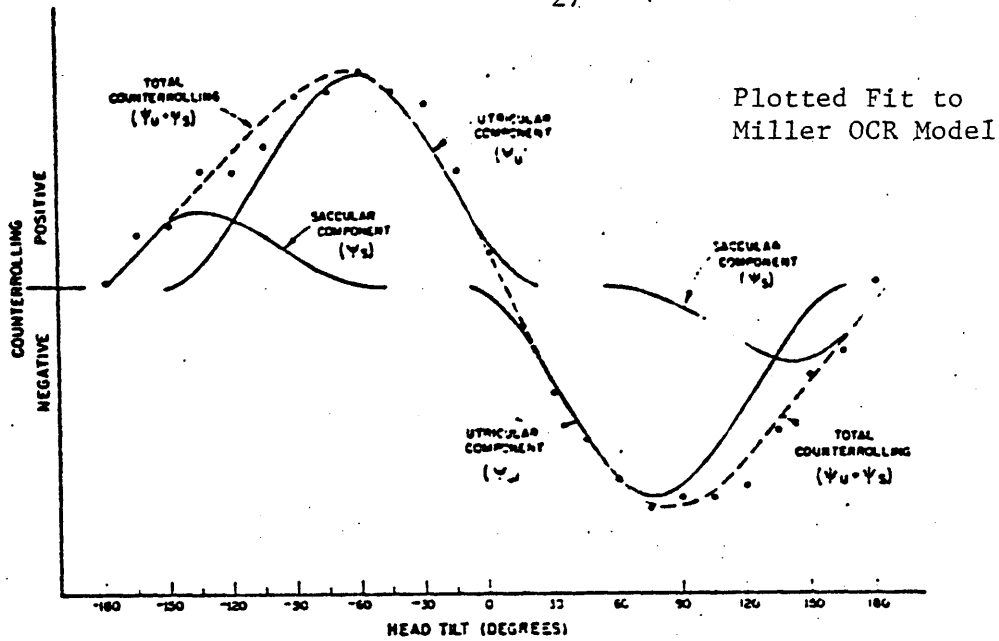


FIGURE 2. Semicircular Canal Model and Plotted Response
from Young & Oman (1969)

The other balance mechanism contained within the inner ear is gravity sensitive. The utricular and saccular otoliths are small linear accelerometers positioned to measure acceleration in all three planes (Wilson and Melvill Jones, 1979). In the absence of gravity, however, the message obtained from an acceleration or from the otoliths in general is erroneous.

Miller (1962) proposed a model for static OCR based on data gathered from slow rolling of a subject with respect to gravity and measuring the induced OCR. The model proposed is strictly a fit to the data and proposes no physiological foundation apart from the known alignment of the related organs. It is shown in Figure 3. As can be seen, it is referenced strictly to the gravity vector, and gives no indication of eye position in zero gravity. A dynamic model for the otolith system as proposed by Young and Meriy (1968) may be more enlightening for the weightless environment. The linear model relating specific force to perceived tilt or linear velocity is also described in Figure 3. This model too, however is based on measurements made in 1 g and may not reflect the motions perceived in zero gravity.

Thus, in weightlessness, motions which appear visually to be perfectly normal, send vestibular cues to the CNS which may be in total contrast. Similarly, while below deck at sea, a cabin will appear fixed with reference to a contained observer, yet vestibular cues may indicate motion of a dramatic nature. These two situations represent similar types of conflict between the visual and vestibular

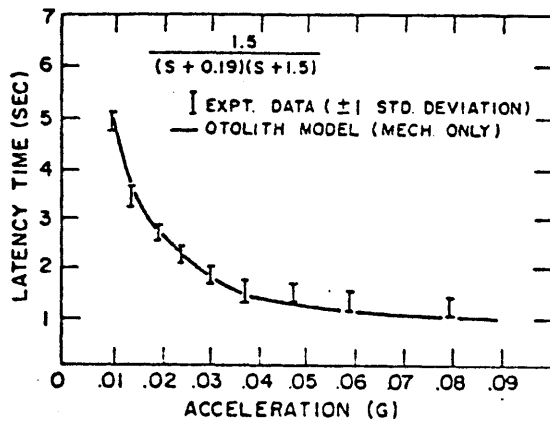
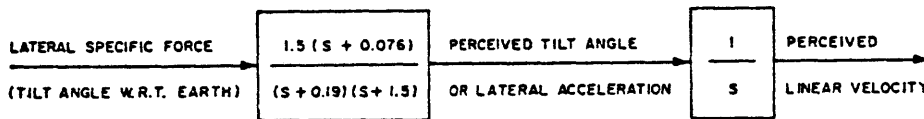


A. Miller OCR Model

designate the angle of tilt α as the angular displacement of the cephalocaudal axis of the head from vertical. Then equations for counterrolling (ψ) for various degrees of lateral tilt can be written as follows:

$$\begin{aligned} \psi_T = \psi_U + \psi_S = & U_R \cos^2(84 - \alpha) - U_L \cos^2(276 - \alpha) \\ & + S.A_R \cos^2(134 - \alpha) - S.A_L \cos^2(226 - \alpha) \\ & + S.P_R \cos^2(158 - \alpha) - S.P_L \cos^2(202 - \alpha), \end{aligned}$$

where ψ_T is the total amount of counterrolling (sum of utricular, ψ_U , and saccular, ψ_S , components) and where U_R , U_L , etc. represent the maximum amount of counterrolling contributed by each macula.



Time for perception of constant linear acceleration

FIGURE 3. Miller Model of Otolith Mediated OCR Response & Young Meiry Model of Otolith Response

systems which often lead to motion sickness. It is hypothesized by Reason, Benson, Oman, Young and others that it is this conflict which produces motion sickness and that with habituation, the conflict and thus the sickness can be overcome. It is the method of habituation that is under scrutiny.

In visually induced roll, a conflict is generated between the vestibular and visual systems. Initially, observers of a constant rotating visual field report only field motion. After a short latency period of 1 to 10 sec, however, the observer reports self motion in a direction opposite the visual field, with the apparent motion of the visual field ceasing. Immediate perception of self motion would necessarily have to be accompanied by a semicircular canal cue indicating a step acceleration in angular velocity. However, constant velocity rotation requires no semicircular canal input since the SCC only senses acceleration. Experiments performed in constant rotation of human subjects about the vertical axis report that after a latency, the subject feels no rotational motion, nor does he indicate any vestibular cues of rotation such as nystagmus (Guedry, 1962; Tole, 1970; Bock, 1979). In the same sense, once the time constants for the SCC have died out, self motion is perceived when viewing a rotating visual field. It is hoped that by watching how the absence of confirming otolith cues in zero g change this vestibular inhibition of VIR that a better understanding of the roles of each organ in the balance mechanism will be obtained.

The static response of OCR is thought to be otolith mediated (Dichgans, 1972; Held, 1975; Miller, 1962; Graybiel, 1968). Yet, in zero g, the otolith organ is rendered useless as a static orientation sensor. Cilia of the otolith no longer remain bent under the influence of gravity and thus otolith influence on OCR is minimized. This is the case for supine observation of VIR in a 1 g environment. The utricular otolith is in its least sensitive position, yet the saccules are still transmitting accurate information. The saccules, however, do not present a conflict to the visually induced self motion. It is hoped that by comparing 1 g and zero g data in both a standing and supine position that further useful information can be gained about the otolith function, its effect on OCR, and its adaptation to weightlessness. Therefore, the data collected in zero g will have two components to match with ground based results. First, free float VIR will be recorded for onset and OCR measurements. (Subjects will be restrained by a biteboard to keep head position constant and allow for OCR measurements.) Second, the same measurements will also be made on a subject who is exposed to the tactile equivalent of a 1 g environment. The subject will don a harness to which are connected four shock (bungee) cords which will exert the equivalent force upon the subject's body and legs that he would experience in 1 g. This should help to sort out the effect of tactile stimulus on the VIR sensations as compared to the strict otolith cue.

To gain additional background knowledge on the effects of tactile stimulus both on earth and in short zero g parabolic flights, an equivalent tactile sensation was generated through foot pressure.



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Adjustable foot restraints were available both in the laboratory and onboard the KC135 aircraft for applying a tactile sensation of down while still lying in a supine or right ear down position, respectively. Although not as effective as hoped, it provides a basis for helping to sort out the influences of OCR and CV in VIR.

CHAPTER 3

METHODS

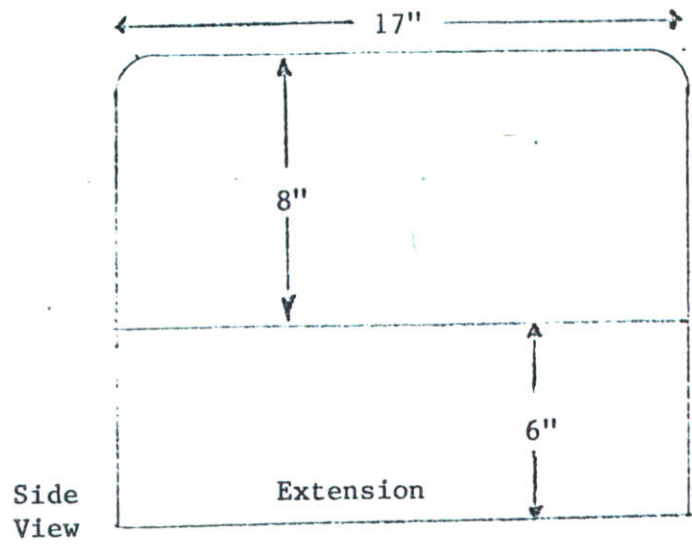
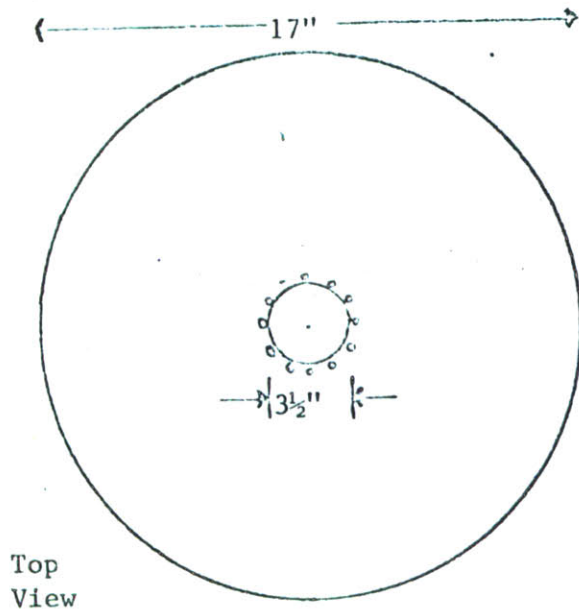
3.1 Visual Pattern

Three separate patterns were used to create the illusion of self motion about the line of sight. For the first crew training and testing of the Spacelab astronauts in February 1979, the pattern consisted of a gray anodized aluminum background with a 3% coverage of 1/4" diameter random black dots. Second, for the parabolic KC-135 flights, the pattern was a blue and white flowered wallpaper pattern inserted on the front face in an annulus around the OCR camera and cylindrically around the dome extension (Figure 4). Viewing for the above two patterns was monocular and depth of field limited to 8 inches. The third pattern used in the final testing in September 1979 and for later laboratory subjects was a white background with 20% coverage in six colors of randomly placed 3/4" diameter dots (Figure 5). In addition, the depth of field was increased to 14" and viewing was changed to binocular.

The colors chosen for this final pattern were fluorescent green, fluorescent red, dark blue, light blue, dark red, and dark green. The size and coverage of dots followed from a paper by Brandt et al. (1975) who found 30% coverage to be optimum (with 10 and 72% being his two nearest comparisons) with 0.25% of total area per dot. In our configuration, this led to each dot being 0.886" in diameter, which was approximated with 3/4" diameter Avery labels. They were affixed in a random manner over the entire surface with equal numbers of each color presented. A separate study performed after the KC-135 flights was



FIGURE 4. Photograph of Dome Pattern & Apparatus on KC-135 Flights



Camera and Ring Flash

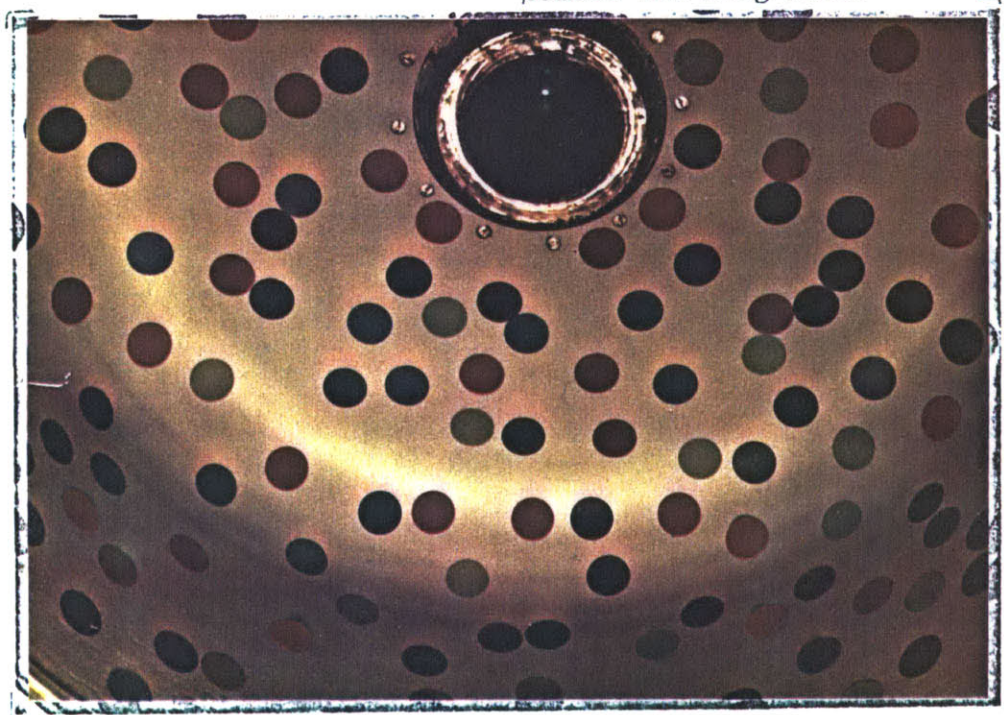


FIGURE 5, Photograph of Present Pattern and Dimensioned Dome.

aimed at correlating visual pattern, viewing style, and vection quality. It is discussed in further detail in Section 4.3.

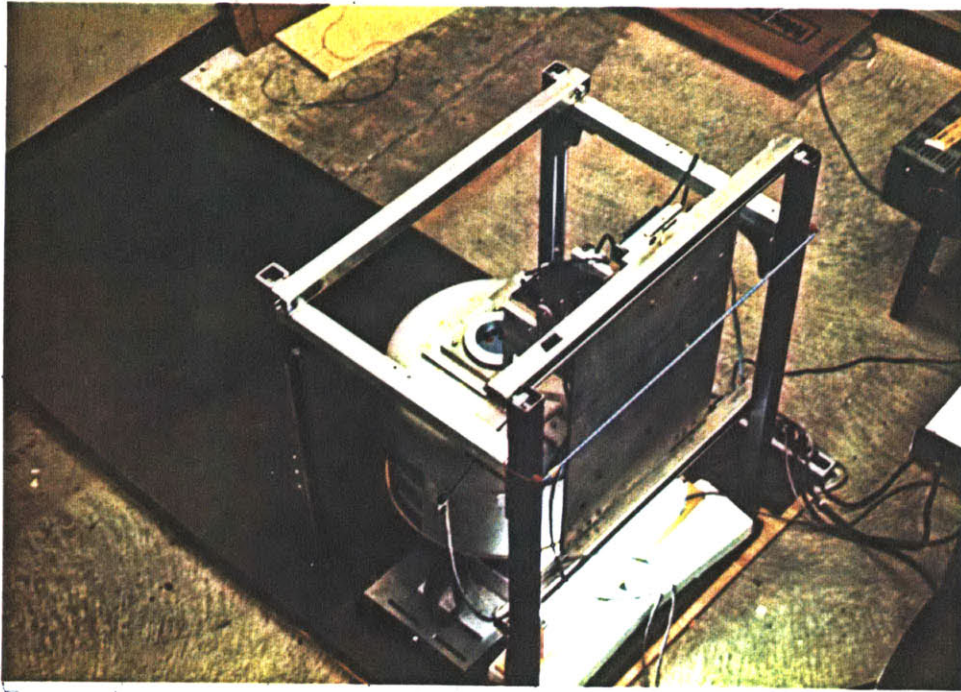
The surface upon which the patterns were placed was a 17.5" diameter 'dome' that is presently 14" deep and thus subtends a full 180° visual angle. The center of rotation is cut out to a 3 1/2" diameter (13.5° visual angle) through which a circular ring flash and 35 mm camera are visible (Figure 5). The rotation speeds used to induce vection were 30°/sec, 45°/sec, and 60°/sec, with additional testing performed at 15°/sec onboard the KC-135.

3.2 OCR Data Collection

The methods of data collection for this experiment were fairly simple. For the 1 g laboratory testing, the dome and apparatus were mounted on four legs (Figure 6). The subject lay supine under the dome, with his entire field of vision filled by the random pattern on the inner dome surface. His head position was fixed with a foam and aluminum headrest. Positioning was not a severe problem in this case since no subject movement was involved.

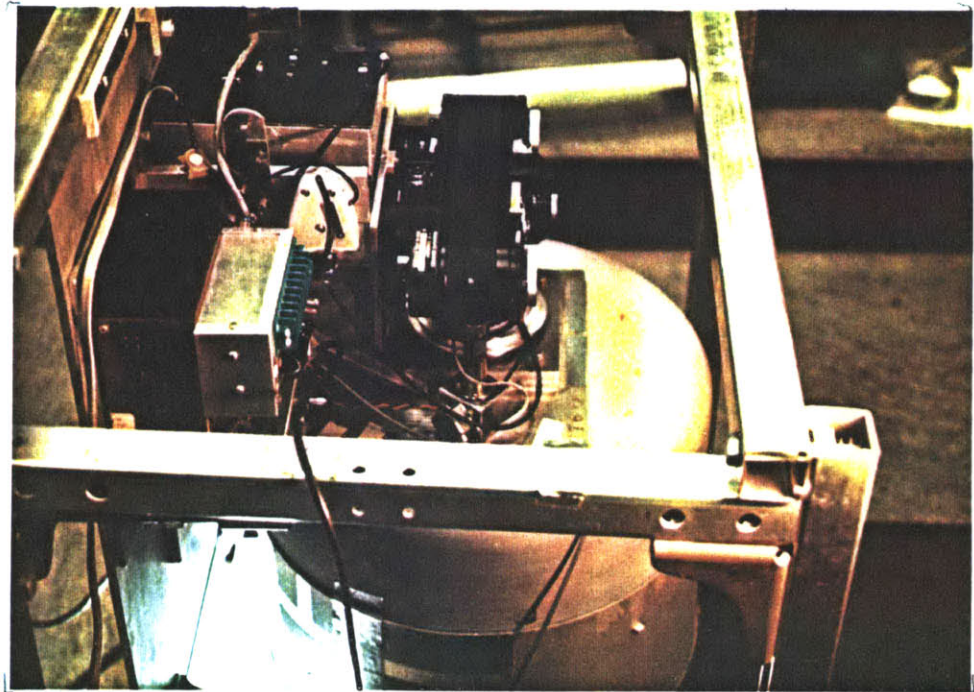
A Nikon F2 35 mm camera, equipped with a 105 mm microlens, 250 frame film magazine, motor drive, and circular reworked Honeywell Prox-O-Lite ring flash (Figure 7) were mounted through the center of the dome so as to have a full view of both of the subject's eyes. The visible camera lens and ring flash subtended a central visual angle of 13.5° at a distance of 14". Early experimentation involved using only monocular vision and recording. The second eye was covered with a patch and the focal area was reduced with a PN-1 extension tube to include only one eye. This method was abandoned for several reasons. Binocular photography provided more focusing range, greater depth of field, bettervection with binocular vision and more available light, as well as providing the added binocular data.

The protocol used in data collection remained constant over all subjects. Each subject was exposed to six dome runs of three speeds (30, 45, and $60^\circ/\text{sec}$) in two directions (CW and CCW as defined from the subject's point of view) in random order, each lasting 50 seconds. Vection information was gathered throughout the run - the methods for



Overview of Apparatus

Camera



Power Supply
& Controls

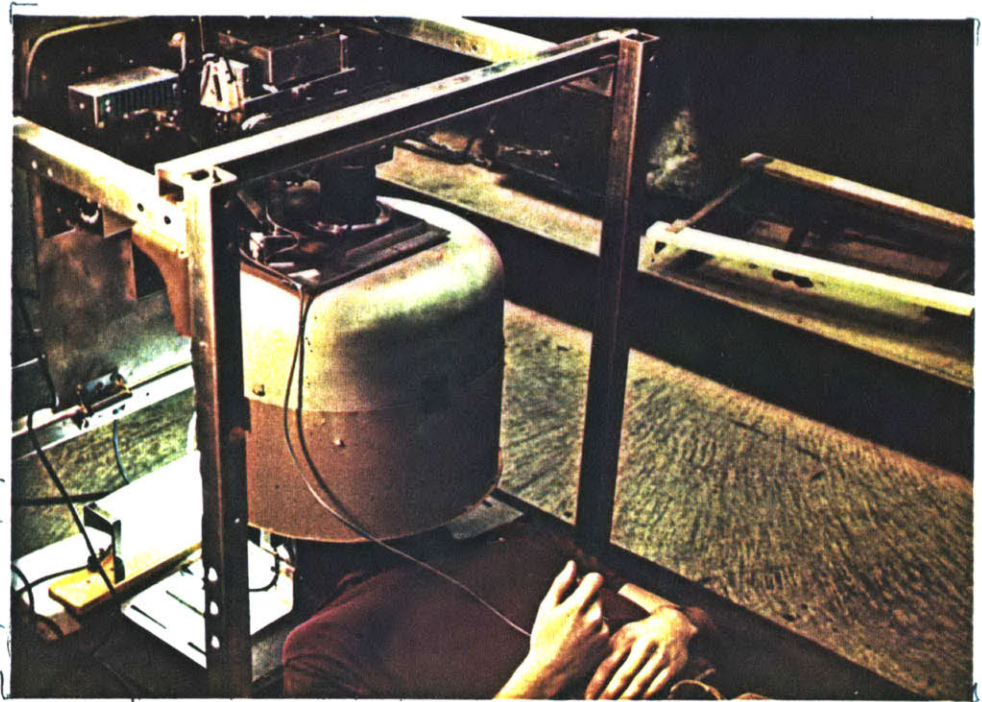
Output Signal to Tape

FIGURE 6. Several Views of Laboratory Apparatus

Dome Extension



Aluminum & Foam Headrest



Background
Light

Subject Signal Button

FIGURE 6 (Cont.) Several Views of Laboratory Apparatus



Camera & Flash
Control

Dome
Control

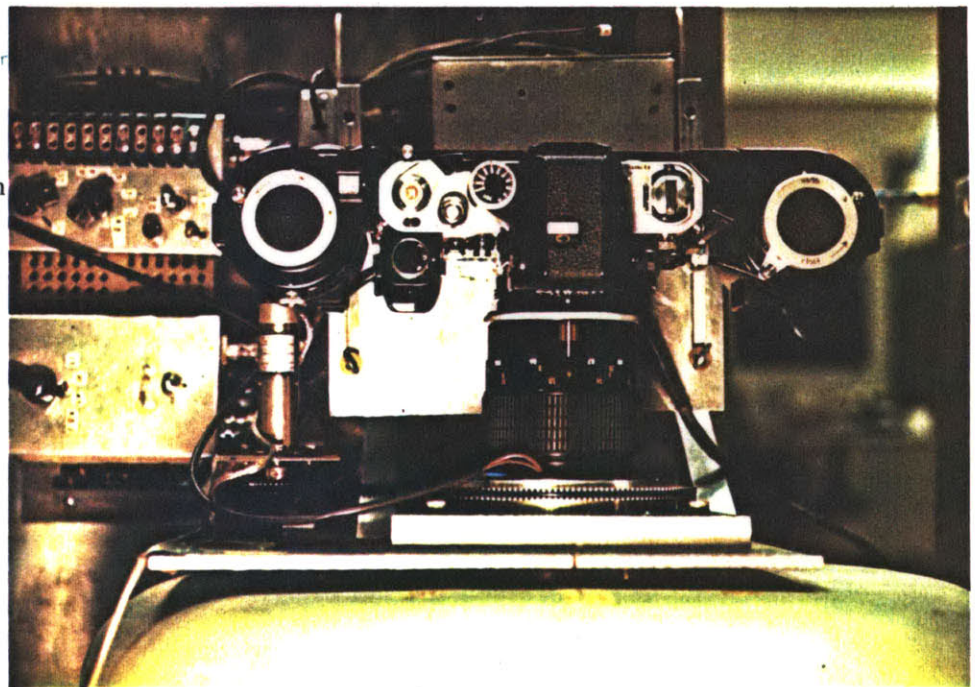


FIGURE 7. Photograph of Nikon Camera used for OCR Recording

which will be discussed later. Photographs of the eyes were taken at a rate of three per second at the following times during the run: beginning at 1 second before dome operation and continuing through the first 2 seconds of rotation, at the 25th and 26th seconds of rotation, and on the 49th and 50th seconds of operation, with the last second of operation (i.e., the last three photographs) occurring after the dome had stopped. This gave 21 photos per run or 126 per session. Each 250 frame cassette could then hold two complete data runs before camera reloading was required.

To provide a reference for monitoring eye movements, subjects were fitted with a bite board fiduciary. The mouth piece was fitted to the subject's upper teeth with Kerr Dental Compound. This assured a tight fit and yet allowed the subject to make comments as to the quality of vection. Two small dots were affixed to the small metal appendages of the mouthpiece. These appendages were then bent to position the dots within the picture frame and at nearly the same focal range as the subject's iris (Figure 8). The subject was instructed to keep the bite board tight against his upper teeth at all times. Thus, the fiducial marks (small dots) remained fixed to the subject's skull and therefore provided two accurate landmarks for determining a reference line from which to measure counterrotations of each eye. This is felt to be a major improvement over a previous method adopted by Graybiel (1959) of affixing landmarks to the skin near the eye, as these were subject to a great deal of movement with respect to the skull.

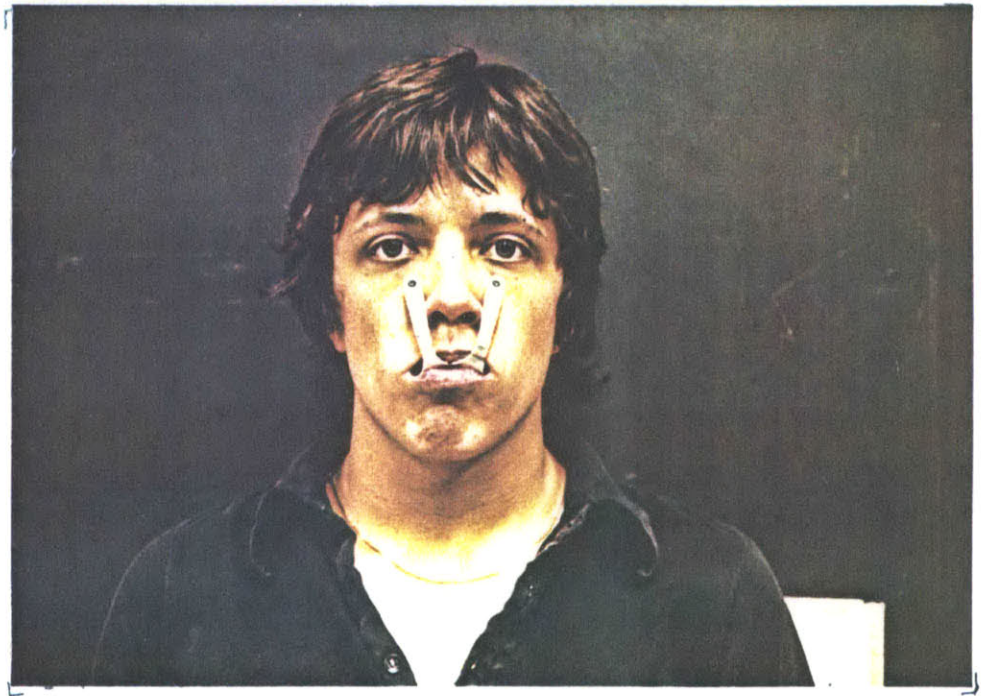
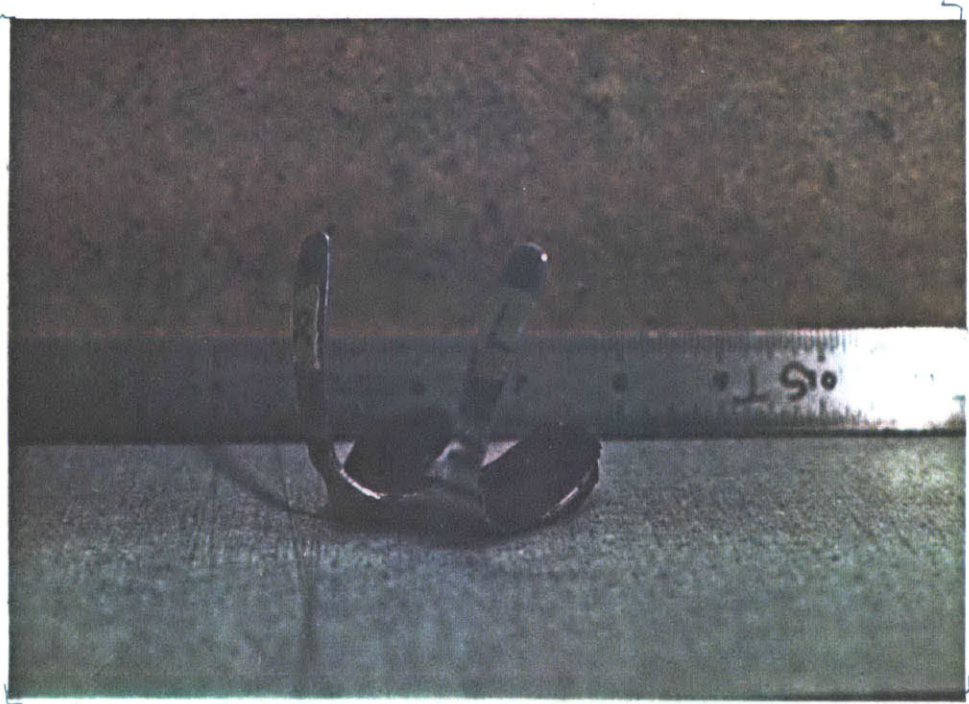


FIGURE 8. Mouthpiece and Fiduciary
Scaled and in Place Photographs

The subject was also instructed to maintain a constant gaze into the camera lens: subjects either chose a reflective spot on the lens, the shutter, or 'focused on infinity' through the camera lens, whichever they preferred. This kept the influence of eye position and gaze on vection to a minimum, and thus improved the repeatability of the experiment. It also kept eye movements from interfering with the analysis of the data. As pointed out by Miller (1962), it is easily seen that moving the eye horizontally through a large angle could produce distortions in the actual angle seen between two landmarks when the eye is projected onto a flat screen, as it is in data reduction. These distortions were assumed to be negligible in the data analysis. Another previous source of error and concern in photographic OCR analysis, film slippage, was not present in this study. This was a concern of Miller's (1962) and was eliminated as an error here since this method of analysis removed film orientation from the calculations, which were strictly based on fiduciary versus eye angle. In addition, film stretch was considered negligible or, at worst, a constant over all measurements.

3.3 OCR Analysis Methods

The photographic film used in the 35 mm camera was Kodak Ektachrome color film for slides with an ASA rating of 200. It was shot at F-4 for brown eyes and F-5.6 for blue or green, at an ASA setting of 400. The 250 frame cassettes were then developed by Image Maker Inc. (440 Summer St., Boston, Mass.) through a bulk processing method. The film was processed and 'pushed one stop', a photographic term for over-developing, since we had purposely under-exposed it during shooting. This produced slightly more grain in the film, but brought out as many landmarks as possible. The film was returned to us as full length rolls, which prevented any mis-ordering of frames and allowed the film to be spooled for analysis on the Hermes Senior Film Analyzer (HSFA). Each frame was numbered with a four digit number and correlated with vection data as to time and sequence of exposure.

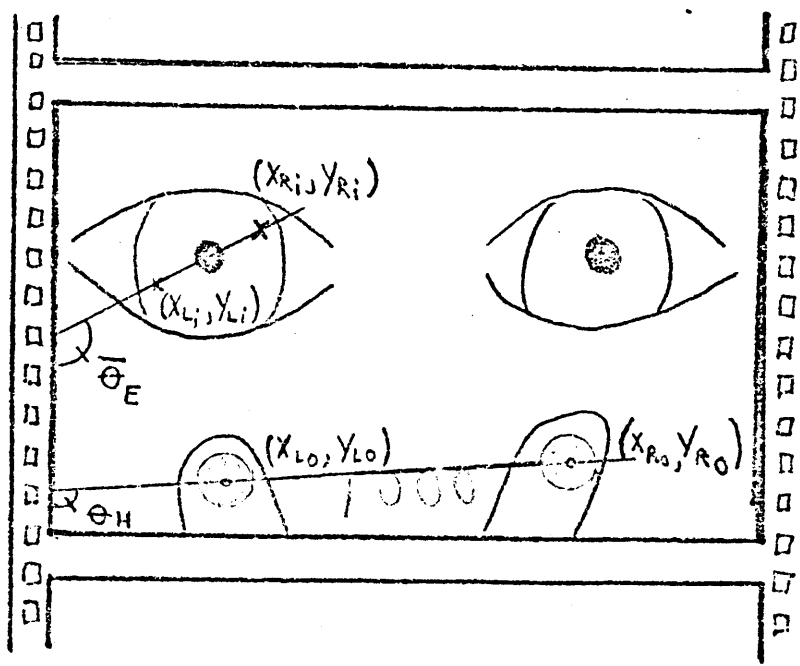
Time on the HSFA was rented from the MIT Lab for Nuclear Sciences (LNS) (in the Polaroid building at Technology Square, Cambridge) and scanners were then hired to run the analyzer for data reduction. The HSFA enables the images on photographic film to be accurately plotted on an x-y scale. The rolls of film are motor driven and positioned for analysis by a vacuum system. The film images are blown up 50 times and displayed on a screen 64 cm by 64 cm. The operator or scanner locates identifiable landmarks on the eye by positioning the x-y film table beneath a central crosshair, and enters their position into the HSFA, which is connected to a PDP 8 computer for data storage. The scanner first enters the frame number and then the reference angle from

the two points on the fiduciary marks which are securely fixed to the head via the aforementioned biteboard. The scanner next picks two iral landmarks located on opposite sides of the eye which appears on the left side of the screen. (Because of the reversals created by photographing upside down, numbering frames on the backside of the film for permanence, and magnification in the HSFA, this is actually the left eye projected as it would be seen in a mirror.) Scanners were instructed to choose points located as closely as possible to the horizontal. This prevented the landmarks from being obscured even if the eyes were partially closed, and kept the angles measured from being near the singularity in the tangent function used to calculate averages in later analysis. The scanners were also instructed to choose points located as far radially as possible from the pupil. This kept the variations due to pupil constriction to a minimum. Further discussion of this subject is contained in Section 4.5.

The scanner repeated entering each iral landmark into the HSFA four times, thus giving repeatability, resolution and accuracy information from the standard deviation of values obtained in further analysis. The analysis programs used later allowed for more or fewer data points, since it is extremely easy to lose track of the number of repetitions entered. The scanner then went on with the same procedure on the other eye, and then onto the next frame. The nature of the work necessitated working in short segments, so the scanners were requested to sketch the landmarks used in each session for identification when returning, in order to retain initial position information. The volumes of data collected, however, necessitated the use of several scanners,

so each scanner change repeated the previous three frames to reference the base angle. A further discussion of this topic is contained in Section 4.4.

Data from the HSFA was stored on magnetic tape and then transferred out of LNS to the Joint Computing Facility VAX computing system on cards. A Fortran program entitled BINOCIN (Appendix A) originally written by Anthony Arrott and revised to eliminate propagation of errors, was used to divide the binocular data into two files, each formatted for monocular reduction by a later program. (This method was chosen since earlier OCR recording had been monocular and thus the monocular program was already in existence.) The two files created for data from left and right eyes were then run through a Fortran program entitled SCANOR3, also written by Anthony Arrott (Appendix B). This program calculated the fiducial angle, average eye angle and standard deviation of the angle from the x-y coordinates as plotted on the HSFA. Whereas now each file contained the identical fiducial information, the program used the following equations for calculating averages and standard deviations with the variables defined in the sketch below.



where:

θ_H is head angle with respect to the camera

$\bar{\theta}_E$ is the average of four repeats of eye angle with respect to the camera

and $\rho = \bar{\theta}_E - \theta_H$; therefore $\rho =$ eye angle with respect to the head.

The formulas are as follows:

$$\theta_H = \tan^{-1} \left[\frac{Y_{R0} - Y_{L0}}{X_{R0} - X_{L0}} \right]$$

$$\bar{\theta}_E = \tan^{-1} \left[\frac{\frac{4}{\sum_{i=1}^4 (Y_{Ri} - Y_{Li})}}{\frac{\sum_{i=1}^4 (X_{Ri} - X_{Li})}{4}} \right]$$

The following equation is used to determine the standard deviations of the angle obtained in the four repeats taken on each iral landmark:

$$\sigma_\theta = \left[\left((\bar{X}_R - \bar{X}_L)^2 + (Y_R - Y_L)^2 \right)^{-1} \left[\sin^2 \bar{\theta}_E (\sigma_{X_R}^2 + \sigma_{X_L}^2) + \cos^2 \bar{\theta}_E (\sigma_{Y_R}^2 + \sigma_{Y_L}^2) \right] \right]^{1/2}$$

Angles determined by this algorithm resulted in a sign convention such that positive changes in ρ from one frame to the next indicate counter-clockwise rotation of the eye with respect to the head as seen from the subject's point of view.

The output of SCANOR3, used to perform the above calculations, was divided into two files. One, labeled Filename.ANG, provided the frame number, measured angle, and calculated standard deviation. The other, labeled Filename.SCN, printed out the fiduciary points (in millimeters of distance across the film), four repeats of the landmarks used, average and standard deviation of the four repeats, along with head angle with respect to film, eye angle with respect to film, eye angle with respect to head, and standard deviation of this eye angle. This file was helpful in sorting out caused for 'wild' points in the data, which were usually a result of mis-entered points or scanner keypunch errors.

Individual plots of eye angles were done on a Varian plotter from the `***.ANG` file. A program entitled PLOT allowed for adjustment of the axes to include only data points within a given run, and to allow scaling for varying amounts of OCR. The program also allowed for labeling of both axes. Frame numbers, however were limited to a three digit number on the scale, and thus a constant factor is added to the label for identification. The program could not plot standard deviations, but the values were available on file. Extra data points may appear on individual graphs since PLOT only allowed for X-axis scaling in 2's or 5's, depending on the number of points requested per plot. Scale factors for OCR were varied between runs, but were kept constant for left and right eyes on any single run. This allowed for easy binocular comparison. OCR scales generally range from 7 to 14 degrees.

Data files collected during the course of this project began to use up large amounts of disk space at the Joint Computer Facility and

were therefore transferred to magnetic tape (labeled TAC01) for permanent storage and future reference. Raw data from LNS is under files labeled DOME01.RAW - DOME08.RAW. Separated files for the right eye are under DOMER01.DAT - DOMER08.DAT or RDOME1.DAT - RDOME8.DAT

ANG	ANG	ANG	ANG
SCN	SCN	SCN	SCN

Data are stored similarly for the left eye.

3.4 Vection

The illusion of self motion created by the rotating visual pattern was recorded through a subjective position switch. Subjects were instructed to depress the spring loaded button twice when they first began to perceive self motion, whether it was saturated or not. Saturation was defined as self motion in which the visual field appears to come to a complete standstill and it is only the observer who is rotating. In unsaturated vection, both the observer and visual field appear to rotate in opposite directions. The subjects were also instructed to depress the button one short time each time they felt that they had rotated through 90° relative to the room. This allowed us to determine whether vection was saturated or not, as velocities would be lower in unsaturated vection. This instruction was later changed to 1 button push for every 45° . It was found, especially on the KC-135 flights, that with 90° measures, it was easy to lose reference to where the last button push appeared. A study was done to compare these two methods (i.e. 45° vs. 90° button pushes) and is discussed in Section 4.1. The third instruction to the subjects was to depress the button two long times when the sensation of self motion ceased, called a drop out. (As has been reported in previous works, the illusion of self motion comes and goes with little known about the cause.) In addition to the signal button protocol, the subjects were provided with a microphone for recording subjective comments on the quality of vection and on any additional experienced after-rotation seen or felt.

The button pushes were recorded on magnetic tape and later transferred to strip charts for analysis. The channel carrying the vection information also contained the flash pulses from the camera superimposed over dome speed and direction information. The schematic for the electronics package, worked out by Robert Renshaw, is contained in Appendix C. It also contains a block diagram of the system, the schematic for the dome controller and the flash unit, and a labeled sample output.

In an attempt to simulate the experiments onboard Spacelab, two full data sets (i.e. six runs of three speeds in two directions) were taken on all the SL-1 science crew members. The order was varied to prevent it from influencing the analysis. On one data set, they were lying supine with feet fully extended to eliminate additional directional cues. On the other runs, blocks were placed between the subject's feet and the wall in order to simulate a 1 g tactile force. This same simulation will be provided with bungees onboard Spacelab. Care was taken that this force did not move the subject up and out of the frame of the camera. Comparisons are made for tactile vs. non-tactile cues in Results chapter.

3.5 Vection Analysis

The analysis of vection data was fairly straightforward. Individual averages were obtained for each subject for onset of vection times, drop out times, and subjective velocity. The velocity information was obtained by taking the average time between button pushes and dividing by 45 or 90°, whichever was being signalled.

Individual averages will be useful for comparison with data collected on the Shuttle astronauts in Spacelab, and to watch their adaptive changes. Lumped averages of all subjects over one speed or condition is useful in determining the overall quality of vection presented by each condition. The actual results are presented later in graphic form.

3.6 KC-135 Methods

The parabolic flights flown on the specially equipped NASA KC-135 presented several problems in both the data collection and reduction. By flying Keplerian or ballistic trajectories, it is possible to obtain approximately 24 seconds of zero g time with an accuracy of within ± 0.05 g. The physics of the system dictate a nearly equal period of 2 g. The time onboard was used to evaluate the OCR and vection phenomenon in both zero and hyper-gravity experiments, both qualitatively and quantitatively, prior to the Spacelab mission. Two sets of flights

were taken - KC1 (as it has been labeled) with Bob Renshaw and Professors Young and Oman as subjects on February 26-27, 1979; and KC2 with the Spacelab Mission Specialists and Payload Specialists as subjects on March 14-15, 1979.

In order to perform both the dome vection OCR study and a separate OCR study during the zero g to two g pullouts, a suitable method was needed to restrain the body comfortably, safely and accurately in a position with the right ear down. This position allowed photographic observation of the effect of 'turning on and off' the gravity vector, similar to lateral accelerations created in the 'space sled'. The second experiment often necessitated turning the dome off prior to pullouts to allow its effect on OCR to diminish before the gravitational effects appeared. Also, total zero g time, on the order of 24 seconds per parabola, did not allow for long runs in which to see good saturated vection, collect much drop out information, or see steady state eye position and the effect the dome had on eye position.

The method adopted for body and head restraint was to use a medical stretcher filled with a Full-Body Immobilizer (available from Picker Corp., Boston, Mass.). The Immobilizer, a bag filled with styrofoam pellets, could be evacuated to form a surprisingly rigid cast which could be molded to fit body contours. Care was taken, especially around the head and neck, to assure proper positioning within the dome and relative to the camera, as well as a safe restraint for the 2 g pullouts. The zero g to 2 g accelerations, however, often caused the subject to move in and out of the frame of the 35 mm camera that was being used to photograph eye position. This movement not only caused the subject

and/or his fiduciary marks to leave the frame, they caused many frames to be out of focus and thus to be impossible to analyze on the Hermes Analyzer.

The same camera and control mechanism were used in the KC-135 as in the lab. The dome, however, was mounted to a locking plate release mechanism that allowed the dome to be slid into and away from the subject's face. This eased the entry to the dome as well providing a quick safety valve for the nauseous subject. (Nearly all subjects reported nauseousness or actual vomiting for some part of the set of KC-135 tests, including those on medication. No subjects were sick during the dome runs however. The topic of drugs is discussed more fully in a later section.)

As in the lab, vection was signaled with the push button. Subjects indicated 90° on KC1 and 45° on KC2 (the protocol change was made after experiencing the reference problem on KC1). The dome was run during 2 g, zero g and transition conditions, with photographs taken intermittently throughout. In keeping with the Spacelab protocol, a system was devised to assess the effectiveness of tactile cues in limiting vection. The system involved two foot pads that could be slid up and down the rails of the stretcher, and could be positioned so as to provide pressure against the bottom of the feet. Unfortunately, they were not as effective as had been hoped because in zero g, the upward force resulted in an equivalent pressure on the upper shoulders. In the 1 g environment, this reaction force was taken up in friction between the subject and the foam pad on which he was resting. Therefore, only a limited number of

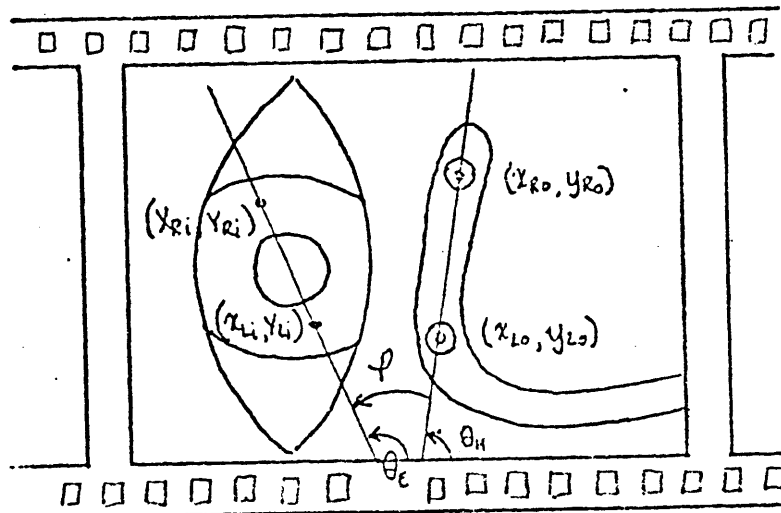
runs were taken in this configuration. A comparison, however, is made between the two conditions in the Results section. In addition, several runs were made, without photography, in a free float position. Subjects held themselves near the center of the dome with the handrails on the stretcher. Little signalling was done for onset times and velocities, but subjective sensation ofvection was recorded and the comments are helpful in gaining an insight into the roles of gravity and tactile sensations created within the confines of the Immobilizer bag.

In addition to the acceleration problem on OCR measurements, two equipment malfunctions caused several data runs to be unanalyzable. The first was a total loss of the voice channel for about 60 parabolas. The second was the loss of the accelerometer trace for several parabolas. These failures went unnoticed until the analysis was performed in the lab.

3.7 KC-135 Data Analysis Methods

The data collected on the KC-135 were analyzed with the same methods as the laboratory data, with a few minor differences. The strip chart recording of the button pushes and camera flashes also contained another channel of accelerometer readings for correlation with the gravity data. The accelerometer contained some drift that was not corrected for after the first calibration. The precision of flight was assumed to remain within the ± 0.05 g range claimed and measured on earlier parabolas.

The other differences between the KC-135 flight data and the laboratory data was in the film analysis. The change to binocular viewing and measurement occurred after the flights. Also, because of the positioning of the subjects relative to the apparatus and the gravity vector, the eye was rotated 90° relative to the camera. The governing equations (see page 46) remained the same for the analysis, with the variables now being defined as in the sketch below.



This rotation, however, led to gross errors in averaging when the landmarks used resulted in angles that were averaged across the singularity in the tangent function. (The preferred horizontal or lateral landmarks were now lying along the vertical axis of the Hermes Analyzer.) To correct for this problem, the singularity in the tangent function was rotated 90° for the analysis.

3.8 Subjects

The subjects used for the experiments were the prospective Spacelab Mission and Payload Specialists from NASA and ESA (European Space Agency), as well as others, both naive and experienced in CV. In the laboratory experiments, the astronauts were all tested twice, once on February 26-27, 1979 and again on September 27-29, 1979. They were: Owen Garriott, Micahel Lampton, Byron Lichtenberg, Ulf Merbold, Claude Nicollier, Wubbo Ockels, Robert Parker and their Life Sciences Coordinator, Gloria Salinas. They ranged in age from 28 to 48, and are all male except GS. These same astronauts were subjects on KC2. The subjects on KC1 were Robert Renshaw, Laurence Young and Charles Oman.

Much of the photographic data on the above subjects was lost for various reasons: (1) The accelerations on the KC-135 flights produced head movements large enough to put many frames out of focus or out of the frame of the camera; (2) Late in the project,

after the dome had been modified to its present high contrast pattern, the flash was found to produce enough light to reflect the random dot pattern onto the cornea of brown eyed subjects. Focusing range on brown eyes was already minimal at F4, making several frames out of focus. This added moving pattern reflection made the eyes impossible to analyze on the HSFA. The blue eyed subjects did not have the same problem as enough light was reflected off the iris to overcome the reflected dots. The rest of the subjects chosen, therefore, were all blue eyed. This is not thought to have affected the data, since no eye-color differences had been seen or reported before. A solution has been worked out for future KC-135, laboratory and Spacelab OCR data collection on brown eyed subjects by placing an extension tube out past the ring flash and thus limiting the amount of light available for reflection off the inner surface. Subjectively, it has little or no effect on vection.

In addition to the above subjects, six unpaid, blue eyed subjects were obtained for further laboratory testing and OCR measurements. They were Charles Oman, Cammy Pane, Robert Renshaw Jr., Patricia Rich, Tom Stephens, and myself. Their ages ranged from 15 to 34, 4 male, 2 female, of which 4 were naive. The methods and apparatus were identical to those used for the astronauts, and as much as possible, the methods and instructions conformed to those to be used onboard Spacelab. Additional subjects were used numerous times for various studies involved in this project and are discussed elsewhere in the thesis.

3.9 Drugs

Another factor clouding the KC1 and KC2 data is the use of anti-motion sickness drugs. Due to the unpleasant 'roller coaster' nature of the KC-135, a priori 60% of all passengers get violently motion sick to the point of vomiting. The rotating visual field tends to heighten this nausea. To combat this, several subjects used anti-motion sickness drugs. On KC1, all subjects took Scopdex - combination of Scopalomine and Dexidrene. On KC2, one subject took Scopdex, while another wore a Scopalomine patch which allows slow diffusion of the drug through the skin.

The exact affect of these drugs on the data is not known, as the effects of the drugs vary from individual to individual and from day to day. Miller and Graybiel (1968) reported the Scopalomine based drugs had no effect on OCR. A final anti-motion sickness drug has not been chosen for flight on Spacelab yet, but when and if the decision is made, a full baseline study will need to be made to determine how each individual is affected.

CHAPTER 4

REPEATIBILITY AND ACCURACY

There are several reasons for which the results and conclusions of this thesis could be questioned. Because of the evolutionary style of this research project, each step and method needs to be compared to the previous methods within the same experiment. There are five major points or changes that could be questioned in terms of the accuracy and repeatability of the experiment. They are; (1) 45° vs 90° signals in reporting vection; (2) monocular vs. binocular vision in OCR recording; (3) varying patterns, lighting, and depth of dome; (4) changes in scanners working on equivalent data; and (5) dilation of the eyes in OCR measurements. Each will be discussed separately.

4.1 45° vs 90° Signals

In a study done November 13, 1979, I compared signalling systems under the dome in an effort to see if there was a major difference or drawback to either a 45° or 90° measure. Eight subjects were used, four experienced in VIR, four naive. Each subject was given two sets of four runs in random order - 2 at 45°/sec, 1 at 30°/sec and 1 at 60°/sec. On one set they were to signal their subjective position relative every 45° relative to the room. In the other set, every 90° relative to the room. The order of the two sets were interchanged between subjects to eliminate bias. No OCR data was collected.

The data was transferred from its original strip chart form to a data sheet. Average velocities and standard deviations were then calculated for all four runs for each subject for each measurement condition. These are listed by subject's initials in Table 2. As can be seen in all cases, subjective measures are slower than actual dome speed with either measurement system. (The actual average for four runs is 45°/sec.) The yes/no criterion on Table 2 indicates whether the signals show a consistent relation to the actual dome speed. In other words, whether the 30°/sec estimate is slower than the 45°/sec estimate, and whether the 45°/sec estimate is slower than the 60°/sec one. In nearly all cases, this relationship does exist, although the increase is not the same for all subjects. The comparison of standard deviations, on the other hand, indicates that a steadier measurement is made with the 45° measures. And although two subjects indicated that they have no ingrained personal preference for 45° as they do for 90°, it appears that this measure is easier at all but the highest speed. At 60°/sec, the measurements came so fast that it was thought by at least three subjects that they locked onto an internal clock which changed only as conditions or sensations noticeably changed. It is also seen that subjective velocities do not change in a calculatable fashion for all subjects when a change is made from 90° to 45° signals. That is, approximately 50% reported faster vection velocities with 90° signals, and approximately 50% reported slower vection velocities. The changes were on the order of \pm 10-20% and overall increase in subjective speed in 90° was 5.2%, not statistically different by t-test standards. Overall, the conclusion was reached

	CO	LY	BW	OB	BK	BL	BR
Average velocity 45°	21.05°/sec	30.65°/sec	18.53°/sec	37.45°/sec	20.42°/sec	33.22°/sec	27.00°/sec
Signals	yes	yes	no	yes	yes	yes	yes
Average velocity 90°	28.27°/sec	25.50°/sec	27.76°/sec	32.00°/sec	33.22°/sec	39.70°/sec	33.65°/sec
Signals	yes	yes	yes	yes	yes	yes	yes
Average standard deviation 90°/45°	0.545/0.377	0.667/0.337	0.672/0.362	0.430/0.287	0.835/0.813	0.385/0.192	0.447/0.240
Percentage change in velocity 45° + 90°	+26%	-20%	+22%	-17%	-9.6%	-16.0	+20%

Table 2: Average and standard deviation of velocity in 45° versus 90° measures

Comments: Assumes 2 45°/sec runs, 1 30°/sec run, 1 60°/sec run; also velocity: yes = relation apparent; no = no velocity relation apparent.

to continue testing with the 45° measure. The change mid-stream in the experiment had little or no effect on the data.

4.2 Monocular vs Binocular Vision in OCR Recording

Prior to the final round of astronaut testing in September 1979, all OCR measurements were monocular. Hence, all KC-135 data is monocular. The subject wore a patch over his right eye and centered his left eye in the frame of the camera. The bite board was one half size and thus connected only to the teeth on the upper left half of the mouth. The fiduciary marks were presented only under the left eye (see sketch, page). A Nikon PN-1 extension tube was used in connection with the 105 mm lens to produce a reproduction ratio of 1:1.5 (2/3 actual size), in comparison to the present binocular reproduction ratio of 1:2.5 (2/5 actual size). It was hoped that by changing from monocular to binocular data that we could have more available light and thus gain an F-stop. This, however, did not occur. The change moved the camera back and thus did give more focal range and depth of field. This aided in focusing, since it had been difficult to get the fine features of the iris clearly in focus for analysis.

Monocular film developing was identical to the binocular case cited before, except for a sign convention change. Film was being numbered with felt markers on the front side of the film. This, however, was changed because of the characteristics of the film coatings. Felt tip markers are permanent only on the back side of the films,

it is easily smudged or rubbed off on the front side. The reversal of film in the scanner therefore caused a sign change in the convention used to determine angles. Thus prior to binocular data, CW rotation of the eye as seen from the subject's point of view dictates a positive rotation of the eye when plotted. The opposite is true for present binocular methods.

In addition, the HSFA had not been modified to the present binocular setup. It had a magnification factor of 20. That is, film was blown up 20 times and projected on the same 62.5 x 62.5 cm screen. This led to iral diameters of 18 cm (as compared to present magnifications of 50 times and pupil diameters of about 23 cm for binocular photos). The iral diameter is the critical value for determining the average standard deviation found in analysis. The larger the iris, the wider spread the landmarks and therefore the more accurately the angle can be measured. The change in iris diameter did not greatly affect the accuracy of the measurement process, which depends more on the carefulness of the scanner. In addition, this 20% change in iris diameter would only produce a standard deviation change that was well within the noise of such a measure.

A change back to monocular data at this time would, however, increase our accuracy. By blowing monocular data up 50 times, and thus approximately doubling the iral diameter, errors and standard deviations should be cut in half. This is assuming best case conditions and no focusing problems.

The actual difference in measured OCR induced by the two conditions cannot be accurately determined since both techniques were not imposed on the same subject under the same dome on the same day. Static OCR values induced from a rotating GIF are known to have inter- and intra-subject variations, and thus a positive statement cannot be made. It was noted, however, that binocular OCR values are slightly but significantly larger than those obtained with monocular viewing, and that calculated standard deviations are on the same order of 0.2 to 0.8 degrees.

4.3 Varying Patterns, Lighting and Depth of Dome

A study done in April, 1979 after the KC-135 flights, sought to determine the effect of various visual patterns on vection, and to choose the best one for further vection studies. Several suggestions were listed as possible causes for the poor vection created by the existing dome.

Type of vision: We had been testing with monocular vision.

Colors in the dome: We had black on gray and blue on white wall paper.

Fixation point: We had just instructed the subjects to gaze into the camera lens,

Amount of lighting: The back-lighting was low and didn't lighten the gray surface well.

The list goes on to include the shape of the dome, the percentage of coverage of the dome surface, type of pattern, and depth of field.

Several wallpaper patterns were tried without formal testing measures, only subjective evaluation. Most of them were not convincing in producing vection, and they often gave directional cues. I then chose three subjects on whom to test several patterns and conditions to see if it was possible to statistically prove one pattern or condition better than another. Two of the subjects showed little or no vection and were thus dropped from the study. The third subject, although prone to drop outs, was very helpful in pattern determination.

Nine variations in all were tried. They were:

- (1) Gray background with 1/4" dots at 3% coverage.
- (2) Parallel black and white stripes on an insert. (The annular insert extends out from the camera flash - a visual angle of 13.5° - out to the curve in the dome - a visual angle of 55°).
- (3) An offset radial pattern of black stripes on a yellow background as an insert.
- (4) A blank yellow insert to check if the vection was caused solely by the peripheral pattern.
- (5) Four colors of 3/4" diameter dots on a gray background with 30% coverage on the front face, and 13% dot coverage on the dome sides.
- (6) Six colors of 3/4" diameter dots on a white background with 20% coverage on all sides, but having no fixed center point for gaze fixation.

- (7) Same pattern as (6) with the exception of now having a fixed center.
- (8) Same pattern as (7) now with reduced lighting to cut down on eye strain from the white background.
- (9) Same conditions as (8) except viewing monocularly instead of binocularly to test for any difference between the two.

Several runs at different speeds in random order were taken on each pattern with one subject to try and statistically prove one better than the others. The subject was given the same instructions as in normal data runs, measuring 90° rotations relative to the room. The data were transferred from strip charts and averaged over all runs for onset times, subjective velocities, times of drop outs, and their standard deviations (Table 3).

Not enough data runs were taken to prove very many patterns statistically better than others. Using a t-test of significance, it is possible to statistically eliminate the blank insert ($t = 6.91$, $p < 0.001$, d.f. = 5), showing that peripheral vision is not the only cause of vection. This is in contrast to the work of Brandt et al. (1975), who stated that masking the surface to a visual angle of 60° had almost no effect on vection. In addition, the blank moving center, subtending the 13.5° normally taken by the camera, can be eliminated as a viable solution ($t = 5.4$, $p < 0.001$, d.f. = 5). Beyond that, analysis of variance doesn't show any one pattern to be better because of the small sample size and the variances involved. It was noted, however, that parallel stripes gave directional cues, and that bright lighting on the

DOME TYPE	Viewing type	Average time of onset of vection	Standard deviation of time of onset	Average time of first drop out	Standard deviation of drop out	Average std.dev. of 90° signals
1/4" black dots on gray background 30% coverage	M	4.5	2.15	16.83	6.59	0.51
Parallel stripes, black on white	M	2.3	0.71	22.7	6.36	0.38
Offset radial stripes, black on yellow	B	2.53	0.56	18.03	2.32	0.51
Blank insert yellow	B	3.93	0.42	14.2	2.65	0.70
4 colors of 3/4" dots on gray background 30% coverage	B	2.96	0.87	20.75	6.44	0.42
6 colors of 3/4" dots on white, 20% cov. moving center	B	2.93	0.31	6.6	1.38	too poor for vection
Same as above, without moving center	B	1.97	0.31	19.47	6.07	0.58
Same pattern, with reduced lighting	B	2.32	0.15	16.85	4.35	0.38
Same pattern with reduced lighting	M	2.42	1.10	15.92	5.13	4.05

Table 3: Pattern and viewing differences compared. B = binocular, M = monocular

six color pattern with white background caused eyestrain from the contrast. It can also be seen that binocular viewing is slightly better than monocular on all points, thus adding another reason to remain with binocular OCR measures.

Overall, from this study and other separate subjective opinions, it is felt that the 20% coverage with six colors of 3/4" dots on a white background is the best pattern to induce vection. Lighting must be appropriate for the contrast involved; about 24 foot candles incandescent or 12 foot candles fluorescent in this condition. The change was made from fluorescent to incandescent to match the Spacelab lighting scheme. The two light levels are comparable in the contrast produced. Also, since the time of this study, the depth of field of the dome has been increased by 6". This has improved vection, mainly by eliminating any objects visible or 'sensed' in the periphery. Its specific effect on vection was never carefully measured beyond a subjective point of view. It can be shown that subjective measures of velocity and drop out times are not statistically different in the two dome depth conditions. Onset times, however, are statistically different, but the change in visual pattern must also be taken into consideration in accounting for the difference.

Another problem arose from the change to random colored dots on a white background that went unnoticed until after a great deal of data was lost. The high contrast pattern essential in creating saturated vection also interfered with the OCR data. It was found that the flash intensity was high enough and was allowed to disperse enough to cause specular reflection of the dot pattern onto the subject's

cornea. This problem was restricted to brown eyed subjects where the iral patterns were not well illuminated and thus the overriding visual scene was that of the reflected dot pattern (Figure 9). Increasing the light only increased the effect. This was not the case on blue or hazel eyed subjects where the underlying iral patterns overrode the dot pattern reflected on the cornea (Figures 10 and 11).

Several engineering solutions to the problem were attempted. They involved background lighting changes, various coatings over the dome surface to equalize the reflectivity, and flash condenser/restrictors. By placing an extension tube out from the ring flash, it was possible to eliminate all photographic flash light from reflecting onto the cornea. This extension tube, however, interfered with vection sensations since it protruded 6" towards the subject's face. A solution was to cut that length in half, allowing only light that had an angle of incidence greater than that which could return to the subject's eyes to impinge on the dome surface. This tube, approximately 3" in length and painted white to blend in with the dome background color, was implemented for Spacelab experimentation on brown eyed subjects. It does little to effect the flash intensity or vection quality. However, in order to eliminate this from being another factor to contend with in this investigation, all subjects used in the lab for OCR measures were blue eyed. From previous data, no significant difference was noted between brown and blue eyed subjects, as expected, and it is therefore not a cause of concern. The next round of astronaut testing, however, should use the extension tube to get the needed OCR data on brown eyed subjects and to match the Spacelab conditions as closely as possible.

FIGURE 9. Brown Eyed Subject with
Reflected Dot Pattern



FIGURE 10. Hazel Eyes under Same
Conditions as Fig. 9

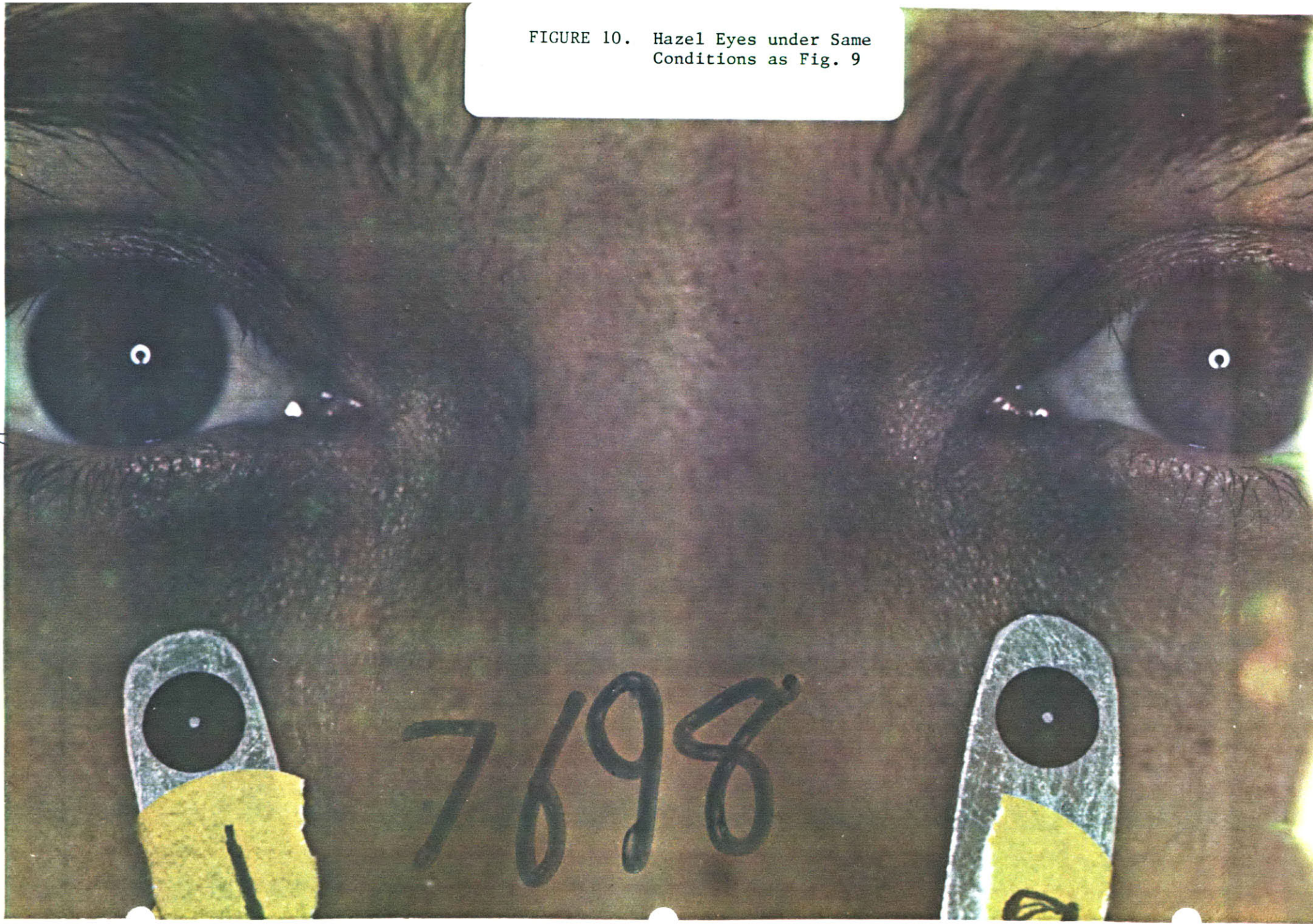
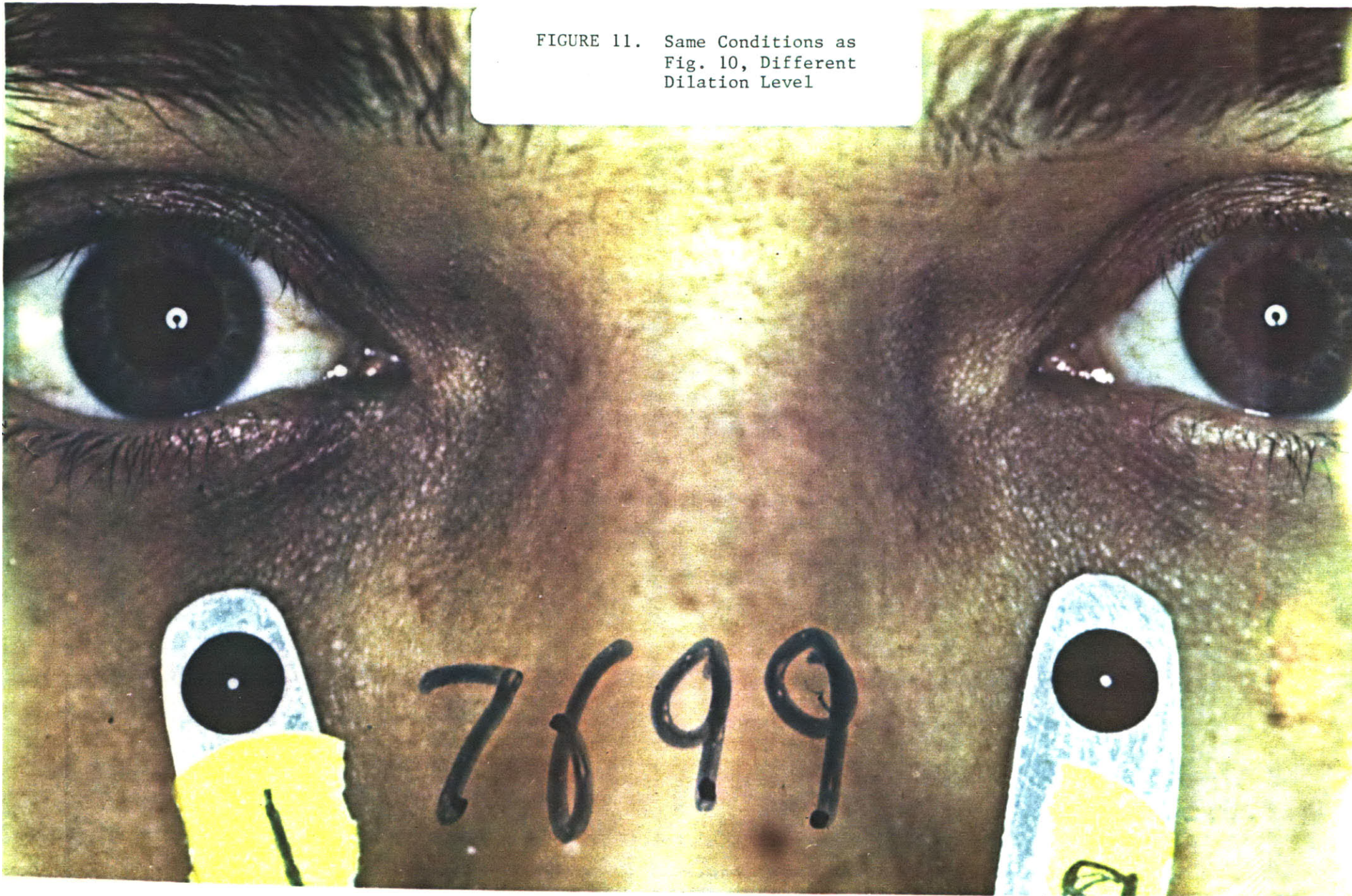


FIGURE 11. Same Conditions as
Fig. 10, Different
Dilation Level



4.4 Changes in Scanners

The volumes of data analyzed for the KC-135 and laboratory data required the use of more than one scanner. For the most part, two were employed: Yao Tsiagbe and Stefania Rubinsky - the latter doing the greatest volume of work. In order that position data not be lost between scanners, the last three data points of a previous scanner were repeated in order to get a position correlation. At the end of each scanning session, sketches of the eyes were made to depict which landmarks were used. This allowed one scanner to return to the same landmarks on a following session, as well as documenting the landmarks for further comparisons with the plotted values as a final check.

In order to test whether both scanners gave comparable results, apart from the accuracy check provided by the standard deviation values, each was asked to repeat 20 frames of binocular data using landmarks of their choosing. By properly scaling the Varian OCR plots, it was possible to see both scanner's values on the same plot, each having their own reference angle to begin with (Figure 12). For a clearer view, these plots were separated and scaled up. The angles found by Yao have been placed on transparencies and overlaid across those found by Stefania, Figure 13 is right eye over right, Figure 14 is left eye over left. To compare the left eye with the right, Figure 15 is right over left.

As can be seen, both scanners show comparable results and both eyes are going through essentially the same rotations. Also, by comparing the graphs and overlays, there is no discrepancy larger than

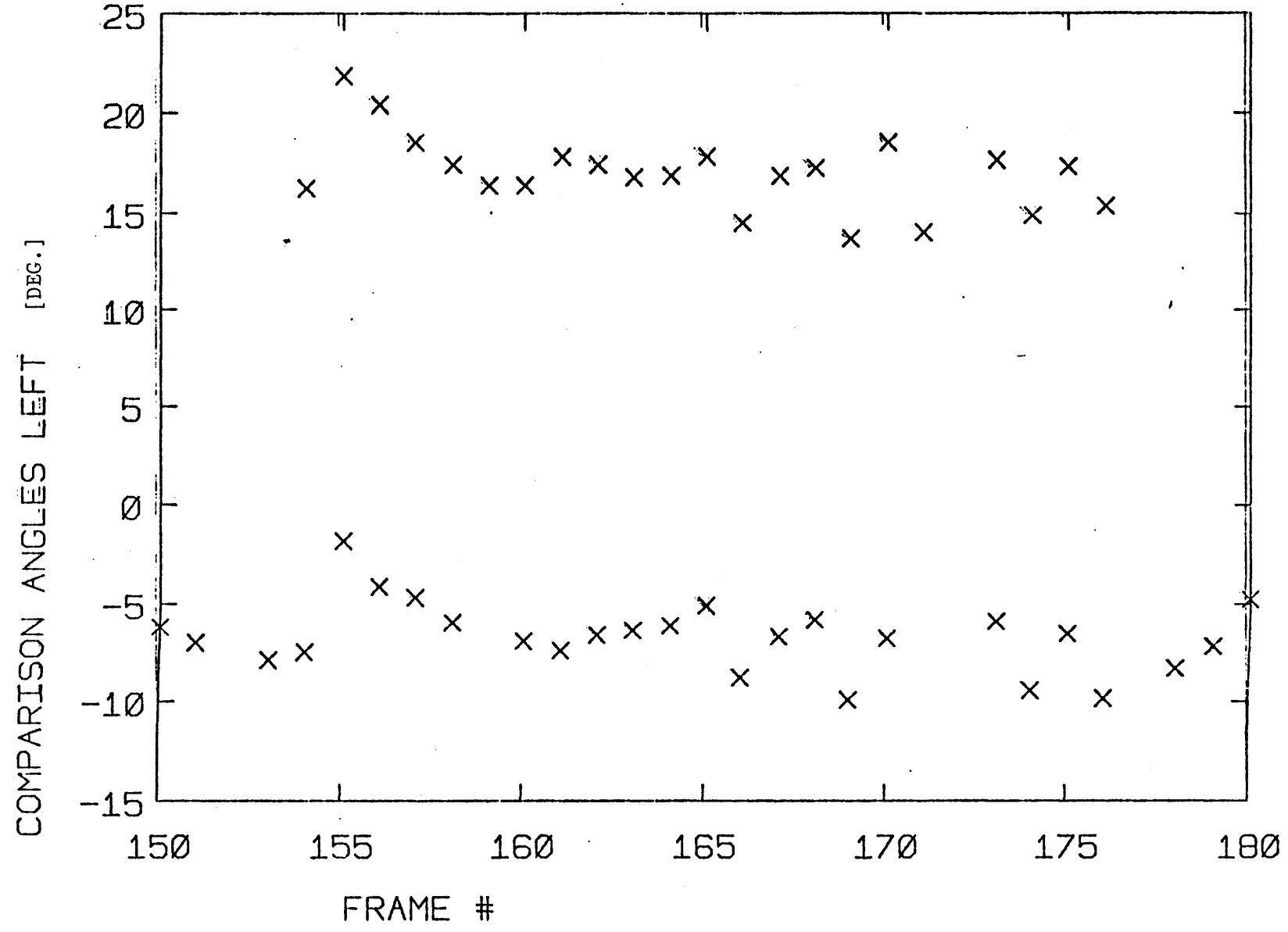
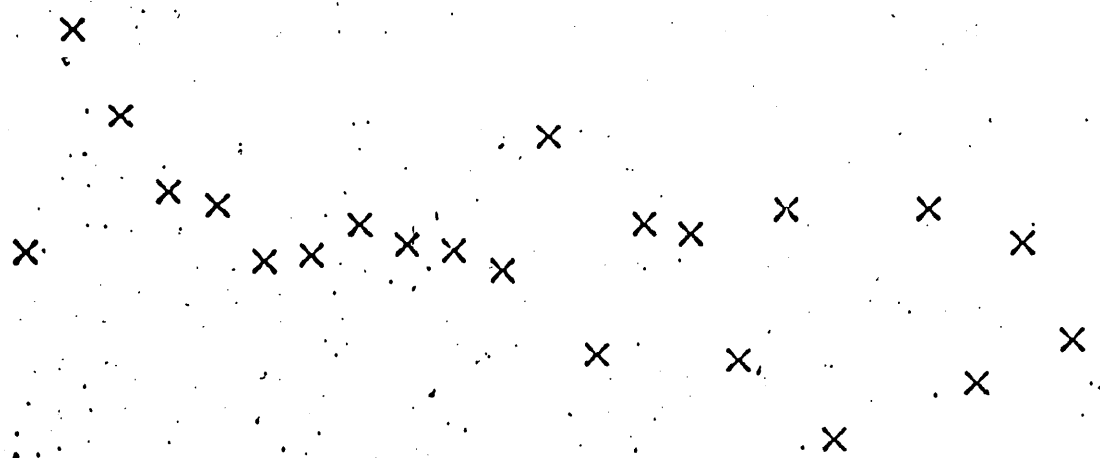


FIGURE 12. Scanner Comparison Plotted on Same Scale



SCANNER - YAO
RIGHT

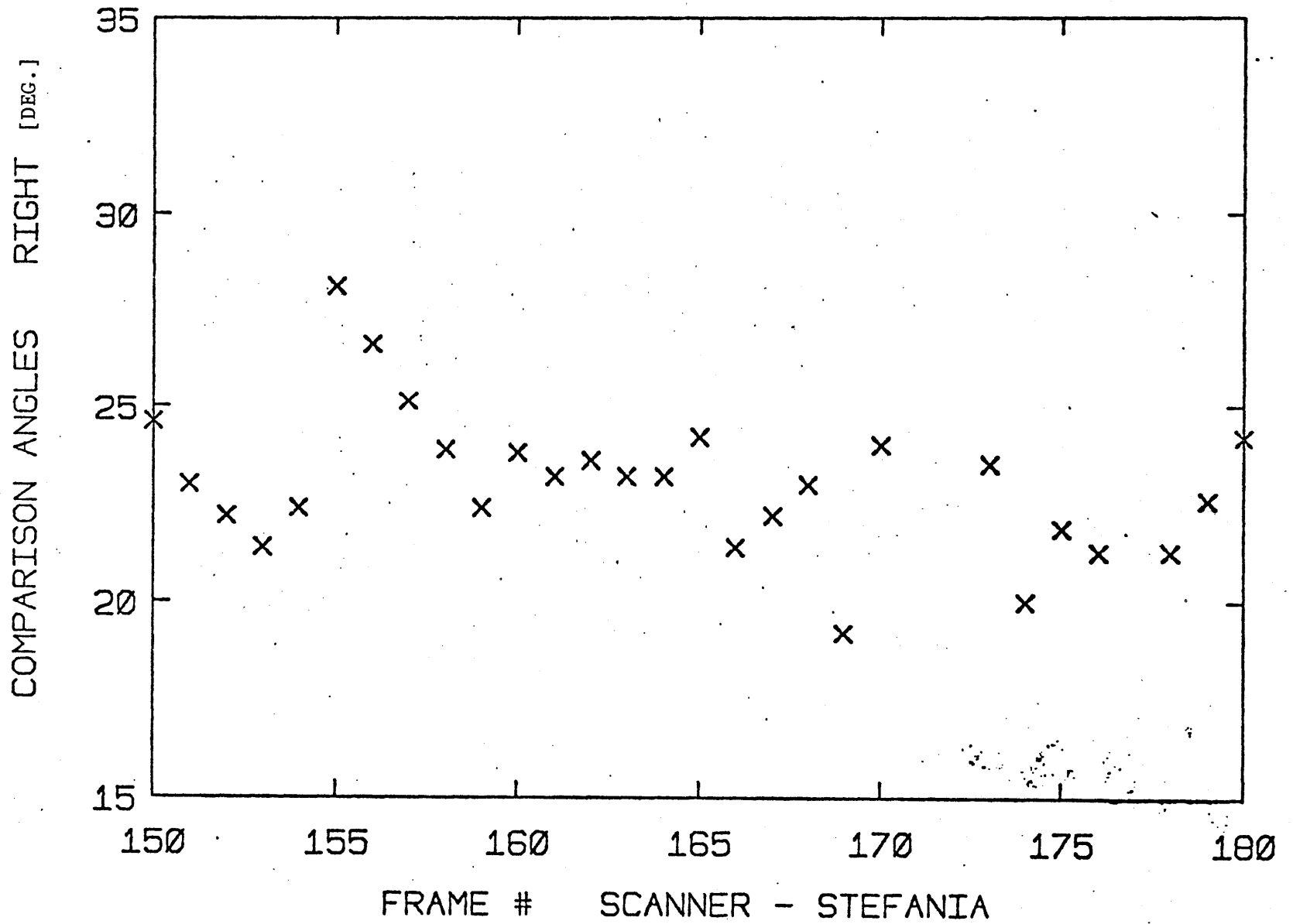
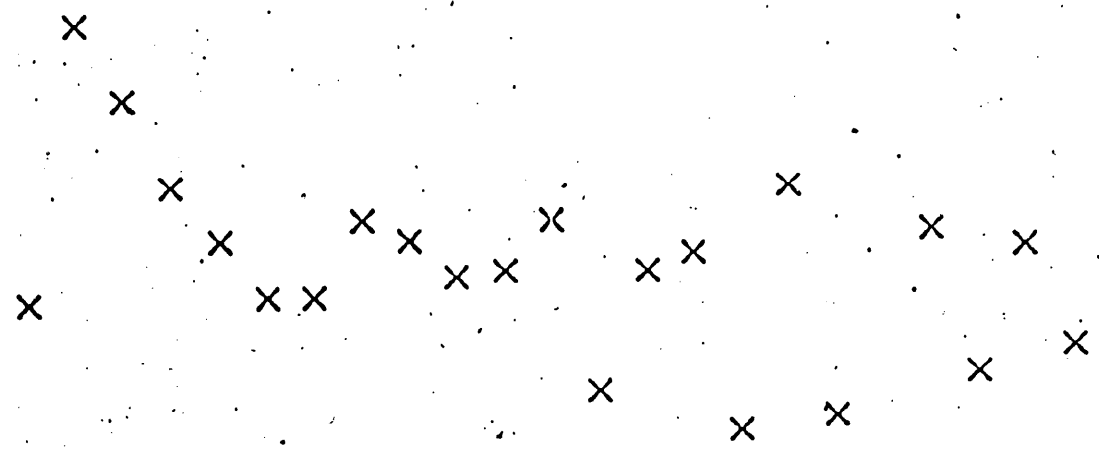


FIGURE 13. Increased Scale Overlay
Yao Right over Stefania Right



SCANNER - YAO
LEFT

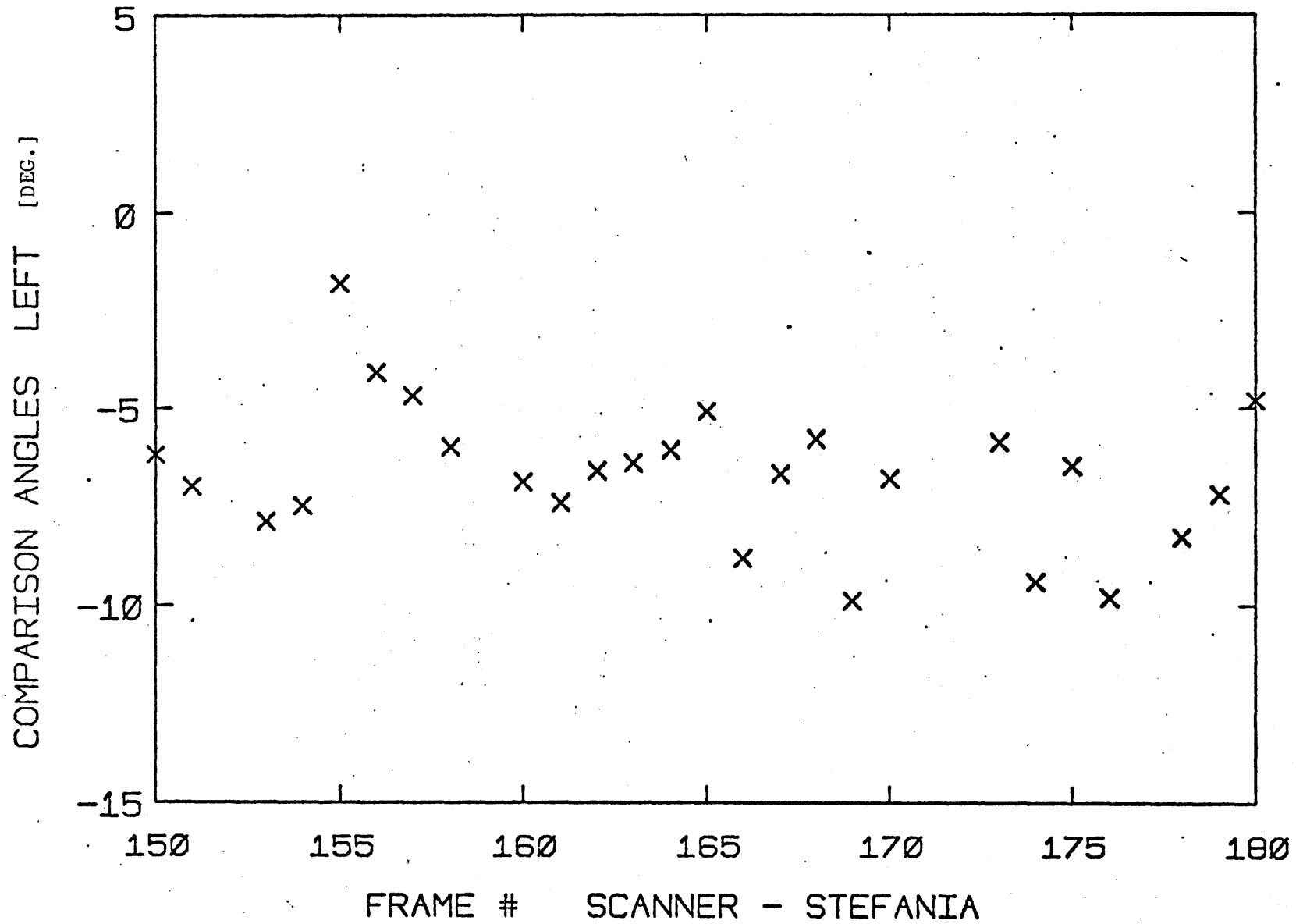
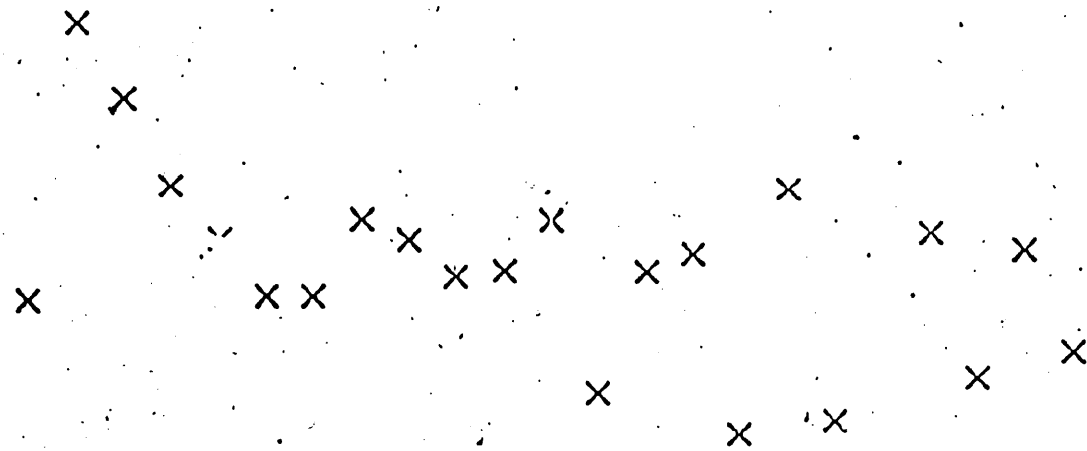


FIGURE 14. Yao Left over Stefania Left



SCANNER - YAO
LEFT

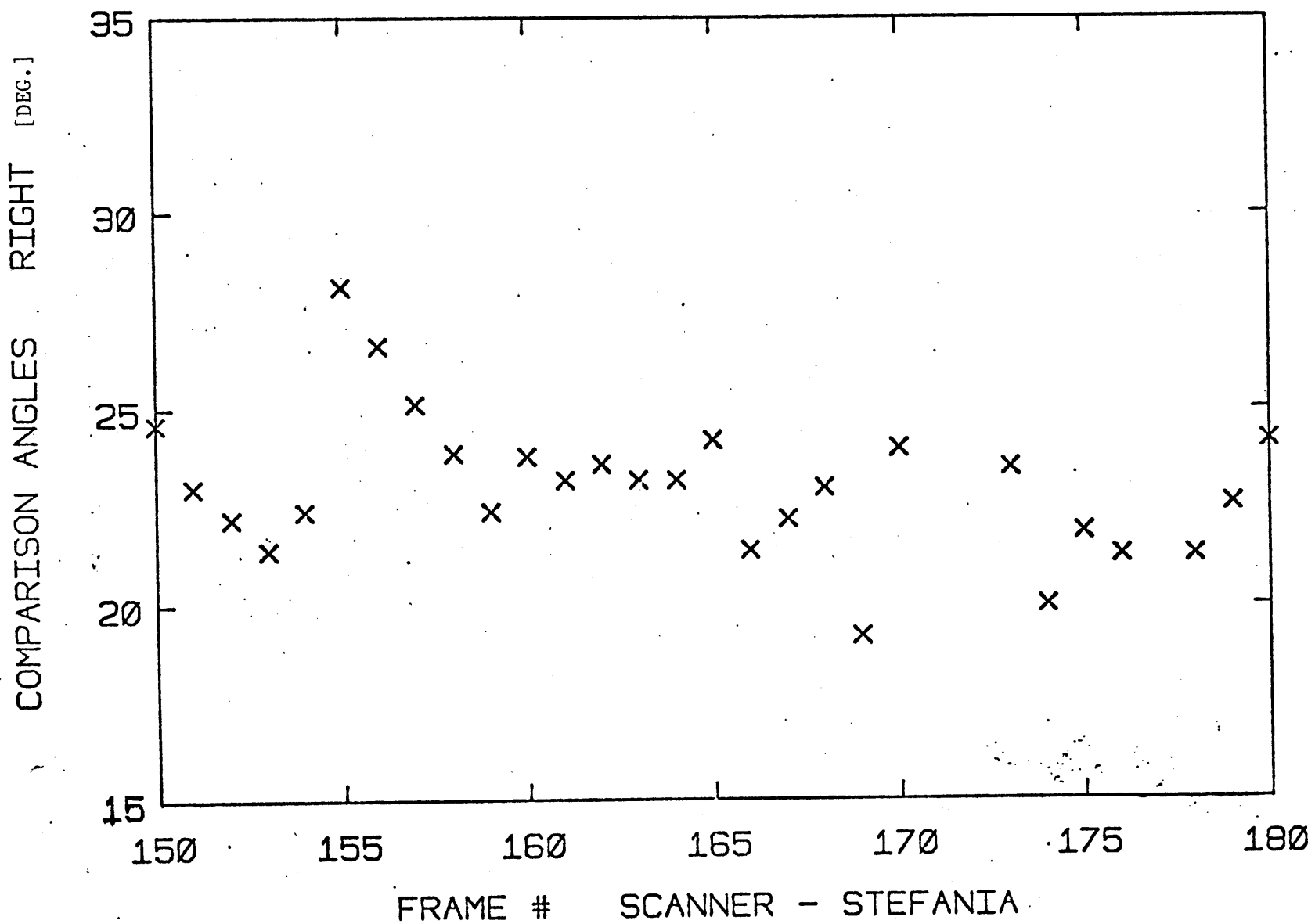


FIGURE 15. Binocular Comparison, Yao Left over Stefania Right

1 1/2 degrees, which only occurs on two occasions, and most are well under a degree. Even the larger differences cannot be proven to be statistically different since each data point has a standard deviation on the order of half a degree. It is also noted in Figure 15, by overlaying one eye on the other, that the two eyes have an equivalent fit. That is, they both counterroll together with no asymmetry visible. (The dome was run in two directions during these 20 photographs.) There are no differences between the two eyes in visually induced roll greater than 1 1/2 degrees, and this is a limit seen only on a very few points. Most are much closer. Overall, the data collected indicates that the method and scanners are not only accurate to within the standard deviations calculated, they are repeatable to within 1/2 degree or less on the average.

4.5 Dilation of the Eyes in OCR Measurements

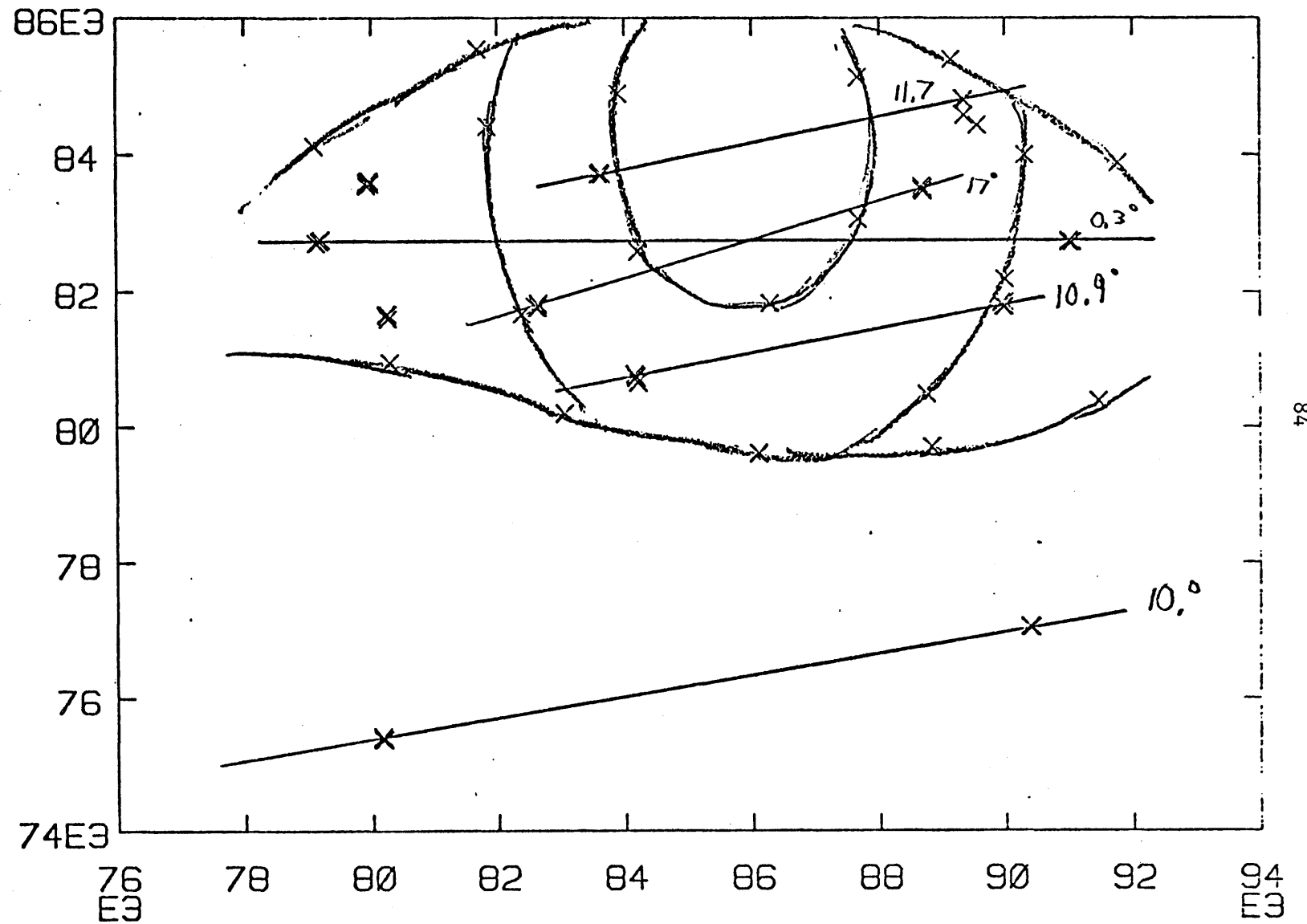
This problem is a result of the timeline and data collection methods used. It was necessary that the dome light intensity be kept down around 10 - 20 foot candles to prevent eyestrain and provide good vection. The photography, on the other hand, requires flash levels on the order of 1000 foot candles, or nearly two orders of magnitude more. It is not possible to take OCR measurements on a continuous basis as the flash would interrupt vection greatly. Taken in short bursts (2-3 sec), however, it can be tolerated without much

effect on vection. The problem arises in that the flashes cause pupil to constrict, or rather the muscles of the iris to constrict to shrink the size of the pupil. This effect was minimized in a previous study by Miller and Graybiel (1970), who placed drops of 1% Pilocarpine Hydrochloride solution in the eye before taking OCR measurements. The drug minimizes the natural fluctuations in pupil size as well as maintains the pupil in constant constriction to allow viewing of as many iral landmarks as possible. Since use of this drug would not be tolerable for operational reasons on Spacelab, it was not used in this study. The photographic flash occurs fast enough to act as a continuous bright light and thus no dilation occurs between flashes. The constriction process, however, lasts 6-9 flashes (2-3 sec) before reaching steady state, depending on the individual. This means that the iral landmarks are moving on the eye during and between each flash. (Figures 10 and 11 (pp. 71-2) were taken on the same subject 20 seconds apart, Figure 10 occurring as the last frame in a series of 9 consecutive, 3/sec flashes, while Figure 11 is the first in the next series.)

To minimize the effects of these non-torsional movements of the landmarks, scanners were instructed to use landmarks spaces as far apart radially as possible and as close to horizontal or at least as symmetrically as possible. It can be shown that the angle between two points located asymmetrically about the eye may change with pupil constriction, while the eye has not gone through any torsional rotations. To qualitatively check the effect of these dilations, scanners

were instructed to choose several identifiable features on a given set of monocular data shot under the dome while it was in motion. Eighty points in all were entered into the HSFA. First 20 points were entered along the eyelids and around the iris and pupil to outline the main features of the eye. Next, ten points on the eye plus the two fiduciary marks were each entered five times, relocating the crosshair used to mark points between each entry. This was repeated over ten frames of film shot at three frames/sec in order to get several levels of pupil constriction. Anthony Arrott, interested in the same data for his studies, wrote a program similar to SCANOR3 which plotted these eighty entries on the same plot, scaled in the same units as the HSFA. The plot is similar to that seen on the screen of the HSFA reduced in size by a factor of approximately four (Figure 16). The eye has been sketched in for clarity. The two lower points not on the eye are five entries of the fiduciary marks. Variations in these entries are negligible. The points that were repeated on the iris and on the blood vessels usually appear as blurred crosses, a result of slight errors in entering the point in five repeats.

An attempt to measure the angles between any two landmarks on a drafting table, accurate to about $1/2$ degree, resulted in a maximum change of two degrees. However, this includes angles chosen between landmarks on the iris and visible blood vessels. It is clear by overlays of the data that at least one of these blood vessels, the one on the far right, is conjunctival. These blood vessels, indistinguishable from scleral vessels, do not move with the eye, but slide over it. Blood vessels are not valid or wise choices for OCR measures. The



Multiple Landmark Data MLØN19 Frame 9

FIGURE 16. 80 Point Dilation Study, small pupil overlay

other cause for large errors was in choosing angles that were made by points near the pupil. As can be seen in comparing the overlay in Figure 16, the point nearest the pupil moved considerably, while the rest of the points remained fairly stable.

In addition to this data, plots of all eyes show no general rotation or trend in the first three frames of a data run. These frames, taken with no dome rotation, show that while there is some movement of the eye, it cannot be attributed to dilation. The movements seen are on the order of 1° in random directions and can be attributed to the noise in the positioning system of the eye seen by Miller (1962). The overall indication of this study is that as long as points are chosen symmetrically and as far radially as possible, good OCR data can be obtained with confidence that it is little affected by the constriction or dilation of the pupil.

In summary, although it is possible that each of the changes or problems induced slight errors into the analysis of the data gathered, it is the author's view that they are negligible. The signalling method of one button push every 45° was not significantly different than that using 90° and it should substantiate itself as more data is gathered. Binocular OCR recording has shown comparable accuracies to monocular, and it has been shown that both eyes are driven in identical directions to similar magnitudes by a singular binocular process. This would allow a return to monocular recording if higher accuracies are desired with a theoretical improvement of 50%. The random dot pattern

with 20% coverage is clearly the best in creating a vection illusion without giving specific reference for influencing position and velocity information. Peripheral vision was also eliminated as the sole cause of vection with a near doubling of onset time and a 50% decrease in steadiness seen when 55° of the central field was masked. Scanners were shown to do accurate work ($\sigma = 0.2 - 0.8$) that was repeatable over a given set of binocular data, giving credence to both the system and the eye movements measured throughout this thesis. And lastly, although not a minor problem, dilation effects can be minimized through the choice of proper foveal landmarks.

CHAPTER 5

RESULTS

The results of this thesis are divided into two sections. The first is an analysis of the vection phenomenon. It contains lumped averages over all subjects for vection speed, onset times, and drop outs, all presented in graphic form. Qualifications are made as variances and differences dictate. KC-135 flight data and tactile differences are compared to standard laboratory conditions. In addition, individual averages are listed for each of the Spacelab crew members as this will be important for comparison with data returned from Spacelab. The second section contains the OCR data and analysis, including both monocular and binocular results. Averages of OCR values obtained in this research only tended to disguise the substantial differences seen within individuals. The OCR seen is clearly not as predicted in all cases, nor does it always match the results obtained by previous authors. The individual plots of eye position are thus included in Appendix D for comparison. Eye to eye comparisons are made for the binocular results, noting any asymmetries or preferential directions. Comparisons are made between the eye movements and induced vection, between monocular and binocular results and between 1 g and zero g results. The 1 g monocular data is presented first, followed by the KC-135 monocular data and 1 g binocular results.

5.1 Vection Results

The following is a summary of the vection results for all subjects, independent of the OCR information obtained. The crew data is averaged over both testing sessions: February and September, 1979, for drop out times and vection velocities since there was no significant difference noted between the two (Figure 17). Onset of CV times, however, did show a significant difference between the two sessions. There are several possible reasons for the significant ($p < 0.02$, $t = 2.33$, d.f. = 15) decrease in onset times at all speeds with the present pattern. The present pattern is more compelling; multi-colored 3/4" dots at 20% coverage on a white background in comparison to the 3% coverage of 1/4" black dots on a gray background. The present viewing is binocular, as opposed to monocular on the gray pattern, and finally, the depth of the dome has been increased (from 8" to 14"). A combination of the more compelling pattern and binocular viewing are considered to be the major reason for this decrease. In the comparisons with zero g and tactile conditions, the data for onset times will use the present pattern only, since it is the pattern on which future Spacelab-1 testing will be done. Any detrimental effects of lumping the averages together for drop out times and vection velocities are considered minimal, as the larger data base is helpful in determining significant differences.

The data for the six laboratory subjects tested is in complete agreement with that collected for the crew on the present pattern. None of the results can be proven to be statistically different and

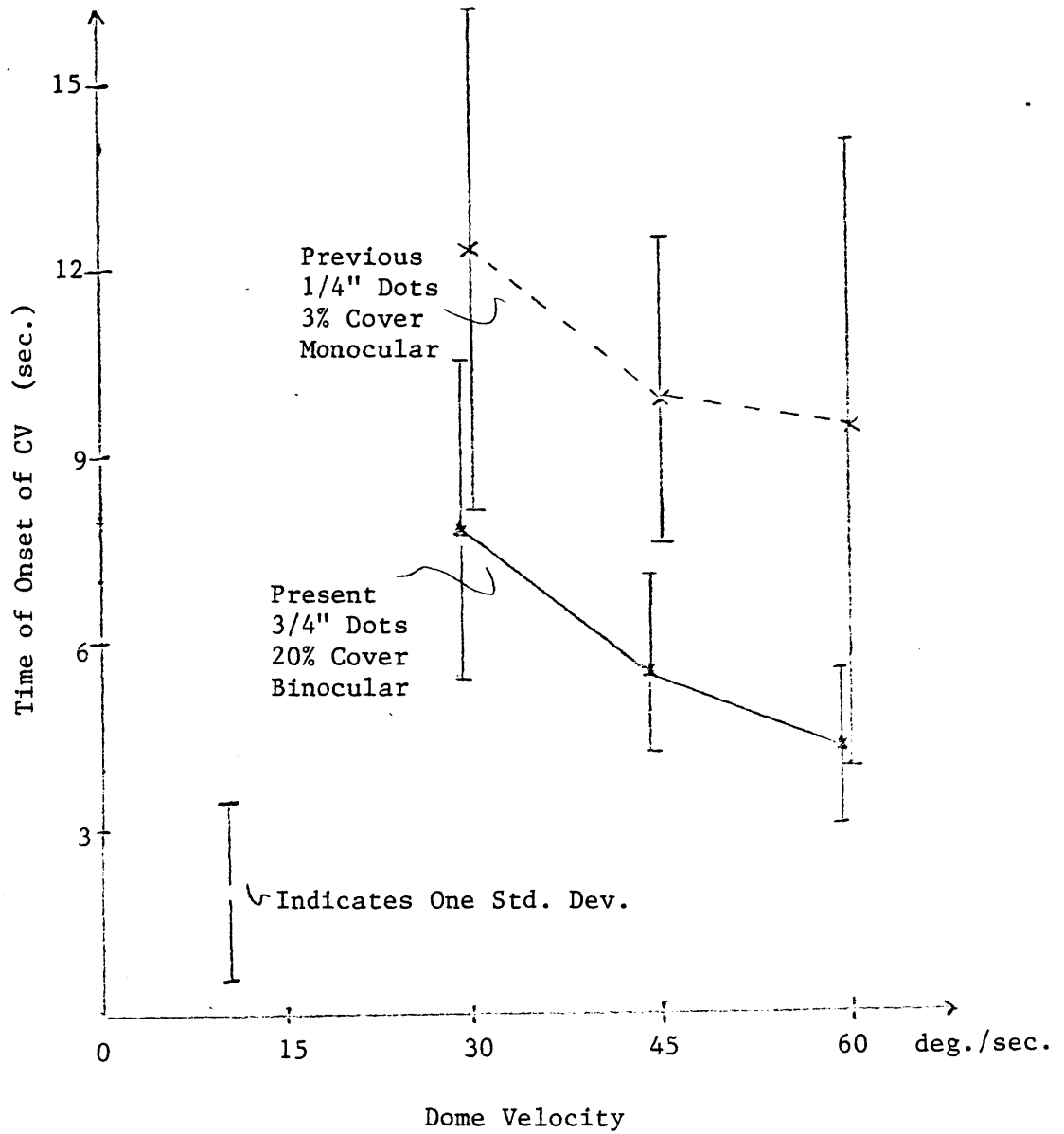


FIGURE 17. Comparison of Onset Times for 2 Patterns

overall averages are surprisingly similar, which attests to the repeatability of the experiments. These averages were lumped together with the crew data for overall averages of onset times, drop out times, and vection velocities. Tactile cues were not tested on the six lab subjects since it was felt that enough data had already been gathered on this, and thus averages presented are calculated from the crew data alone. The total number of data runs under all conditions combined is: 130 non-tactile runs and 66 tactile on a total of 14 subjects.

Vection data for the KC1 and KC2 are lumped together. The total number of subjects on which data was recovered is limited to 9 with a total of 93 data runs.

Figures 18 through 20 present the results in graphic form while Table 4 lists the numerical averages and standard deviations for the data. Vertical lines on the figures represent one standard deviation of the data collected. Data points on various conditions have been shifted slightly for clarity in discerning standard deviation values. Intra-subject variances are much smaller than those found in the combined averages presented. This is in agreement with the findings of Dichgans et al. (1972), Young et al. (1974) and others who also found intra-subject variability to be smaller than inter-subject variability.

Figure 18 presents the average time of onset of CV in four conditions for three speeds. The conditions are: 1 g laboratory data for CV about the vertical in a supine position, same conditions with tactile pressure applied to the soles of the feet, zero g data collected on the KC-135 flights with the right ear down, and fourth, 2 g data with the right ear down. This last position, a 2 g otolith signal, equivalent

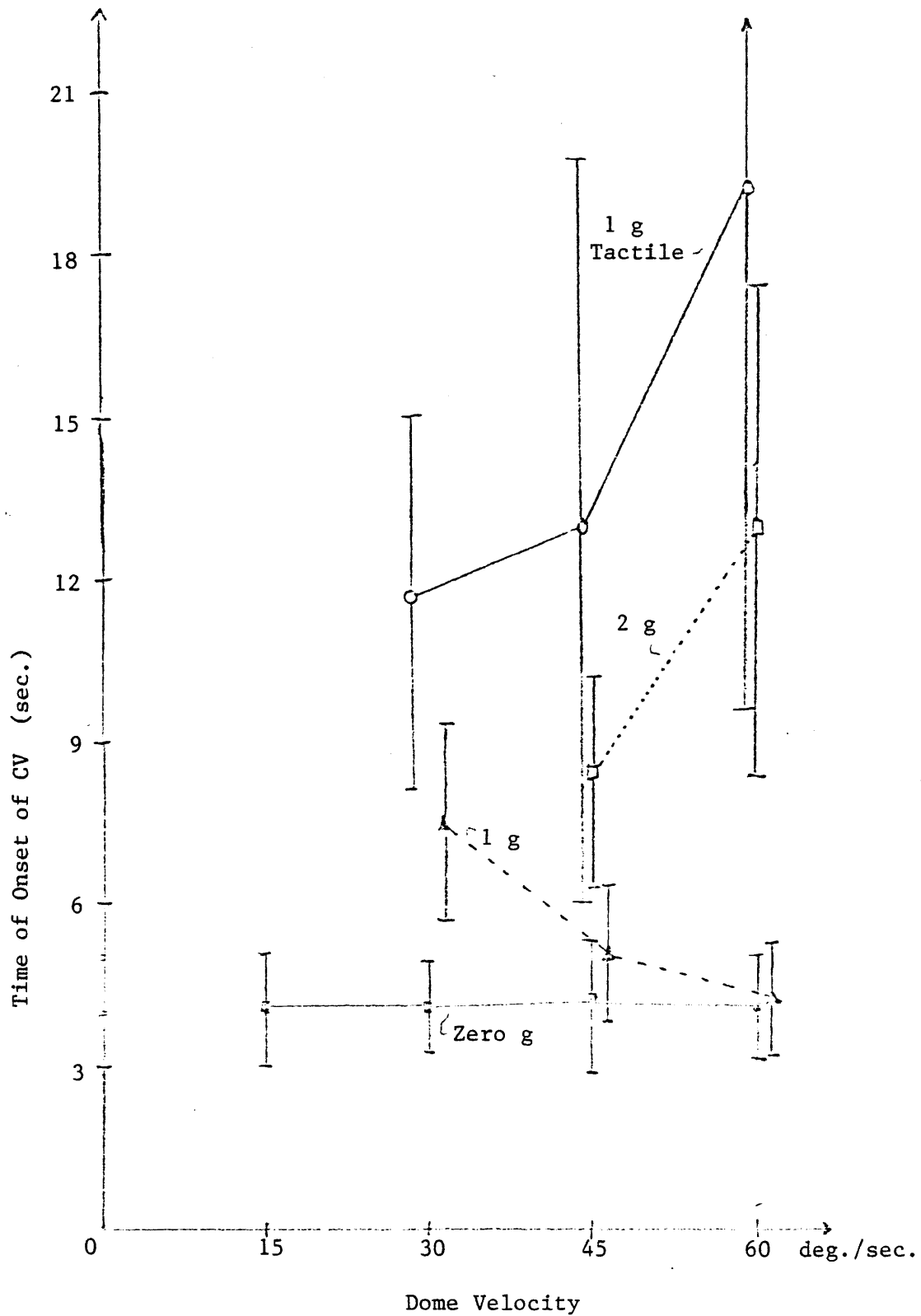


FIGURE 18. Time of Onset of CV in 4 Conditions-
1 g, 1 g Tactile, 2 g, & Zero g.

to standing erect with the head rolled 90° to the right, is such that it should not create continuousvection without also creating an otolith conflict (Young et al., 1974). It is believed, however, that the sinusoidally changing gravity conditions created onboard the KC-135 overrode the already confused vestibular system. Also, the head rolled 90° to the side position minimizes the effectiveness of the otolith sensors (Young et al., 1975). With the gravity vector being turned 'on and off', wild variations in perceived orientation were experienced by all in roll, pitch and yaw axes. There was no 'clear' otolith cue to create the paradox of 'rotation at a constant tilt', and thus signalling of rotation occurred in the two g environment as well as in zero g.

As can be seen, and as expected, the onset times are shorter in zero g than in 1 g at all but the highest velocity. This is significant at $30^\circ/\text{sec}$ ($p < 0.03$, $t = 2.2$, d.f. = 9) and at $45^\circ/\text{sec}$ ($p < 0.04$, $t = 1.98$, d.f. = 23) by the standard t test. It is noted that the onset time in zero g stays constant over all speeds, even down to $15^\circ/\text{sec}$. In comparison, Young et al. (1974) showed that there is a marked increase in yawvection onset times at slower velocities (10 to $30^\circ/\text{sec}$) and the same is seen for the 1 g supine data presented here. Brandt et al. (1973), on the other hand report no change in yaw CV onset times which are on the order of 3-4 seconds for field speeds of 10 to $120^\circ/\text{sec}$, similar to those seen in zero g. The sensitivity and orientation of the utricular otolith can be partly responsible for the shorter onset times in zero g. In a 1 g supine orientation, although the otolith is in its least sensitive orientation, it transmits a valid signal

nonetheless. As the dome speed increases and the visual stimulus becomes more compelling, less emphasis is placed on the otolith interpretation of position, and vection occurs sooner, reaching a peak around 4.5 seconds. In contrast, in zero g, the otolith signal is rendered totally useless as a static orientation cue, and the time to onset is dependent only on the believability of the visual cue and the time constants of the SCC and CNS. This threshold time, the time for the SCC cues to reduce to a level where the visual motion can be accepted as body rotation, is approximately 4.25 seconds over the velocity range 15 to 60°/sec.

The tactile cues are seen to cause a delay in time of onset of CV in a 1 g environment. (Not enough data was collected on 2 g or zero g tactile cues to present any quantifiable average. The tendencies, however, follow those of the 1 g data.) The tactile cues can be shown to be significantly different ($p < 0.01$, $t = 2.6$, d.f. = 15) from standard 1 g supine for all but the lowest velocity, where the inter-subject variance is too large to show significance. The tactile cues do not, however, represent the equivalent of a standing otolith cue, since this would cause complete elimination of continuous vection.

Information can also be gained from the slope of the tactile curve in relation to the slope of the normal 1 g curve. As can be seen, onset time decreases with increasing dome speed for 1 g supine, leveling off slightly in the 45 to 60°/sec range. On the other hand, the tactile curve, as well as the 2 g curve, both tend to show an increase in time of onset of CV with increasing dome speed. This increase is thought to be caused by increasing conflict. As the vection stimulus

quality increases, more of a conflict is generated between the visual and vestibular systems, and as a result onset time for CV lengthens. This is not the case for zero g or 1 g supine where no otolith or tactile cue conflicts with the perceived motion. Thus, tactile cues or increased gravitational cues do tend to limit vection. The tactile cues, however, do not represent a full replacement of gravitational cues gathered by the body, presumably by the utricular otoliths.

Figure 19 plots vection velocities for three separate conditions: 1 g supine, 1 g supine with tactile pressure, and zero g. The results indicate that all three conditions are essentially identical with respect to subjective vection velocity. The 2 g condition was not tabulated independently as no difference was seen in vection velocities over transition conditions on the KC-135 (i.e., in going from 2 g to 1g while experiencing continuous vection, velocities did not show any significant difference). In addition, calculating the velocity in a 'conflict' condition seemed of questionable value given the circumstances under which the data was collected.

The results also show perceived vection velocities to be lower than the actual dome speed. The explanation for this is not totally understood. One thought is that it is a form of information loss or equivocation. Information is collected by the visual system at the given dome speed and is collected, transferred, sorted and fed back out at a slower speed due to losses along the way. This, however, does not offer any physiological insight into the question. Another possibility is that the CNS senses self motion through whatever method, begins signalling an apparent velocity which tends to lock onto an internal clock.

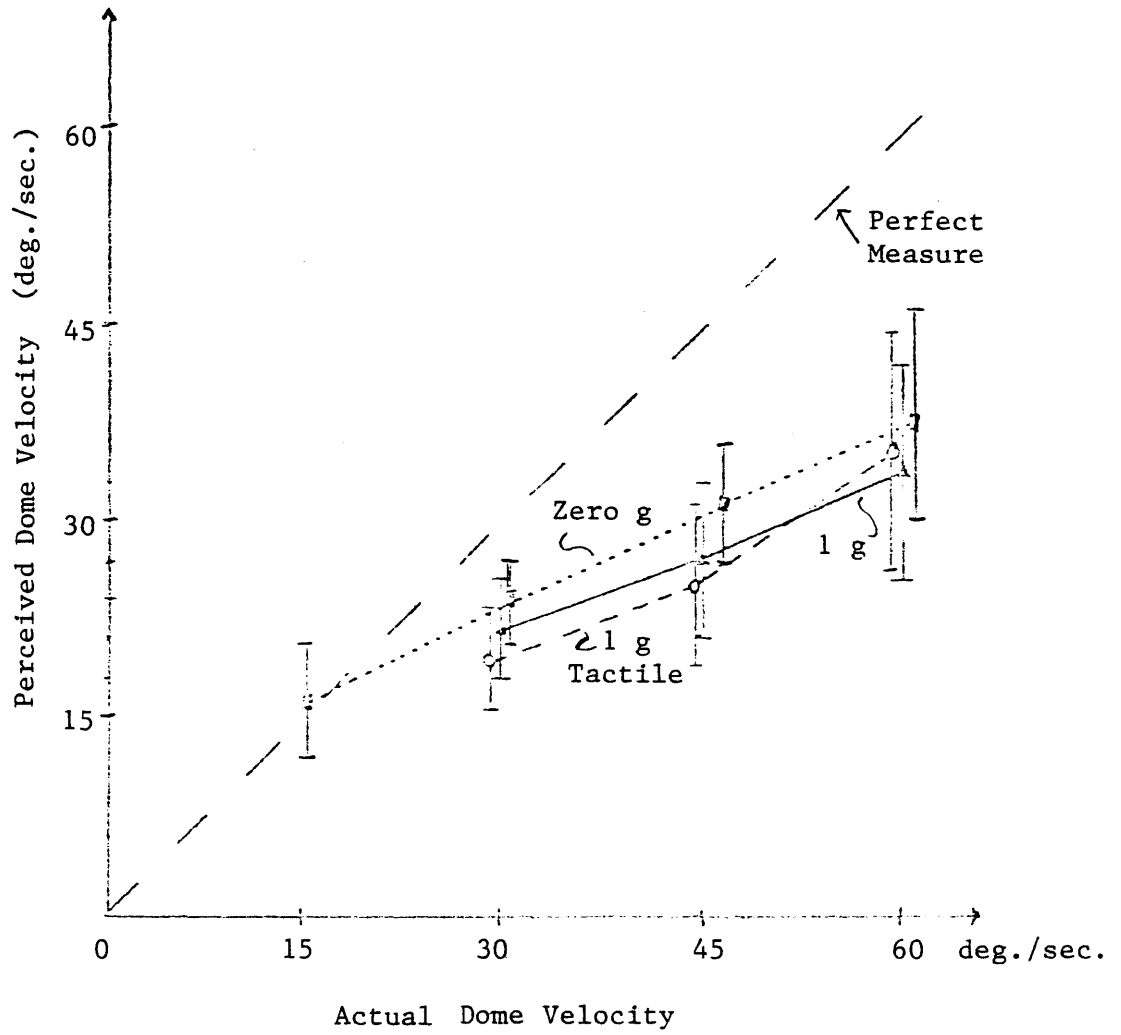


FIGURE 19. Perceived vs Actual Dome Speed in 3 Conditions - 1 g, 1 g Tactile, Zero g.

The rates transmitted , although correlated to the actual dome speed, do not have to exactly match those occurring - there is no feedback or penalty - and thus the estimates remain slow. (To match 60°/sec requires a button push every 0.75 seconds with the present system.)

In comparing the difference in velocities over all speeds, an interesting point crops up that appears to be in agreement with a finding of Diener et al. (1976). Diener used a subjective scale to report CV in the yaw axis. He found that by doubling the spatial frequency of visual stripes - similar to doubling the dome speed - subjects reported an average subjective velocity increase of approximately 60%. In this investigation, doubling the stimulus velocity from 30 to 60°/sec results in an average 58% increase in perceived velocity. In addition, the perceived velocities are an average 62% slower than the actual dome speed in all conditions. Reasoning for this finding has not been offered by Diener or this author.

Figure 20 presents the average length of the first vection period defined as the time from start of vection to the point where it first ceases, for two conditions. The first is the supine 1 g condition, and the second is the same using tactile cues applied to the soles of the feet. It was not possible to collect the same information during the parabolic flights because of the short duration of zero g. It was noted, however, that on nearly every occasion, as the plane entered a 2 g pullout from zero g, vection ceased. Again, subject positioning with the right ear down can account for this observation.

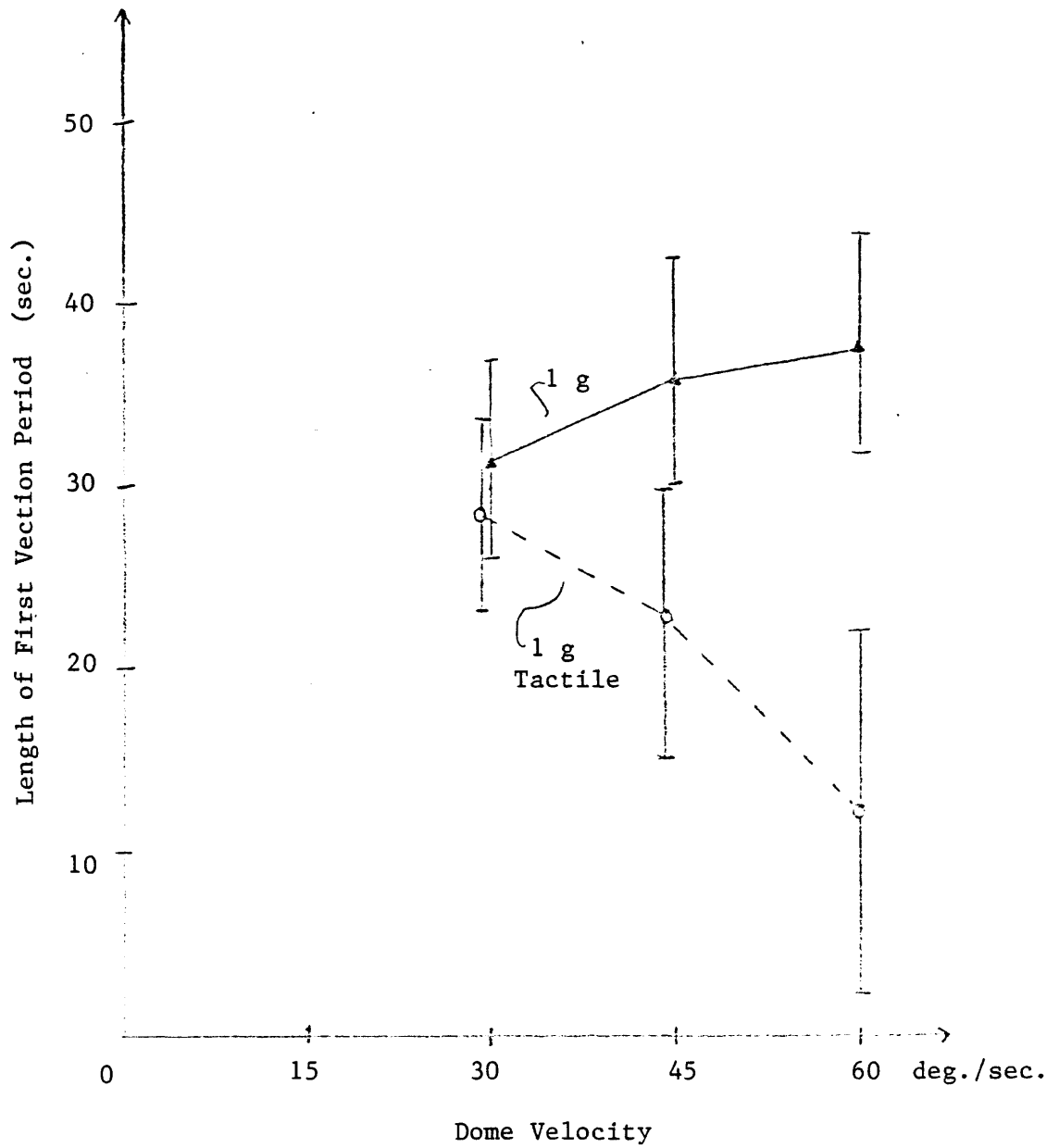


FIGURE 20. Average Time of Vection in 2 Conditions

	15	30	45	60°/sec.
Time of onset 1 g, old pattern		12.34 $\sigma = 8.4$ dp = 18	9.85 $\sigma = 5.05$ dp = 19	9.4 $\sigma = 11.26$ dp = 18
Time of onset lg, new pattern		7.78 $\sigma = 5.6$ dp = 60	5.4 $\sigma = 2.8$ dp = 64	4.48 $\sigma = 2.26$ dp = 60
Time of onset 1 g tactile		11.76 $\sigma = 9.2$ dp = 16	13.3 $\sigma = 14.2$ dp = 18	19.5 $\sigma = 19.6$ dp = 16
Time of onset zero g	4.28 $\sigma = 2.47$ dp = 7	4.21 $\sigma = 1.76$ dp = 10	4.59 $\sigma = 2.71$ dp = 24	4.24 $\sigma = 2.25$ dp = 8
Time of onset 2 g			>8.37 $\sigma = 4.45$ dp = 26	>13.09 $\sigma = 10.3$ dp = 7
Subjective velocity lg		22.3 $\sigma = 8.7$ dp = 60	27.1 $\sigma = 11.6$ dp = 64	34.0 $\sigma = 15.3$ dp = 60
Subjective velocity 1 g tactile		20.4 $\sigma = 7.1$ dp = 42	25.5 $\sigma = 12.7$ dp = 44	35.7 $\sigma = 17.9$ dp = 42
Subjective velocity 0 g	16.2 $\sigma = 7.4$ dp = 6	24.1 $\sigma = 4.9$ dp = 8	32.7 $\sigma = 9.2$ dp = 42	38.93 $\sigma = 14.9$ dp = 11
Length of first vection period lg		31.3 $\sigma = 11$ dp = 60	34.5 $\sigma = 12.8$ dp = 64	35.2 $\sigma = 12.0$ dp = 60
Length first vection 1 g tactile		28.8 $\sigma = 9.97$ dp = 16	23.4 $\sigma = 15.2$ dp = 18	12.0 $\sigma = 20.1$ dp = 16

σ = standard deviations
dp = number of data points

Table 4: Compiled averages and standard deviations as plotted in Figures 17 through 20

It can be seen from Figure 19 that tactile cues shorten the length of sustained vection, especially at the higher speeds. Due to intersubject variability, this cannot be verified at $30^\circ/\text{sec}$, but it can be shown to be a significant difference at higher speeds ($p < 0.2$, $t = 2.2$, d.f. = 15). A reason for this decrease at higher speeds can be seen again in the conflict model. As more directional cues are provided by tactile force, the conflict increases between the visual and non-visual systems and thus vection is limited.

In addition, an attempt was made to see if a correlation existed between either subjective velocity or latency times and age or sex. The results indicate that no such correlation exists. That is, onset times and subjective velocities are independent of age and sex of the subject over a range from 15 to 48 years of age.

Overall, the findings were as predicted in all except one case. Onset of vection was quicker in zero g and slowed with tactile cues and in 2 g. Tactile cues do not fully replace otolith cues for "sense of down", but can be shown to effect both onset and drop out time in a manner detrimental to vection. The fact that vection velocities do not increase in zero g is quizzical. Information transfer or an internal clock, either running at 60% of the stimulus velocity, are suggested reasoning that would not be affected by gravity or tactile cues. The hypothesis that vection would be more compelling in zero g was substantiated in voice comments made during 'free float' viewing of the dome. Comments by all, indicated that they felt immediate saturated

vection in zero g, during free float especially, and that it often caused them to lose total orientation. In addition, subjects involuntarily exerted reactionary forces on the litter and rails so as to physically rotate the body in a direction opposite to the dome rotation.

For comparison with later data, averages for each crew member were compiled for time of onset, subjective velocity and drop out times, and are presented in Table 5. Values were taken from the present pattern and viewing conditions only.

		OG	ML	BL	UM	CN	WO	RP
Time of onset of CV	30°	5.3	6.1	2.9	8.7	8.1	4.9	10.5
	45°	3.8	5.0	6.7	9.3	8.3	0.95	6.3
1 g/1 g tactile	30°	4.7	12.3	2.4	9.0	12.2	14.4	6.9
	45°	3.5	6.3	2.0	8.3	12.6	8.8	34.4
1 g/1 g tactile	30°	4.8	3.8	2.9	6.7	6.1	2.3	7.2
	60°	3.1	N.V.	3.2	6.2	19.3	37.5	9.5
Subjective Velocity	30°	18.0	13.1	20.6	15.1	33.0	18.1	28.8
1 g + 1 g tactile	45°	22.9	20.0	27.2	15.3	50.9	20.7	25.6
	60°	30.3	15.7	34.7	25.2	67.8	29.1	27.7
Average time of first drop out*	30°	50	40.1	50	32.4	31.8	44.1	23.5
	45°	50	42.9	50	38.2	44.0	50	16.8
	60°	50	40.1	50	42.5	34.8	50	18.1

* No drop out = 50

Table 5. Individual averages for astronauts - time of onset, subjective, velocity, drop out times

5.2 OCR Results

The results for monocular and binocular viewing are varied enough to warrant separate discussions of each condition. First the monocular results followed by the binocular. KC-135 results are included at the end of the monocular discussion as they too are all monocular.

The plots of monocular OCR values are in Section 1 of Appendix D. The arrows in the lower right hand corner of each plot show the direction of dome rotation as defined by the scanning convention. The vertical line represents a span of time indicated by the values written on the lower axis. Frames are taken at a rate of three per second from that initial time. The first six shots were taken immediately after startup of the stimulus, the second six when the subject was reporting vection. On occasion, this was not possible and the second set came during 'no vection'. The condition is clearly indicated by the words 'no vection' or 'during vection'. There were no photographs taken with the dome stopped.

5.2.1 Monocular Results

There are essentially two different types of eye movements noted in the 1 g monocular data. The first was experienced by two subjects, OG and BL. This result is similar to the findings of Finke and Held, (1978), but more dramatic in the case of OG. The pattern of eye movements was as follows: The eye immediately follows the dome rotation with an OCR of 2-3 degrees. Then after a latency, the eye appears to counterroll back past its nominal steady state position and roll 4-6

degrees in a direction opposite to the dome rotation. Photographs taken at this time were always during vection, and it is not known if this same counterrolling occurs in a 'no vection' situation. It appears so, since BL had similar torsional eye movements. His eye would follow the dome, and then counterroll, to a lesser extent, back in a direction opposite the dome. This time, however, a set of photographs included a 'no vection' condition which show this same apparent counterrotation. This would indicate that the OCR was not connected with the vection sensation, but more with the length of exposure to the stimulus.

In addition, it is noted that all these eye movements appear extremely steady. Although there may be large differences between the values at 'no vection' and 'during vection' conditions, the eye remains steady during the two seconds of photography. This is especially true for the data on BL. This will be contrasted with the binocular data later.

It is also seen that there is no correlation between dome speed, tactile cues, and amount of induced OCR. This again would indicate that the OCR process is independent of vection as vection is greatly influenced by these two factors. If the processes were dependent, OCR should also be limited by tactile cues and increased with increasing dome speed. These differences are not apparent.

The second type of OCR noted involves purely a motion following the dome. For three subjects, ML, UM and CN, the eye begins to follow the dome immediately after it is turned on, and is increased in the

second set of shots. At first glance, this would indicate more OCR during vection and that the eye was controlled by this perceived motion. It is noted, however, that several times when vection was not present, the eye has rolled through the same angle in the same direction as the dome. The three subjects in which this motion occurs show similar amounts of OCR, although it is not identical in all cases. Again, there is no correlation between amount of OCR and vection. Nor is there a correlation with tactile cues or dome speed.

Visual pattern is another factor which cannot be totally responsible for the differences noted between monocular and binocular viewing, nor can it be the sole factor in determining the amount of induced OCR. CN was exposed to two patterns, one immediately after the other, under the same instructions and conditions. One pattern was the usual 3 % coverage of black on gray, while the other was a parallel stripe insert. This insert was noted in Section 4.3 to have stronger vection producing properties than the gray pattern and produce vection similar to the present 3/4" random pattern. The OCR induced by the two patterns is nearly identical and again is unaffected by dome speed or tactile forces, indicating a separate central determinant. (The plots are included in Appendix D and are labelled S for stripes and D for random dots.)

Total amount of OCR induced by each run averages 4.0 degrees with a standard deviation of 2.5 degrees. (This is the absolute value of induced OCR and thus not direction dependent, as such averages would give smaller values due to the opposing types of movements seen in

different individuals.) The intersubject variation is large; ML showed average induced OCR of 2° , while OG showed an average of 7° with differences as large as 10° between sets of photographs. Similar differences between the two subjects were not noted in vection quality, onset times, drop out times, or subjective velocity, once again indicating that the processes are independent.

No statement can be made about the noise in the steady state positioning of the eye since no photographs were taken while the dome was stopped. The binocular and zero g data, however, include photographs of steady state eye position and thus this will be discussed in those sections. The sampling theorem dictates that no positive statement can be made about torsional velocity due to the slow sampling rate. It is noted that the eye often appears to travel in the direction of the dome for the last subjects, but it does so at an apparent rate much slower than the rate of the dome. The eye will follow at a rate of approximately $3^\circ/\text{sec}$ and then jump back to follow it again. The limits of the ocular muscles have not been reached, as the distances traveled are much less than those seen by Miller in altering the GIF or seen in these same subjects on zero g to 2 g pullouts in the KC-135. Logically, however, it seems that the eye would not want to reach these limits, but would prefer to stay in the generally optimum central region of movement in the orbit. This can account for the smaller dynamic torsional nystagmus values seen in this investigation over static OCR obtained in centrifuges, slow body rolls or zero g to 2 g pullouts, where gravity forces the counterrolling motion of the eyes.

5.2.2 KC-135 Results

The plots for the KC-135 zero g data also contain much additional information. The plots are in Section 2 of Appendix D, and are labeled by an ID number which corresponds to the parabola on which the data were gathered. Subject's names have been added for convenience. Data points which do not involve the dome operation, usually photographs taken during zero g to 2 g pullouts, have been double crossed to form a star image. Again, the arrow in the lower right corner of each plot indicates the dome direction during the photography. There is a limited amount of OCR data from the KC due to the acceleration problems already mentioned. Data exists for three subjects on 25 parabolas of dome operation.

The results for OCR on the KC-135 are similar to those for 1 g monocular data for all involved. The average induced OCR is 3.9° with $\sigma = 1.7^\circ$, not significantly different from the 4° obtained in 1 g. In addition, each subject showed generally the same amount of OCR in zero g as in 1 g, and in the same direction. That is, OG again appears to track the dome in its direction, and then counterroll in a direction opposite to the dome. The result is not as steady nor as marked as in the 1 g lab data. In fact, two parabolas show a tracking type motion continually in the same direction as the dome. This implies that the various eye movements seen are not universal even in a single subject. OG reported that thevection onboard the KC-135 was much more compelling than in the 1 g supine position. (He claims to have never been fully convinced by the illusion until the zero g periods.) This difference,

however, was not reflected in the eye movements, which did not substantially change between the two conditions, again indicating separate processes for the two phenomena.

The results seen for CN are similar to the 1 g data. His eye tracks the dome rotation and tends to roll more as time goes on. This does not depend on whethervection is present or not, thus indicating their separate processes. Steady state eye position, that is with no dome rotation, showed the same variability as in the 1 g environment. That is, 1 to 2 degrees of eye torsion was seen in the pre-dome shots, and the eye did not return to the same rest position after each parabola or run. The noise involved in the eye positioning system does not appear to be affected by the loss of gravity information, at least not dynamically. The zero g to 2 g pullouts as well as previous work by Miller and others show static OCR to be dominated by the otolith organ.

5.2.3 Binocular Results

The binocular results are plotted in Section 3 of Appendix D. Each page contains the plot for one data run, right eye on top of the left. Again, arrows in the lower right corner indicate the direction of dome rotation. (The sign convention is opposite to that of the monocular data.) The vertical lines on each plot indicate the passage of 25 seconds. The first three OCR values are, in general, those photographs taken before dome operation. The next six are the first two seconds of dome operation. The first vertical line indicates the

passage of 26 seconds when the next six photographs are taken. The final six photographs are taken at the end of the 50 second run, with the final three occurring after the dome has been turned off. The 'NV' and 'DV' indicate 'no vection' and 'during vection', respectively. Erroneous or extra data points are cross hatched to form a star image. Data exists on six subjects for 40 data runs.

All plots show good correlation between the two eyes. That is, both eyes appear to rotate in synchrony. This is in agreement with Hering's Law of Equal Innervation which states "Innervation to the extrinsic muscles of one eye is equal to the other eye, resulting in movements of the two eyes that are equal and symmetrical or parallel." (Dictionary of Visual Science, 1968). There are cases, however, of differences on the order of two degrees, and occasionally more. This can be attributed in part to the accuracy of the measuring system, but must also be caused in part by the inaccuracy of the positioning system of the eye. The 1-2° of noise is not necessarily generated purely binocularly. The noise does not affect both eyes equally in the same direction, nor does it have any apparent asymmetries.

The major difference between binocular and monocular viewing is in the amount of OCR seen. The average amount of OCR induced in binocular vision is 6.5°, $\sigma = 1.9^\circ$, which is significantly larger ($p < 0.01$, $t = 4.6$, d.f. = 24) than the 4° seen in the monocular data. This, as stated before, cannot be attributed solely to the pattern and must be a result of binocular vision. The visual system is receiving nearly twice as much information and therefore reacts with a correspondingly

larger OCR. Vection was also improved with binocular vision, but this does not necessarily indicate a relation between OCR and CV. The contrary is pointed out when looking at induced OCR with and withoutvection. Overall, there is no significant difference between either the average counterrolled angle nor the direction of rotation of counterrolling duringvection and with novection.

In binocular vision, the eyes again immediately follow the dome rotation, and later perform rotations opposite to the dome direction. The eye, however, does not remain as steady as in the monocular case. Binocularly, the eye continues to slow phase roll in the direction of the dome and appears to go through saccadic jumps to reposition the eye within the orbit. These nystagmus type rolls and jumps occur on both sides of the median steady state eye position. However, it appears that most of the cases involve eye movements that have started with the eye rotated opposite the direction of dome rotation. This is similar to the results noted in yawvection where the eye performs nystagmus eye movements about a line off center and in the direction of the oncoming field. An evolutionary explanation would suggest that this would be desired for survival; the eye moves to fixate the object entering the visual periphery as soon as is physically possible. Similarly in VIR, the eye rolls to catch the visual pattern as early as possible and the eye is then capable of stabilizing the image on the retina and following it as long as possible. This would be useful in recognition and identification of predators from any position. Here, however, the eye seldom follows the pattern to full extension due to its high angular velocity, random pattern, and low threat.

The questions may be asked, "Why the difference between monocular and binocular data? Why is the eye more steady in monocular viewing? Why are tracking motions much slower than dome velocity? Why the magnitude differences in OCR values obtained?" All of these questions and more cannot be fully answered until more data is taken and more eye movements monitored. High frequency components of the data are essential in explaining the tracking motions observed. A sampling rate of 3 per second is not nearly adequate in describing the phenomenon.

The findings of this study can explain those of Finke and Held (1978) who used an even slower sample of once per run. Their findings indicated more torsion in State 1 (no vection). This would be commensurate with sampling the phenomenon as the eye is performing its initial roll in the direction of dome rotation, and sampling again during vection along the eye's path as it crosses back and forth across the zero eye position. This one time sample and averaging only disguised the actual motion occurring. Similarly, averaging eye position over vection and no vection here tends to show a steady deviation in the direction of the dome rotation, being greatest in the no vection state since this is usually the time early in a data run when the eye initially follows dome rotation. Periods of no vection later in the data run do not follow this same pattern of eye movements pointing out that it is not the NV condition, but rather the initial dome conditions. The occurrence of tracking movements across the eye-at-rest position averages out to show little OCR during vection. As can be seen from the binocular plots, however, this is not the case. The eye movements are identical under both conditions and do not depend on the perception of self motion.

CHAPTER 6

CONCLUSIONS

Although previous research projects on VIR are limited, there are several results brought out in this study that differ from earlier ones. To begin with, the work of Brandt et al. (1973) on yaw CV was not in agreement with the findings on latency of onset. In this study, latency decreases with increasing stimulus velocities. Whereas Brandt et al. (1973) found that latencies are independent of stimulus velocity, Young et al. (1974) found latencies to decrease with increasing stimulus velocity in yaw CV. The values obtained were similar to those found in this study. The comparison is made in that both illusions involve motion about the vertical, yet each stimulates a different set of semicircular canals.

Brandt et al. (1973) found that masking the central field up to 60° has no effect on vection, a statement which was not supported by this study. A marked decrease in vection quality and an increase in vection onset time were noted when 55° of the central visual field were masked, thus indicating that the periphery is not the sole contributor to the vection illusion.

Vection was shown to be limited by additional g forces and by the presence of tactile cues indicating the 'down' direction. The tactile cues were not a full replacement for the gravity vector, as this would have caused a complete elimination of the continuous vection sensation. The proprioceptive information is used nonetheless as

additional information in subjective position determination. Latency to onset of vection was decreased substantially in zero g at all but the highest stimulus velocity. It also remained independent of dome speed, indicating that otolith cues are totally ignored and that time to onset becomes purely a function of the SCC threshold times, the time it takes for the visual information to override the competing SCC cue, which appears to be about 4.25 seconds. This is not the case in 1 g supine conditions where the otoliths still transmit useful orientation information which must be taken into account by the CNS at all but the highest stimulus velocities tested. The gain of this otolith cue, however, is low enough to be essentially ignored at the highest velocity where the visual stimulus is so overwhelming, the canal threshold time is the major limiting factor. Average onset times of less than 4 seconds are seen in some individuals, indicating that they possess a higher gain in the visual system which overrides the canal signal earlier.

Vection velocities were shown to be independent of competing gravitational and tactile cues. Velocities were constant over all conditions indicating a process that is independent of the otoliths. Vection velocities are consistently lower than stimulus velocities, but are in agreement with Diener et al. (1976) and others who reported that they increase linearly with increasing stimulus velocity. The perceived velocities show a 58% increase when doubling the stimulus velocity, a finding similar to that of Diener et al. (1976) in yaw CV. A reason for this 60% increase has not been put forth. An internal clock which is updated only on changing conditions could be responsible for the invariance of velocity over changing otolith and tactile cues. The

rapidity of signal required or a form of information loss in receiving the visual information seem plausible explanations for the slowness of velocities.

No direct correlation betweenvection and OCR could be found. Eye movements varied from individual to individual and between monocular and binocular viewing. In general, binocular viewing produced the greatest amount of OCR and the strongest sensations of CV. This does not indicate a direct correlation, since the amount of induced OCR was similar in bothvection and novection conditions.

The direction of initial eye rotation is clearly the same as the moving pattern. That is, a clockwise rotation of the field produces an initial clockwise rotation of the eye. This would be the same eye movement induced by rolling about the line of sight if the subject were standing erect. Once the CNS realizes that this visual input cannot be the same visual cue as falling with respect to the vertical, since more than a 90° rotation should begin to produce a negative gravity condition, the eye subsequently counterrolls to be able to view the oncoming visual field and track it in the direction of rotation. This rotary nystagmus does not always occur at the leading limit of eye position. Tracking motions and saccades are seen on both sides of the median eye-at-rest orientation. This differs from individual to individual and between binocular and monocular viewing, but appears constant over varying gravity conditions. Thus these dynamic eye movements cannot be mediated solely by otolith input and must be driven by the rotating visual scene. Survival evolution is offered as a cause for

these types of torsional eye movements.

Reasoning for why the eye seems to perform such slow rotations, on the order of $3^\circ/\text{sec}$ in the direction of field rotation, cannot be offered until the high frequency component of OCR can be measured with accuracy. There are too many possibilities of underlying movements which cannot be detected with the photographic method used in this thesis.

This thesis lays the ground work for data to be collected in the future onboard Spacelab. Without a comprehensive data base, the data collected in zero g would have little value in evaluating the effects of weightlessness on the vestibular system and how the CNS goes about the sensory rearrangement that is hypothesized to occur in zero g. The data of interest will be the adaptive changes that occur over the week in zero g and how these affect the onset of CV, drop outs, and subjective velocity. Although some differences and similarities have been noted on the parabolic flights, the 24 second parabolas leave no room to watch steady state zero g responses. And although there appears to be no differences in amounts of OCR in zero g, the results of a week long stay should show a predominance of influence placed upon the visual system. Thus, as the CNS begins its sensory rearrangement, visual and tactile cues will play increasingly dominant roles in subjective orientation and motion perception.

6.1 Recommendations

The results gathered on vection appear to be satisfactory. More data will be provided by the forthcoming Spacelab mission. Results gathered on adaptation will be useful in sorting out the cause and effect relationship between vection, and the visual-vestibular interaction.

The point that needs further refinement, however, is the method of OCR measurement. The system employed does not have the sampling rate to measure slow phase velocities nor to see all the high frequency components of the induced OCR. A continuous, highly accurate method of OCR measurement that does not interrupt the vection illusion needs to be implemented before the underlying system can be fully understood. The present flash system cannot be used for more than 2-3 seconds at a time without interrupting vection. A continuous low light method would eliminate the problems of vection interruption and the associated pupil dilations. A comparison between zero g and 1 g data should then provide the desired ocular adaptation information.


```

C0100      C      ***** BINOCIN ***** V1.01 *****
C0200      C
C0300      C      AUTHOR: ARRCOT
C0400      C      CREATION DATE: 24-JUL-79
C0450      C      REVISED, JAN. 14, 1980 BY CRITES
C0500      C
C0600      C      CREATES FORMATTED DATA FILE FROM SCANNING DATA GENERATED AT
C0700      C      THE LNS SCANNING FACILITY.
C0800      C
C0900      C      DATA IS ASSUMED TO BE IN THE FOLLOWING FORMAT:
C1000      C001      INTEGER EYE, RIGHT, LEFT
C1100      C002      REAL POINT(10), MIDPNT
C1200      C003      LOGICAL*1 LINE(80), IFRAME(10), RFILE(10), LFILE(10)
C1300      C004      DATA RIGHT, LEFT/2,3/
C1400      C005      TYPE 110
C1500      C006      110      FORMAT('BINOCIN>')
C1600      C007      ACCEPT 111, (IFRAME(K), K=1, 10)
C1700      C008      111      FORMAT(10A1)
C1800      C009      OPEN(UNIT=1, NAME=IFRAME, TYPE='OLD')
C1900      C010      WRITE(6, 116)
C2000      C011      116      FORMAT('SCOUTPUT FILE FOR RIGHT EYE DATA: ')
C2100      C012      READ(5, 111) (RFILE(J), J=1, 10)
C2200      C013      OPEN(UNIT=2, NAME=RFILE, TYPE='NEW')
C2300      C014      WRITE(6, 118)
C2400      C015      118      FORMAT('SCOUTPUT FILE FOR LEFT EYE DATA: ')
C2500      C016      READ(5, 111) (LFILE(J), J=1, 10)
C2600      C017      OPEN(UNIT=3, NAME=LFILE, TYPE='NEW')
C2700      C018      IFRAME=0
C2800      C019      N=0
C2900      C020      200      READ(1, 204, END=292) (LINE(J), J=1, 80)
C3000      C021      204      FORMAT(80A1)
C3100      C022      DPCODE(70, 208, LINE, ERR=292) IFRAME, IT, IV, (POINT(J), J=1, 10)
C3200      C023      208      FORMAT(I4, I2, I4, 1CF6.0)
C3300      C024      M=1
C3350      C025      N=N+1
C3400      C026      IF (IFRAME.EQ.LFRAME) GO TO 216
C3500      C027      209      DO 210 I=RIGHT, LEFT
C3600      C028      EYE=I
C3700      C029      WRITE(EYE, 220) IFRAME, PCINT(1), PCINT(2)
C3800      C030      WRITE(EYE, 220) IFRAME, PCINT(3), POINT(4)
C3900      C031      210      CCNTINUF
C4000      C032      LFRAME=IFRAME
C4100      C033      MIDPNT=PCINT(1) + .5*(PCINT(3)-POINT(1))
C4200      C034      EYE=RIGHT
C4300      C035      M=3
C4400      C036      216      IF(M.GT.5) GO TO 200
C4500      C037      IF(EYE.EQ.LEFT) GO TO 218
C4600      C038      IF(PCINT(2*M-1).LT.MIDPNT) GO TO 218
C4700      C039      EYE=LEFT
C4800      C040      218      WRITE(EYE, 220) IFRAME, PCINT(2*M-1), POINT(2*M)
C4900      C041      M=M+1
C5000      C042      GO TO 216
C5100      C043      220      FORMAT(I6, 2F8.0)
C5200      C044      290      CCNTINUF
C5300      C
C5400      C      ERROR IN READ

```

```
C5500 0045 291 TYPE 2915,N
C5600 0046 2915 FORMAT(' ==>FROR(SCANIN): ASCII FILE LINE NO.',I5,/,
C5700 1 'SCONTINUE AT LINE: ')
C5800 0047 ACCEPT 2917,NREC
C5900 0048 2917 FCRTAT(I5)
C6000 0049 GC TO 200
C6100 C
C6200 C END OF INPUT FILE
C6300 0050 292 TYPE 296,N/4
C6400 0051 296 FCRTAT(I5,' LINES OF DATA CCVERTED')
C6500 0052 CALL CLOSE(1)
C6600 0053 CALL CLOSE(2)
C6700 0054 END
```

VAX/VMS ARRCTT
VAX/VMS ARRCTT

SCANCR3 4-APR-1980 15:49
SCANCR3 4-APR-1980 15:49

LPAO: 4-APR-1980 15:49
LPAO: 4-APR-1980 15:49

_SIAO:[OCR]SCANCR3.FOR;2 VAX/VMS
_SIAO:[OCR]SCANCR3.FOR;2 VAX/VMS

AAA	RRRR	RRRR	CCC	TTTTT	TTTTT
A A R R R R O C				T	T
A A R R R R O O				T	T
A A RRRR RRRR O O				T	T
AAAAA R R R R O O				T	T
A A R R R R O O				T	T
A A R R R R OOO				T	T

SSSSSSSS	CCCCCCCC	AAAAAA	NN	NN	OOOOOO	RRRRRRR	333333				
SSSSSSSS	CCCCCCCC	AAAAAA	NN	NN	OOOOOO	RRRRRRR	333333				
SS	CC	AA	AA	NN	NN	OO	OO	RR	RR	33	33
SS	CC	AA	AA	NN	NN	OO	OO	RR	RR	33	33
SS	CC	AA	AA	NNNN	NN	OO	OO	RR	RR	33	33
SS	CC	AA	AA	NNNN	NV	CC	OO	RR	RR	33	33
SSSSSS	CC	AA	AA	NN	NN	NN	OO	OO	RRRRRRR		33
SSSSSS	CC	AA	AA	NN	NN	NN	CC	OO	RRRRRRR		33
SS	CC	AAAAAAAAA	NN	NNNN	CC	OO	PP	PP			33
SS	CC	AAAAAAAAA	NN	NNNN	CC	OC	PP	PP			33
SS	CC	AA	AA	NN	NN	CC	OO	RR	RR	33	33
SS	CC	AA	AA	NN	NN	OO	OO	RR	RR	33	33
SSSSSSSS	CCCCCCCC	AA	AA	NN	NN	OOOOOO	RR	RR		333333	333333
SSSSSSSS	CCCCCCCC	AA	AA	NN	NN	OOOOOO	RR	RR		333333	333333

APPENDIX B.

FFFFFFFFF	COOCCC	RRRRRRR	;;;;	222222			
FFFFFFFFF	COOCCC	RRRRRRR	;;;;	222222			
FF	OO	CC	RR	RR	;;;;	22	22
FF	OO	CO	PR	RR	;;;;	22	22
FF	OO	OC	RR	RR	;;;;	22	22
FF	OO	CO	RR	RR	;;;;	22	22
FFFFFFFFF	OO	CC	RRRRRRR	;;;;	22	22	
FFFFFFFFF	OO	CO	RRRRRRR	;;;;	22	22	
FF	OO	CC	RR	RR	;;;;	22	22
FF	OO	CC	PR	RR	;;;;	22	22
FF	OO	CO	RR	RR	;;	22	22
FF	OO	OO	RR	RR	;;	22	22
FF	OO	OO	RR	RR	;;	2222222222	2222222222
FF	OO	OO	RR	RR	;;	2222222222	2222222222

AAA	RRRR	RRRR	CCO	TTTTT	TTTTT
A A R R R R O C				T	T
A A R R R R O O				T	T
A A RRRR RRRR O O				T	T
AAAAA R R R R O O				T	T
A A R R R R O C				T	T
A A R R R R OOO				T	T

VAX/VMS ARRCTT
VAX/VMS ARRCTT
VAX/VMS ARRCTT

SCANCR3 4-APR-1980 15:49
SCANCR3 4-APR-1980 15:49
SCANCR3 4-APR-1980 15:49

LPAO: 4-APR-1980 15:49
LPAO: 4-APR-1980 15:49
LPAO: 4-APR-1980 15:49

_SIAO:[OCR]SCANCR3.FOR;2 VAX/VMS
_SIAO:[OCR]SCANCR3.FOR;2 VAX/VMS
_SIAO:[OCR]SCANCR3.FOR;2 VAX/VMS

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400 C CREATION DATE: 14-MAR-79
500 C
533 C REVISIONS:
566 C 7-JUL-79 METHOD OF CALCULATING AVERAGE ANGLE CORRECTED
600 C ORDERS SCANNED FILM DATA AFTER IT HAS BEEN TRANSLATED BY
700 C PFCGPAM SCANIN.
800 C
900 REAL CCCRD(40,2),FIDUC(2,2),IPAL(2,2,20)
1000 REAL AVIRAL(2,2),VIRAL(2,2),SDIPAL(2,2) I AVERAGE AND VARIANCE
1050 REAL K
1100 INTEGER CFRAME,LFRAME
1200 INTEGER X,Y,XY,R,LEFT,RIGHT
1300 INTEGER FLAG1
1400 LOGICAL*1 INFILE(10),OUTFIL(10),SCNFIL(10)
1500 DATA Y/1/,Y/2/,LEFT/1/,RIGHT/2/
1600 DATA OUTFIL(8)/*A*/,OUTFIL(9)/*N*/,OUTFIL(10)/*G*/
1700 DATA SCNFIL(8)/*S*/,SCNFIL(9)/*C*/,SCNFIL(10)/*K*/
1800 TYPE 111
1900 111 FORMAT('SCANNING RESULTS FOR FILE ')
2000 ACCEPT 113,INFILE
2100 113 FORMAT(10A1)
2200 CALL ASSIGN(1,INFILE,10)
2300 DO 114 I=1,7
2400 SCNFIL(I)=INFILE(I)
2500 114 OUTFIL(I)=INFILE(I)
2600 CALL ASSIGN(2,OUTFIL,10)
2700 CALL ASSIGN(6,SCNFIL,10)
2800 WRITE(6,116) (INFILE(I),I=1,6)
2900 116 FORMAT(' SCANNING RESULTS FOR FILE ',6A1)
3000 C
3050 C.../

```

```

3075 C
3100 C INITIAL READING FROM FILE
3200 FLAG1=0
3300 R=1
3400 RFAD(1,205,END=900) LFRAME,CCORD(R,X),COORD(R,Y)
3500 235 FORMAT(I8,2F8.0)
3600 C
3700 C SUBSEQUENT RECORDS
3800 200 R=R+1
3900 READ(1,205,END=900) CFRAME,CCORD(R,X),COORD(R,Y)
4000 IF (CFRAME.EQ.LFRAME) GO TO 200
4100 C
4200 C REORDER POINTS
4300 220 MMAX=(R-3)*.5 I NO. OF IRAL MEASUREMENTS
4400 DO 290 XY=X,Y
4500 FIDUC(LEFT,XY)=CCORD(1,XY)
4600 FIDUC(RIGHT,XY)=CCORD(2,XY)
4700 M=0
4800 260 M=M+1
4900 IPAL(LEFT,XY,M)=COORD(2*M+1,XY)
5000 IPAL(RIGHT,XY,M)=COORD(2*M+2,XY)
5100 IF (IPAL(LEFT,XY,M).EQ.0.) MMAX=M-1
5200 IF (M.LT.MMAX) GO TO 260
5300 COORD(1,XY)=COORD(R,XY) I RESET FOR NEXT FRAME
5400 290 CONTINUE
5500 C
5600 C.../

```

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100 C
200 C CALCULATE AVERAGE IRAL COORDINATES
300 DO 420 LR=LEFT,RIGHT
400 DO 420 XY=X,Y
500 AVIRAL(LR,XY)=0.
600 VIPAL(LR,XY)=0.
650 SDIRAL(LR,XY)=0.
700 420 CONTINUE
800 DO 430 M=1,MMAX
900 DO 430 LR=LEFT,RIGHT
1000 DO 430 XY=X,Y
1100 IF(MMAX.NE.0) GO TO 428
1200 WRITE(6,426,ERR=427) FRAME
1300 426 FORMAT (' ==>ERROR[SCANOR]: MMAX=0 IN FRAME NO.',I8)
1400 427 R=1
1500 READ(1,205,END=900) LFRAME,CCORD(P,X),CCORD(R,Y)
1600 GO TO 200
1700 C
1800 428 AVIRAL(LR,XY)=AVIRAL(LR,XY)+IRAL(LR,XY,M)/MMAX
1900 430 CONTINUE
1950 IF(MMAX.EQ.1) GO TO 449
2000 435 DO 440 M=1,MMAX
2100 DO 440 LR=LEFT,RIGHT
2200 DO 440 XY=X,Y
2300 VIRAL(LR,XY)=VIPAL(LR,XY)
2400 1 + (IRAL(LR,XY,M)-AVIRAL(LR,XY))*(IPAL(LR,XY,M)-AVIRAL(LR,XY))
2500 2 / (MMAX-1)
2600 SDIRAL(LR,XY)=SQRT(VIRAL(LR,XY))
2700 440 CONTINUE
2702 449 CONTINUE
2705 C
2710 C.../

```

```

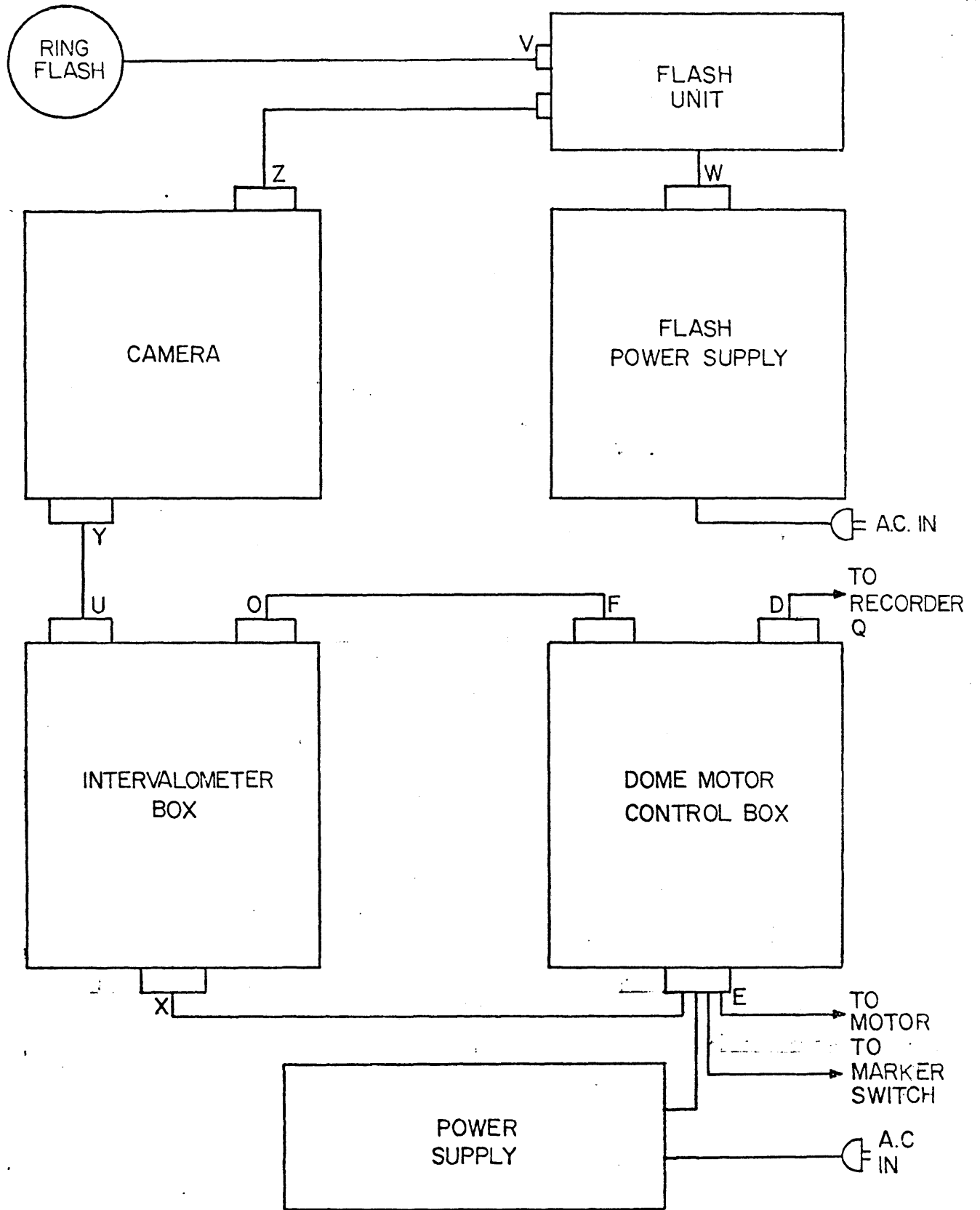
2800 C
2900 C CALCULATE SLOPES AND ANGLES
3000 C##### ZERO DIVIDE CHECK
3100 IF(FIDUC(RIGHT,X)-FIDUC(LEFT,X).EQ.0.) GO TO 325
3200 HSLOPE=(FIDUC(RIGHT,Y)-FIDUC(LEFT,Y))
3300 1 / (FIDUC(RIGHT,X)-FIDUC(LEFT,X))
3400 HANGLE=ATAN(HSLOPE)
3405 C
3410 EANGLE=0.
3415 WEIGHT=1./(FLOAT(NMAX))**2
3420 DO 450 I=1,NMAX
3425 DO 450 J=1,NMAX
3433 C ##### ZERO DIVIDE CHECK
3466 IF(IRAL(RIGHT,X,I)-IRAL(LEFT,X,J).EQ.0.) GO TO 450
3500 ESLOPE=(IRAL(RIGHT,Y,I)-IRAL(LEFT,Y,J))
3600 1 / (IRAL(RIGHT,X,I)-IRAL(LEFT,X,J))
3610 DELTA=ATAN(ESLOPE)
3700 EANGLE = EANGLE + WEIGHT*DELTA
3750 450 CONTINUE
3760 IF(EANGLE.NE.0.) GO TO 452
3770 WRITE(6,451) LFPAGE
3780 451 FORMAT(' ==>ERROR(SCANCR): ANGLE CALCULATION NOT CARRIED',
3790 + ' CUT IN FRAME',15,/, ' SEE RAW DATA')
3800 452 RANGLE=EANGLE-HANGLE
4100 C
4200 C CALCULATE STANDARD DEVIATION OF ANGLE
4225 C##### ZERO DIVIDE CHECK
4237 IF(AVIRAL(LEFT,X).NE.AVIRAL(RIGHT,X)) GO TO 475
4239 VANGLE=0.
4241 SDANGLE=0.
4243 WRITE(6,471)
4245 471 FORMAT(' ==>ERROR(SCANCP): AVG. X COORD. ALIGNED;',
4247 + ' UNABLE TO CALCULATE VARIANCE OF ANGLE')
4248 GO TO 490
4250 475 K=1./((AVIRAL(LEFT,X)-AVIRAL(RIGHT,X))**2
4300 VANGLE=K*(.25*(SIN(2*EANGLE))**2*(VIRAL(RIGHT,X)+VIRAL(LEFT,X))
4350 + (COS(EANGLE))**4*(VIRAL(RIGHT,Y)+VIRAL(LEFT,Y)))
4450 SDANGLE=SQRT(VANGLE)
4900 C
4910 C CONVERT FROM RADIANS TO DEGREES
4920 490 HANGLE=HANGLE*57.296
4940 EANGLE=EANGLE*57.296
5100 RANGLE=RANGLE*57.296
5200 SDANGLE=SDANGLE*57.296
5300 C
5400 C.../

```

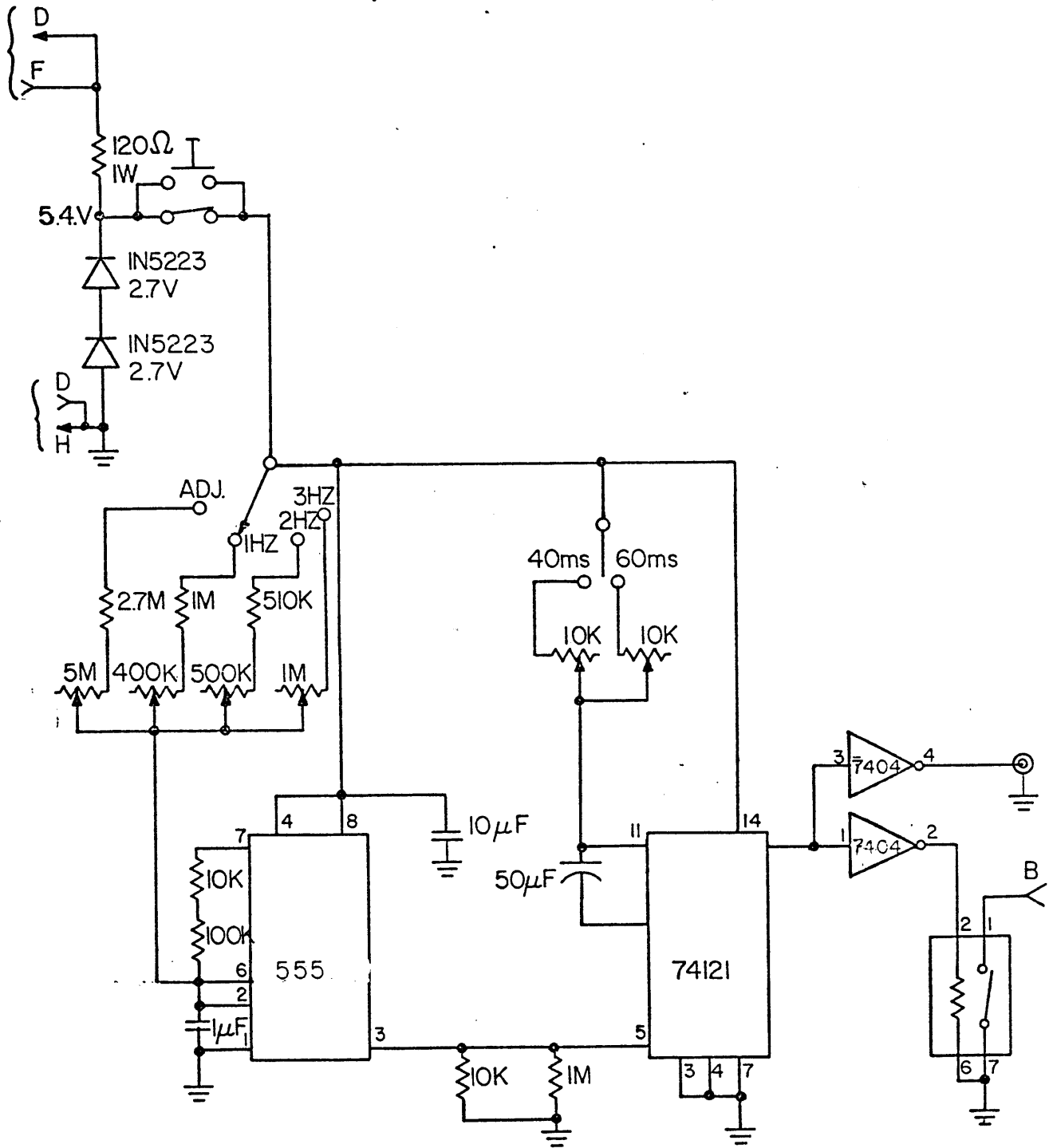
```

100 C
200 C TYPE OUTPUT
300 WRITE(6,305) IFRAME,((FIDUC(I,J),J=1,2),I=1,2),
400 + ((IFAL(K,L,1),I=1,2),K=1,2)
575 305 FORMAT(' FRAME NO.',I4,/,
600 + 17X,'FIDUCIARY MARKS: LEFT(',2F7.0,') RIGHT(',2F7.0,')',/,
700 + 17X,'IRAL LANDMARKS: LEFT(',2F7.0,') RIGHT(',2F7.0,')')
800 WRITE(6,307) (((IRAL(K,L,M),L=X,Y),K=LEFT,RIGHT),M=2,MMAX)
905 307 FORMAT('
910 + ('),2F7.0,')
1000 WRITE(6,309) ((AVIRAL(LR,XY),XY=X,Y),LR=LEFT,RIGHT)
1100 309 FORMAT('
1200 + 2F7.0,')
1300 WRITE(6,311) ((SDIRAL(LR,XY),XY=X,Y),LR=LEFT,RIGHT)
1400 311 FORMAT('
1500 + 2F7.0,')
1600 WRITE(6,321) HANGLE,RANGLE,RANGLE,SDANGLE
1650 321 FORMAT('
1654 + HEAD ANGLE WRT FILM:',F7.1,' DEG',/,
1658 + EYE ANGLE WRT FILM: ',F7.1,' DEG',/,
1662 + EYE ANGLE WRT HEAD: ',F7.1,' DEG',/,
1664 + STD DEV OF EYE ANGLE WRT FILM:',F7.2,
1666 + ' DEG',/,
1800 FRAME=IFRAME ! FLOAT FRAME NUMBER FOR PLOTTING
1900 WRITE(2,323) FRAME,RANGLE,SDANGLE
2100 323 FORMAT(F9.0,F9.1,F9.2)
2200 325 IFRAME=CFRAME
2300 R=1
2400 IF (FLAG1.NE.1) GO TO 200
2500 GO TO 910
2600 900 FLAG1=1
2700 GO TO 220 ! PROCESS LAST FRAME
2800 910 TYPE 911,(INFILE(I),I=1,6)
2850 WRITE(6,911) (INFILE(I),I=1,6)
2900 911 FORMAT('OEND OF FILE ',6A1)
3000 END

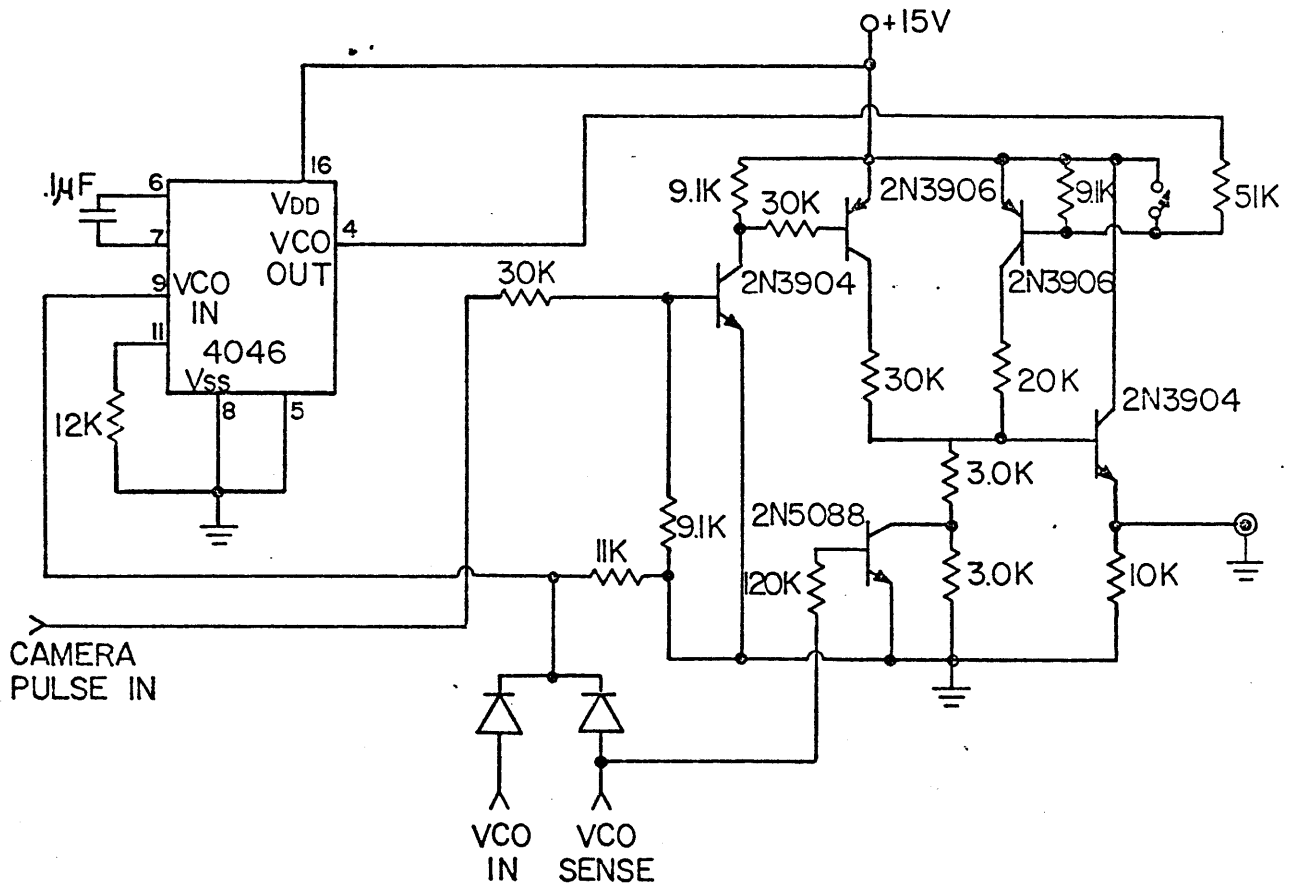
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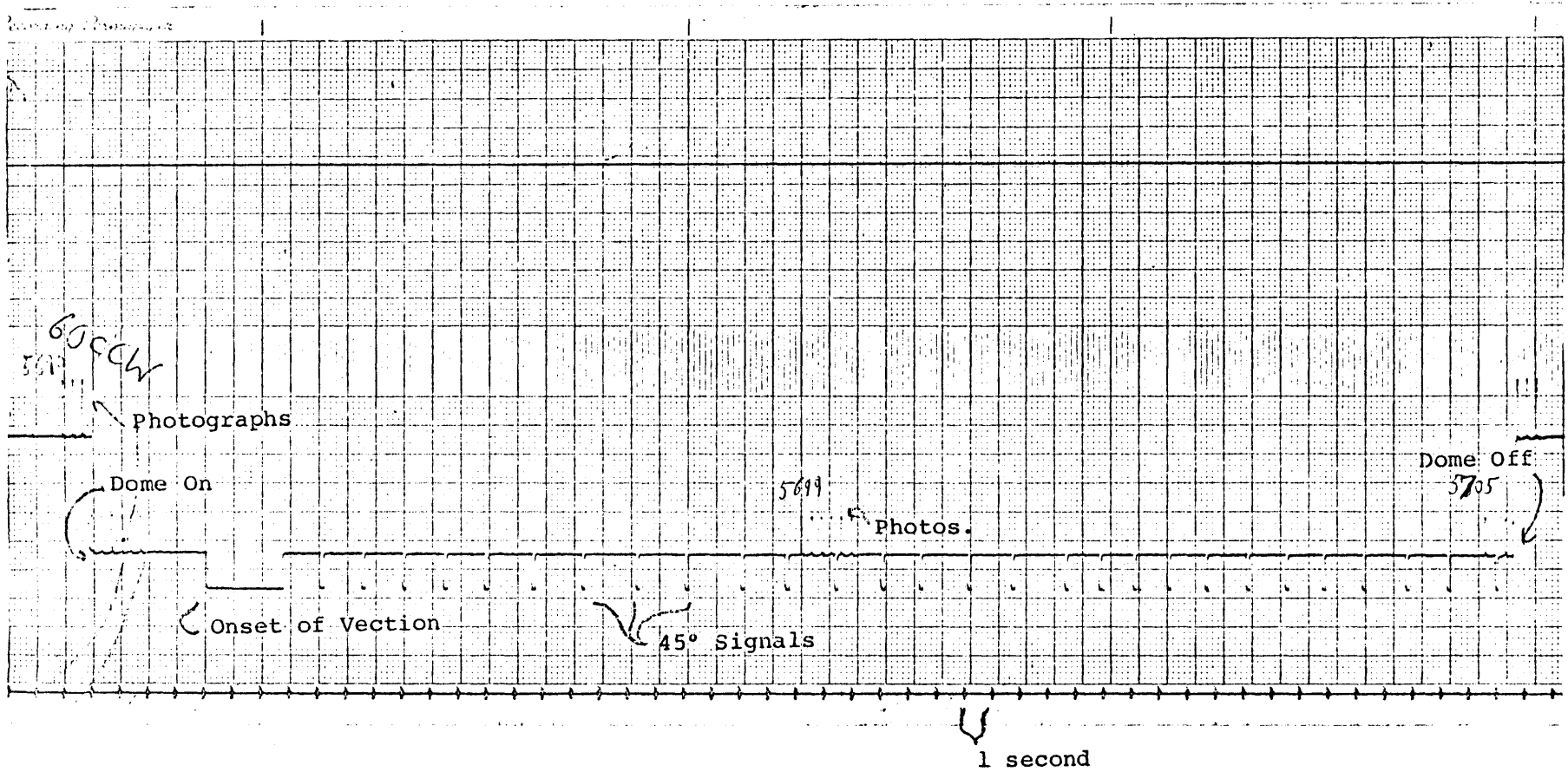
APPENDIX C. Schematic of Dome Circuitry



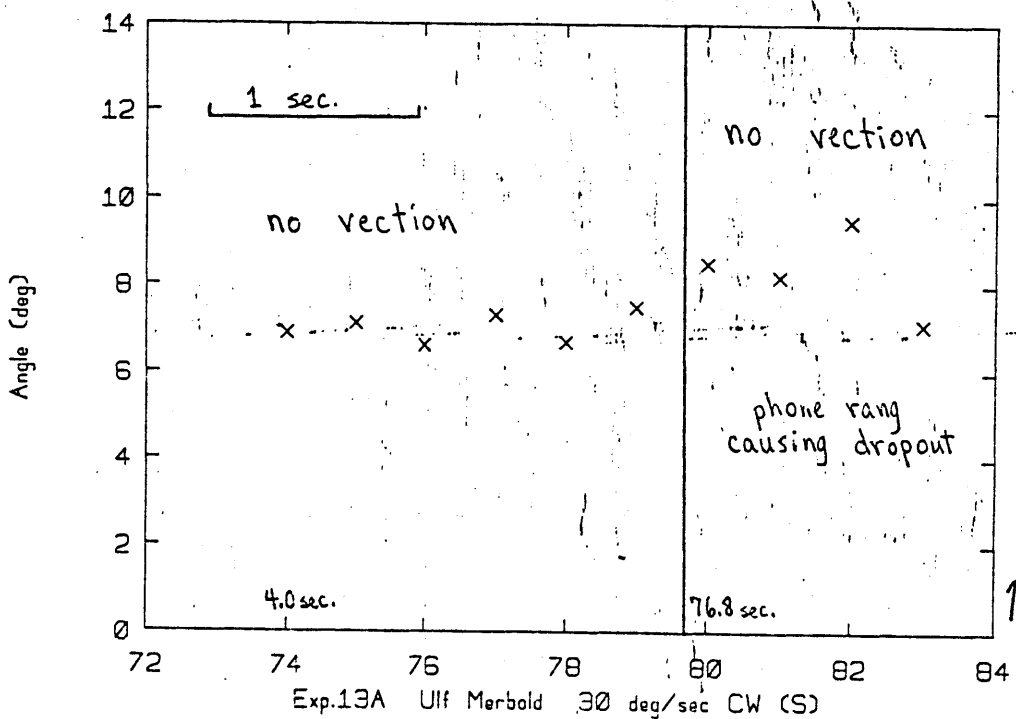
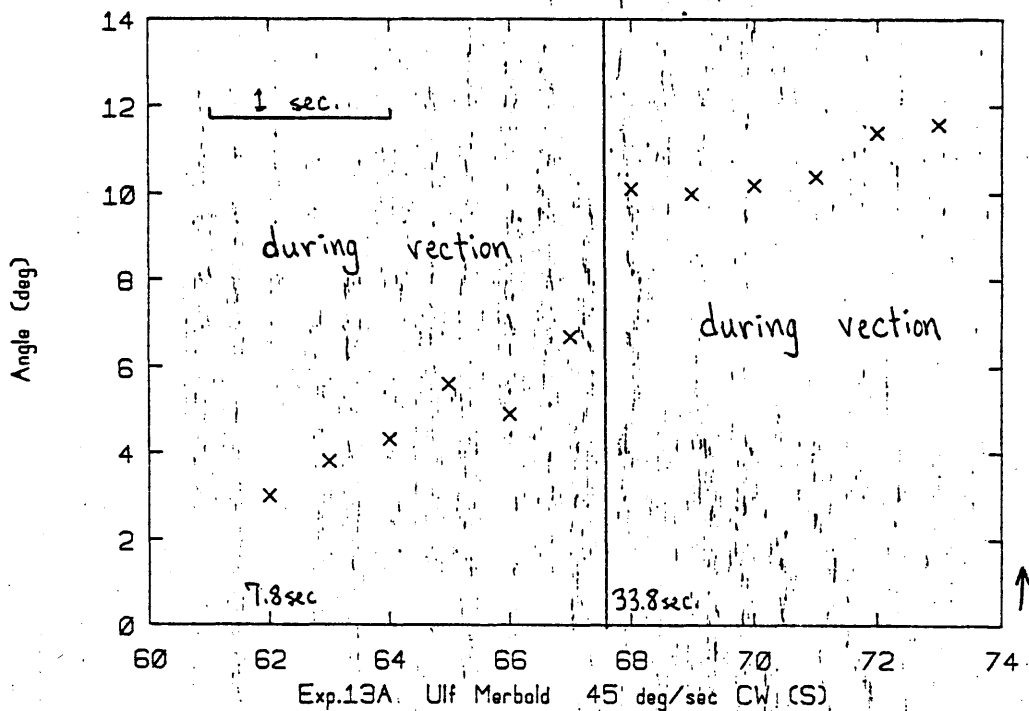
INTERVALOMETER CIRCUIT

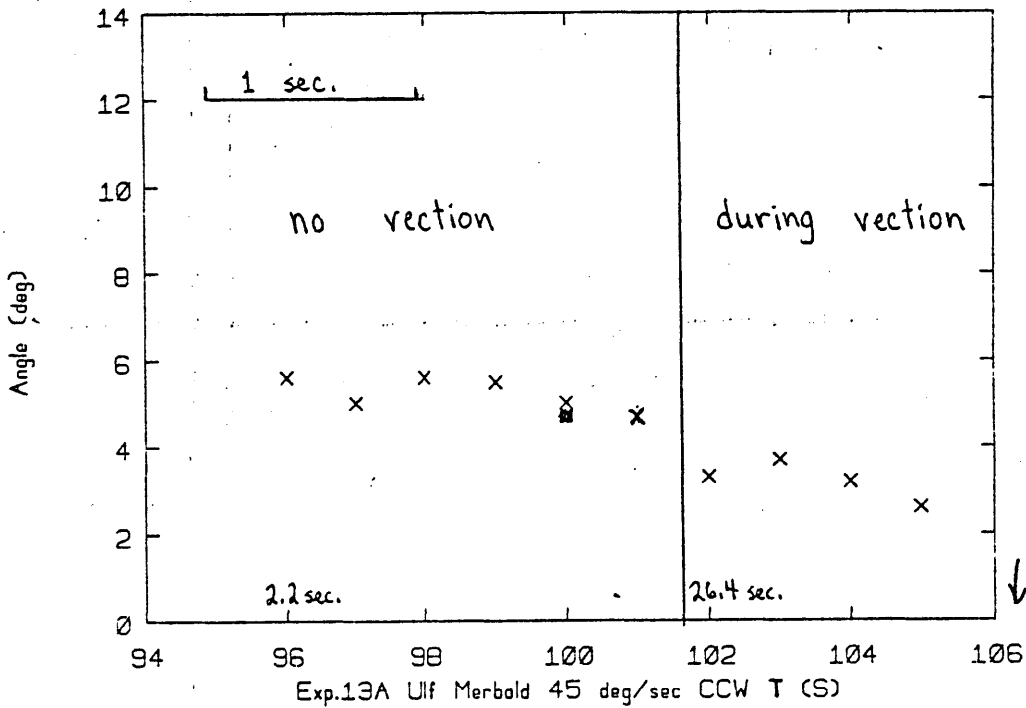
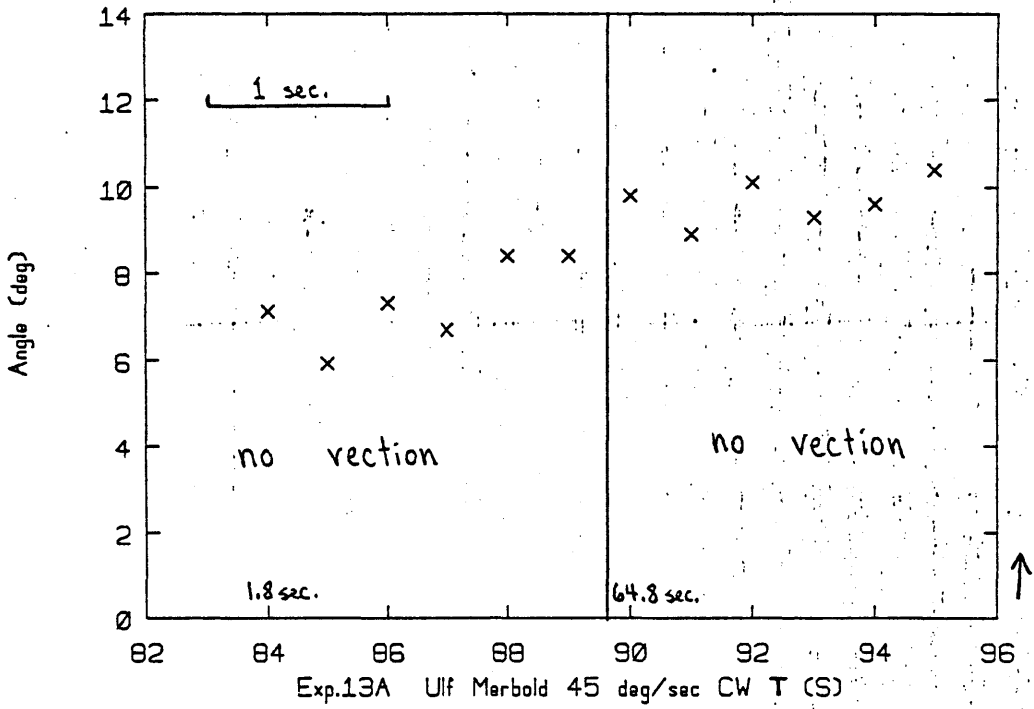


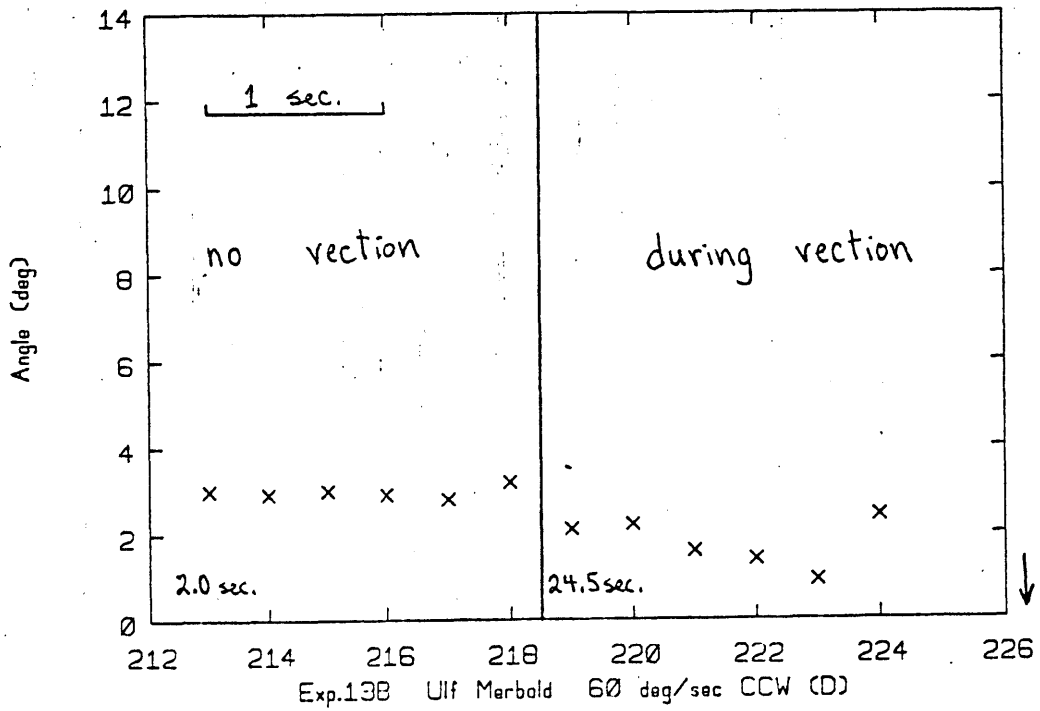
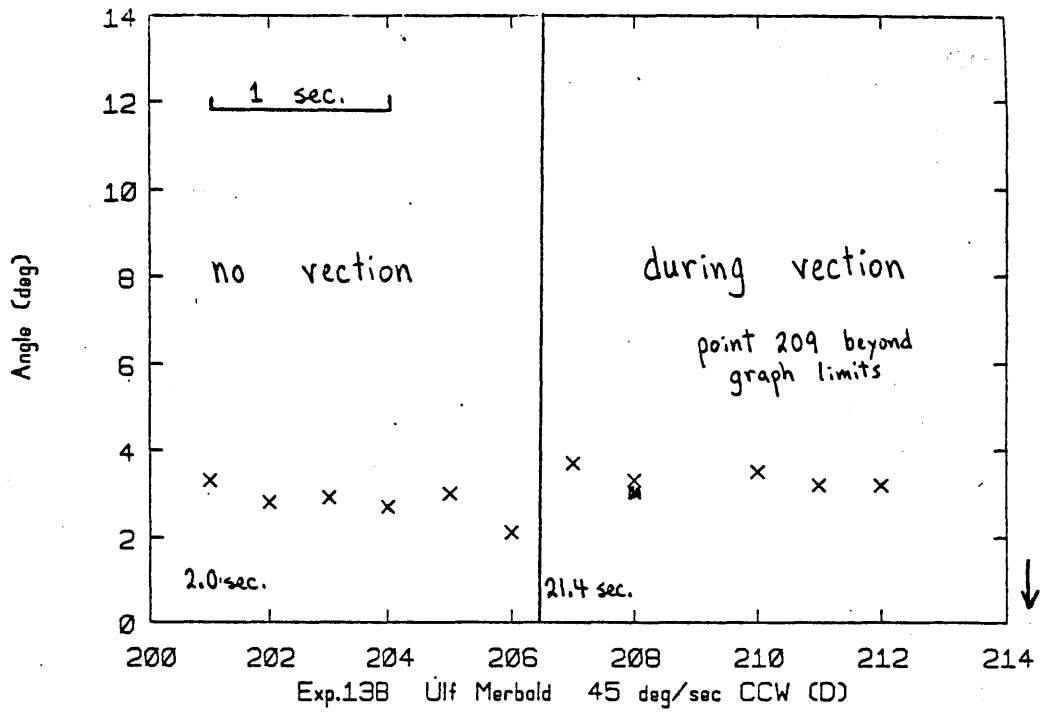
INSTRUMENTATION CIRCUIT

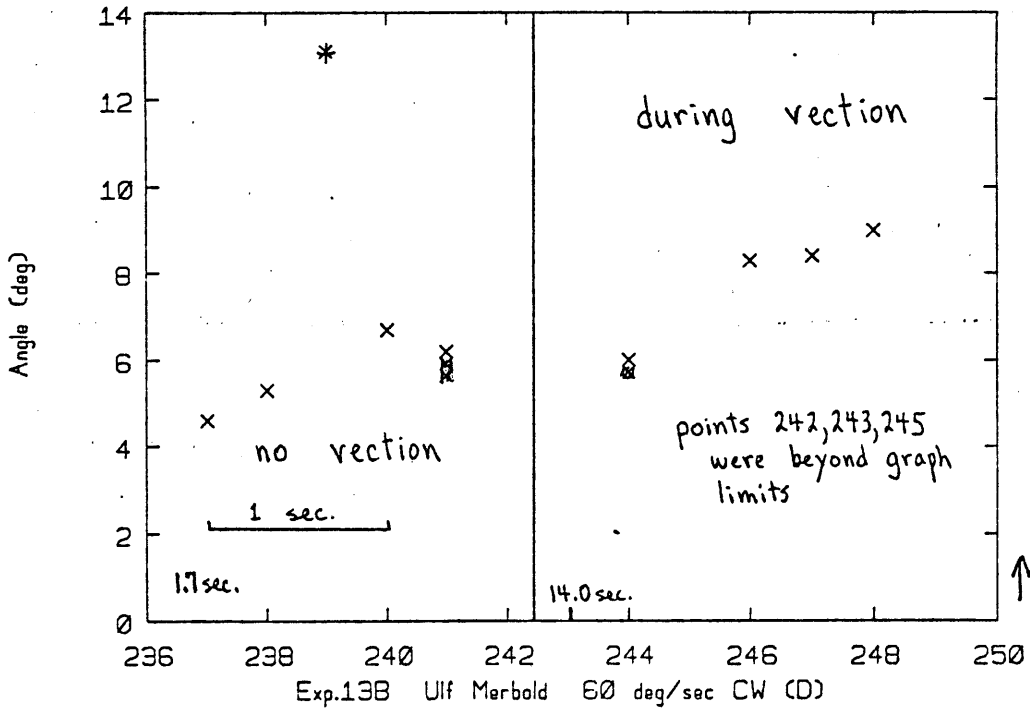
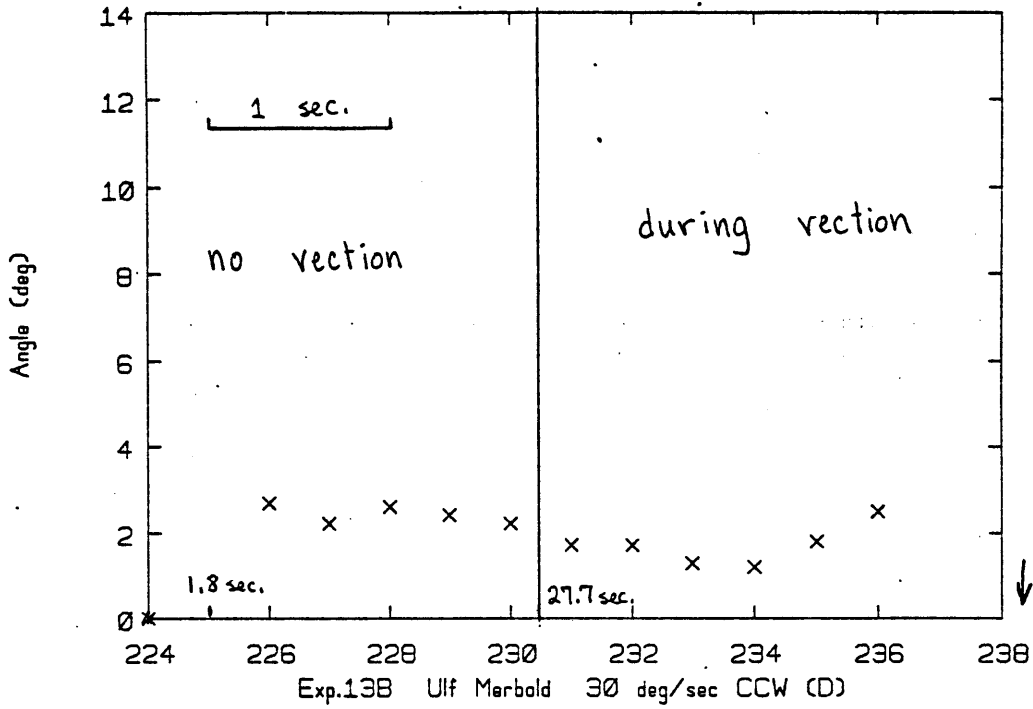


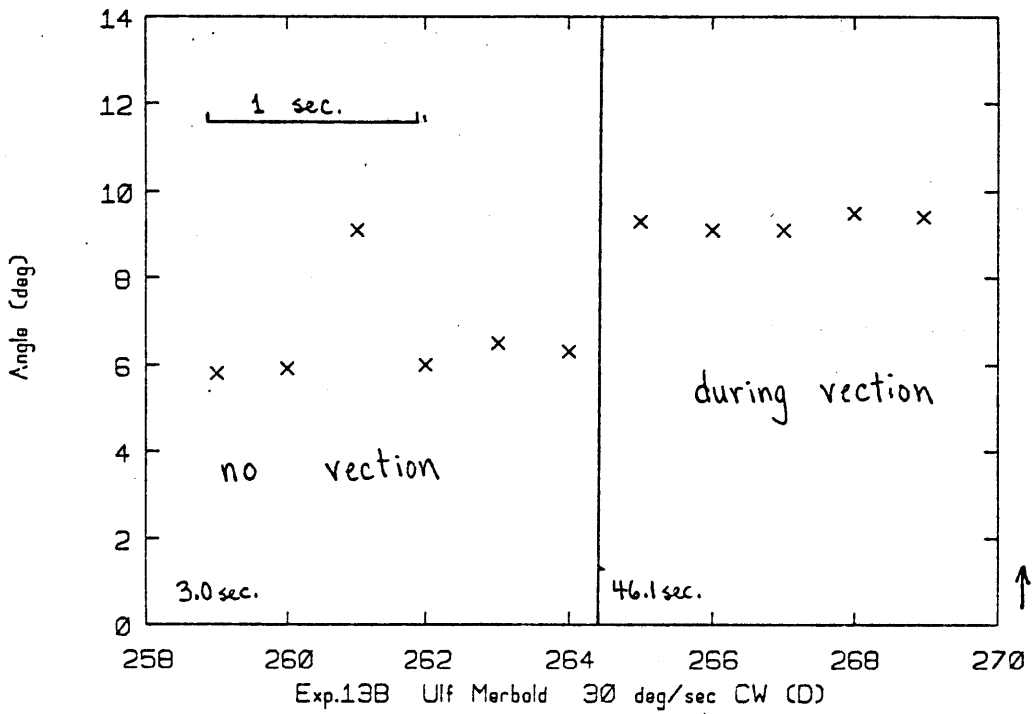
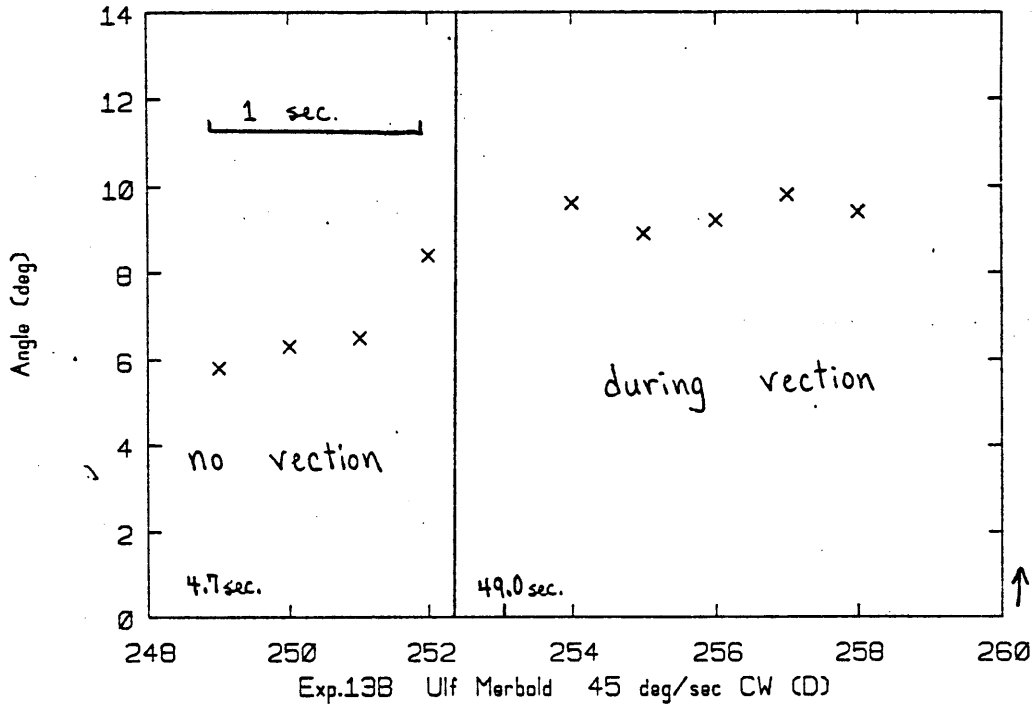
SAMPLE OUTPUT

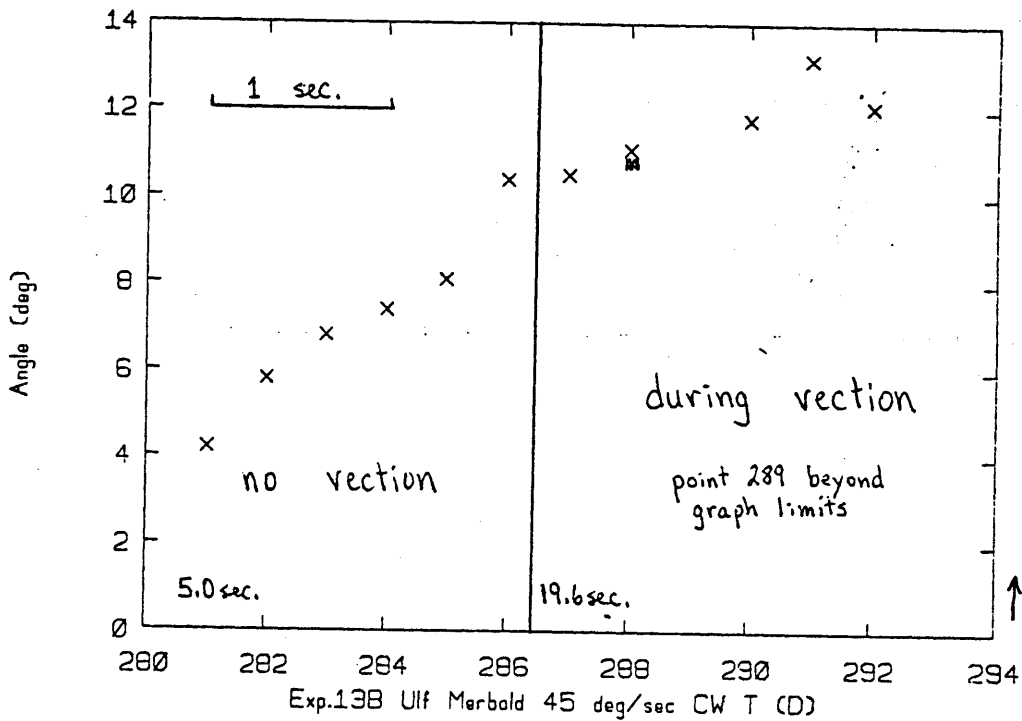
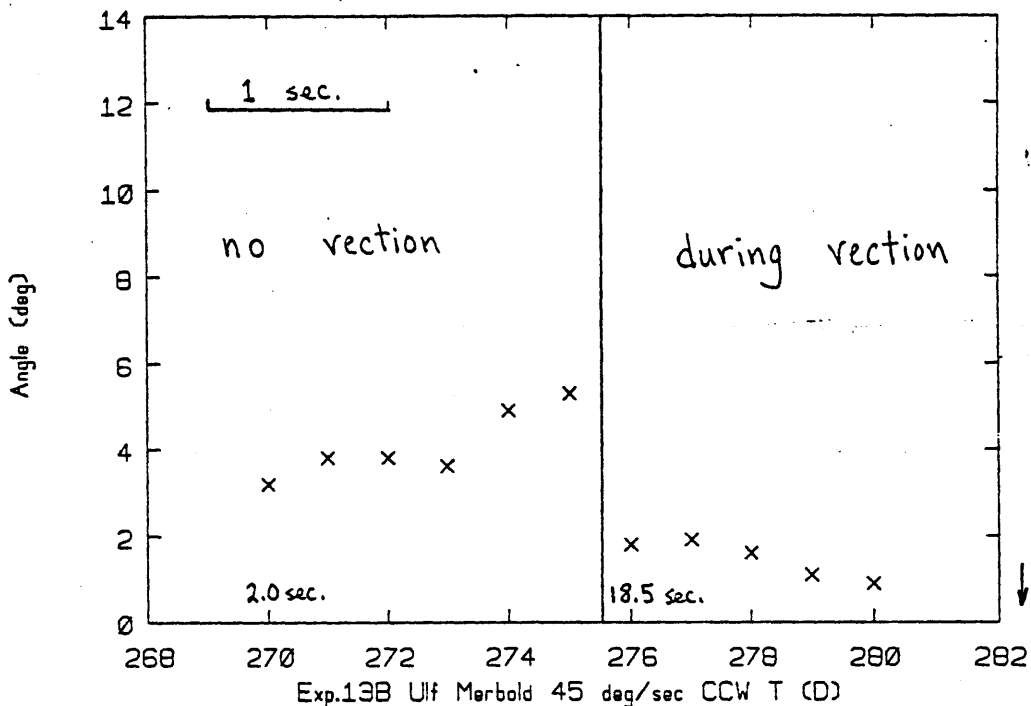


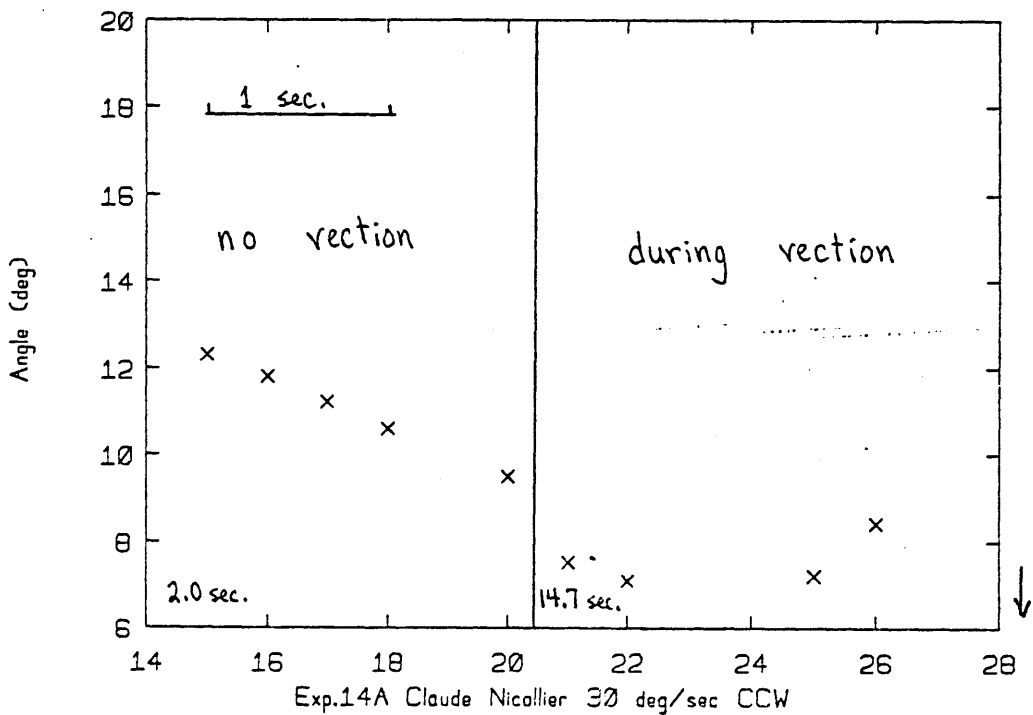
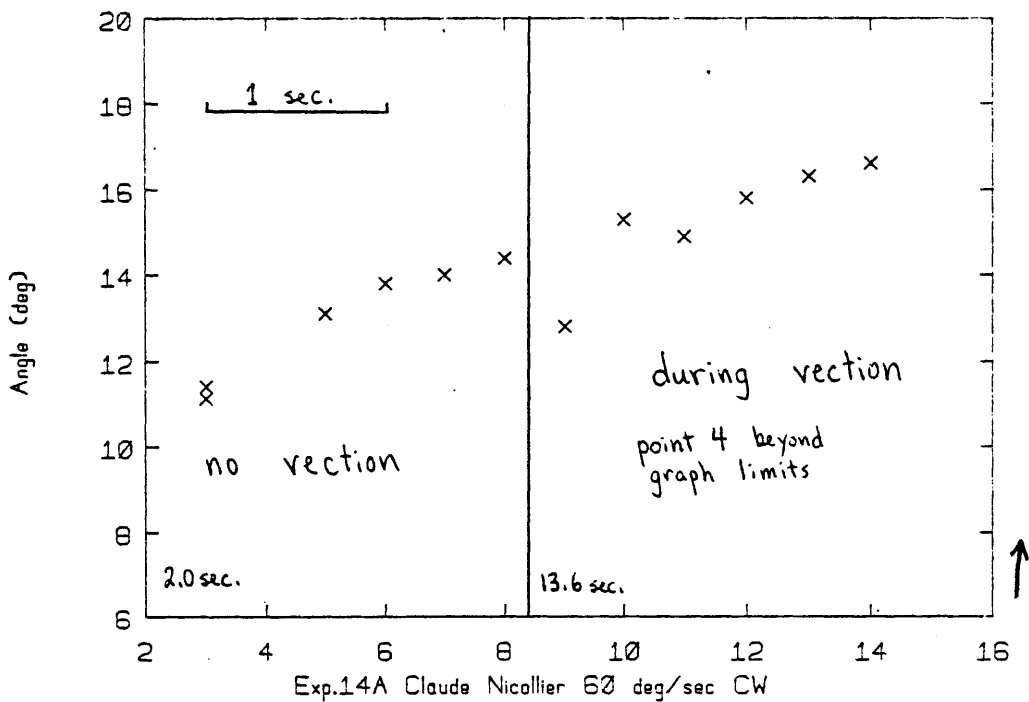


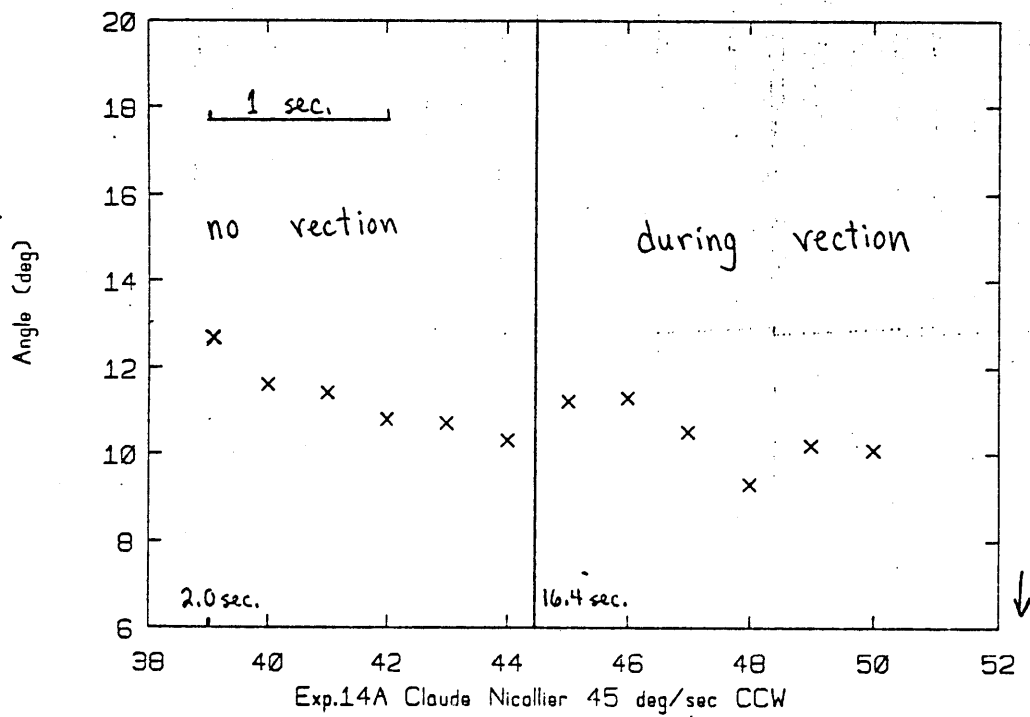
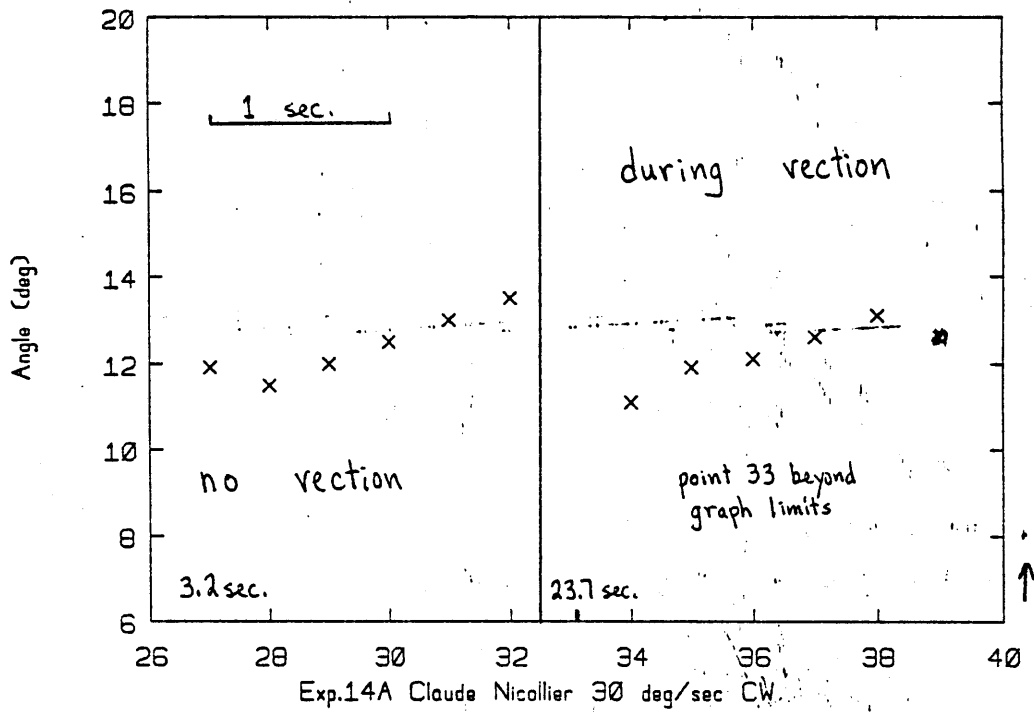


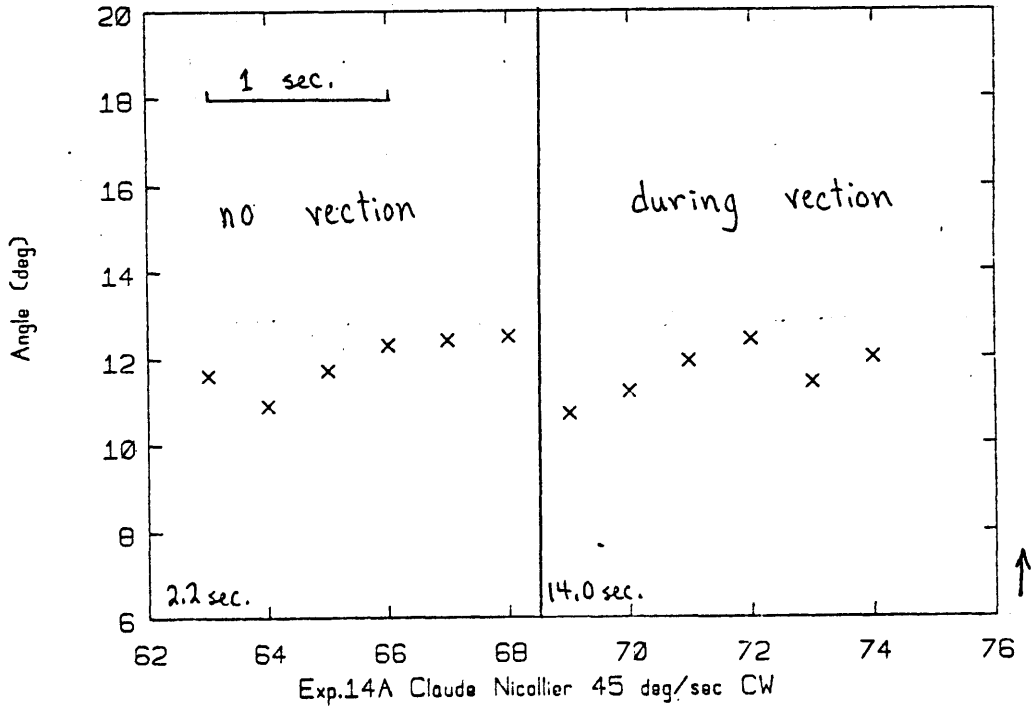
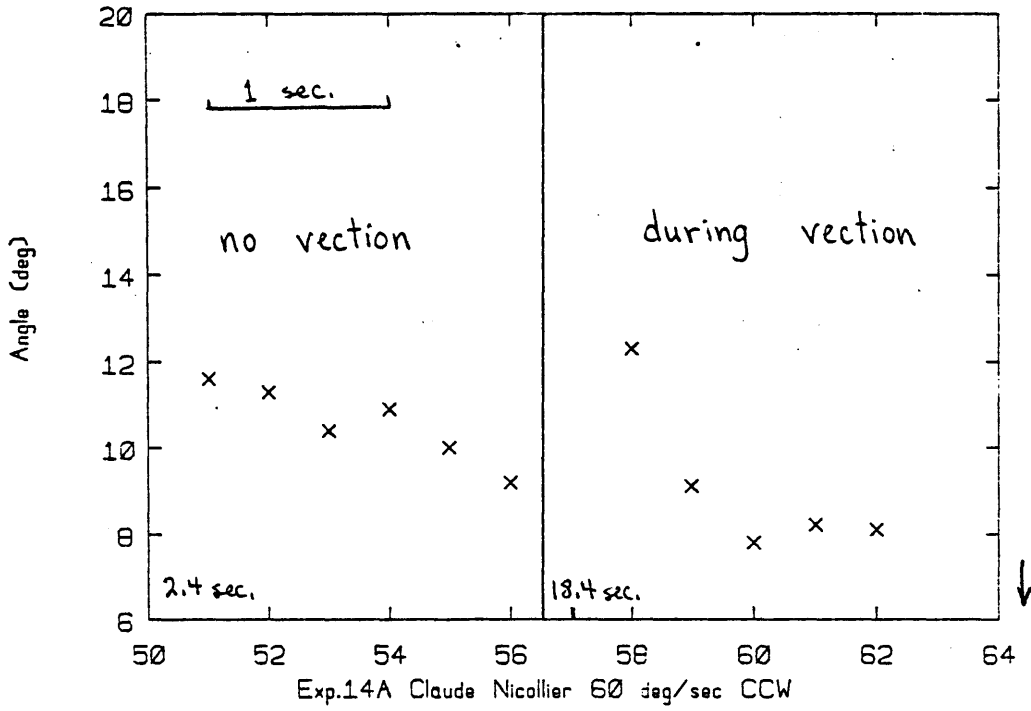


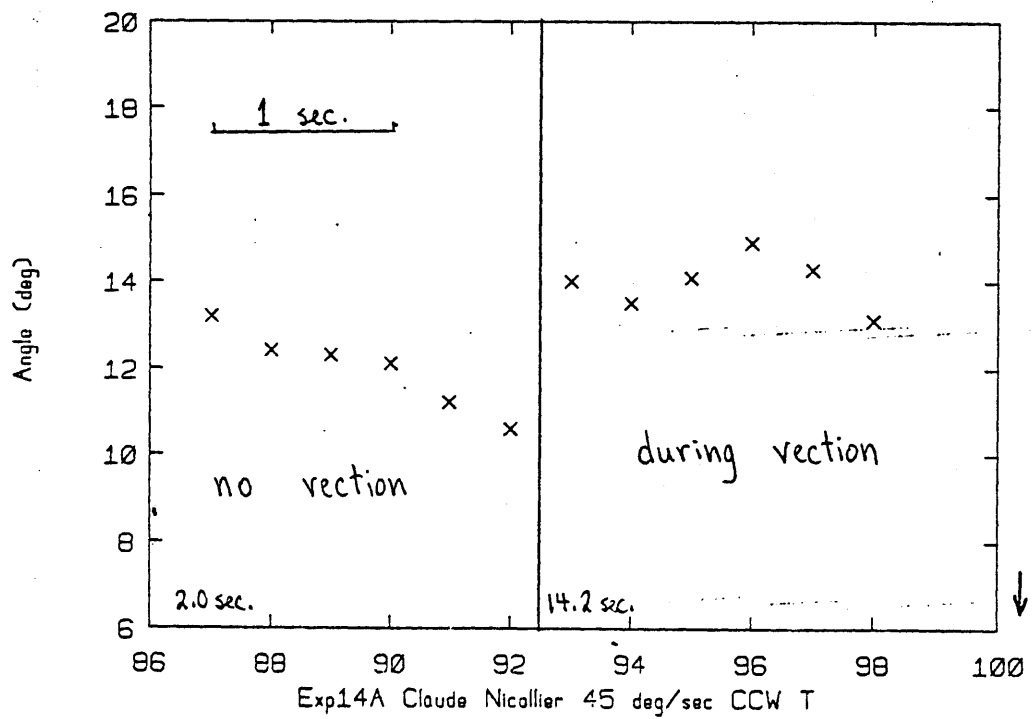
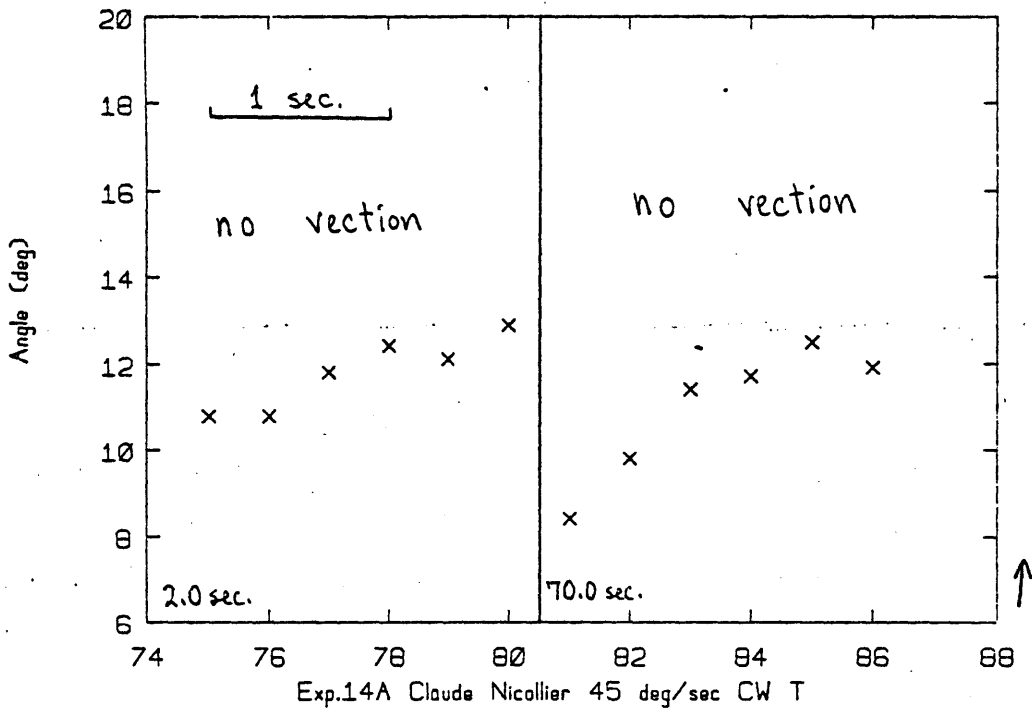


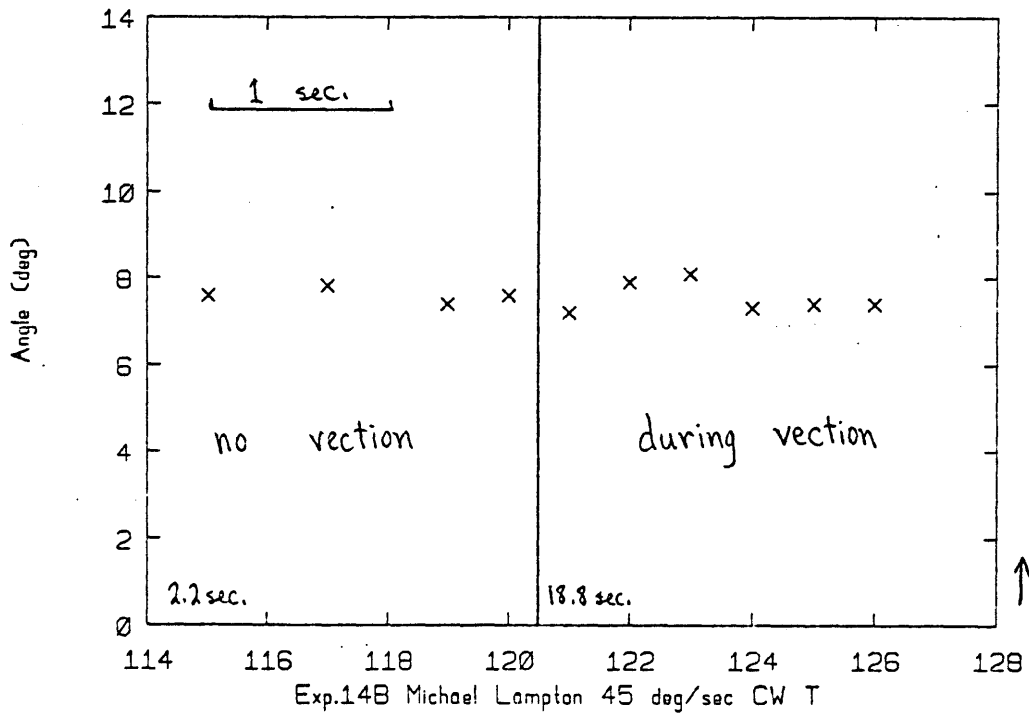
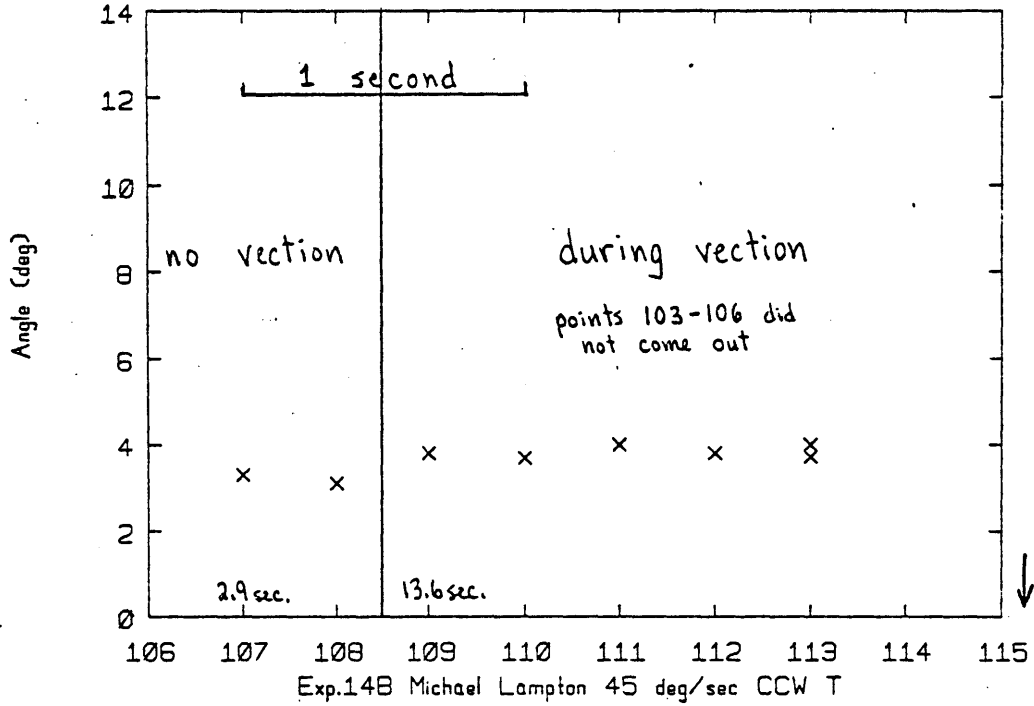


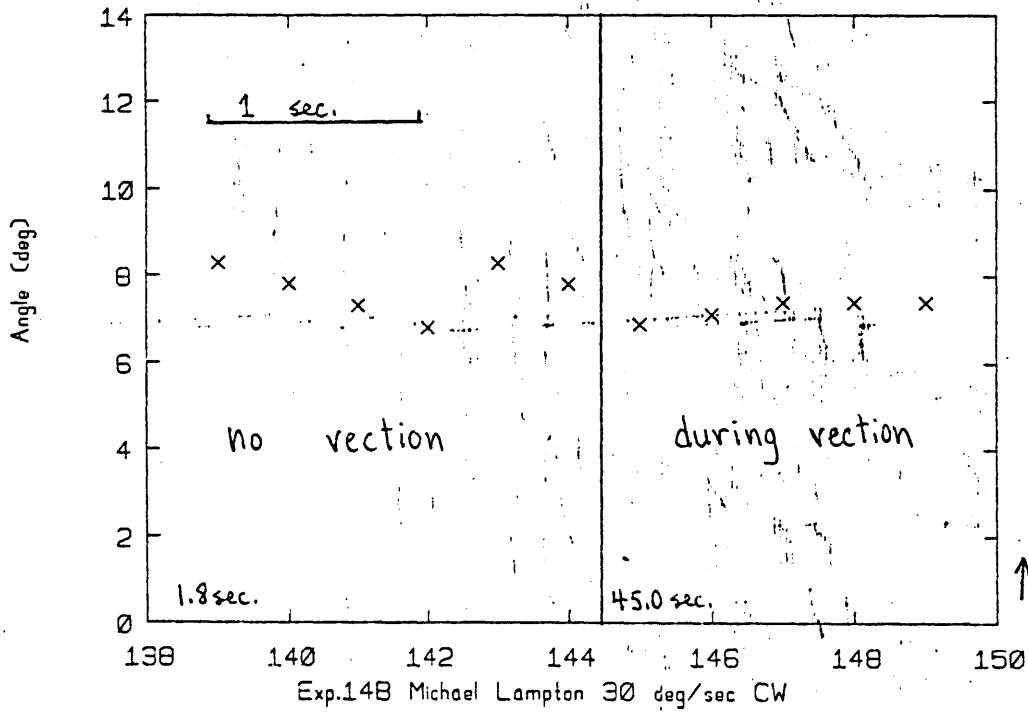
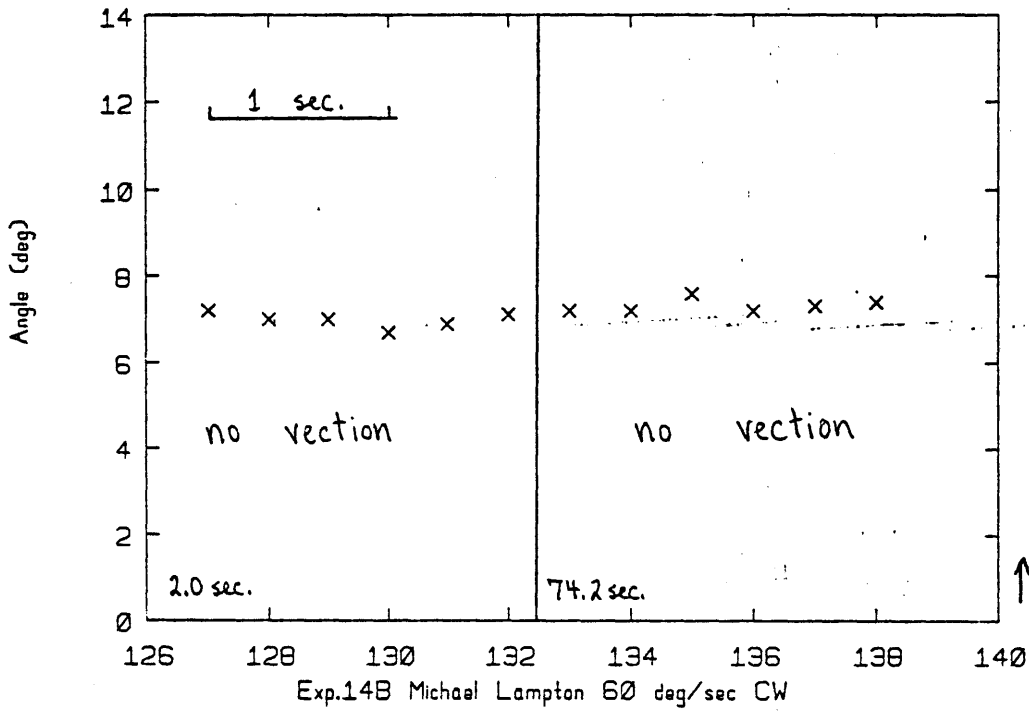


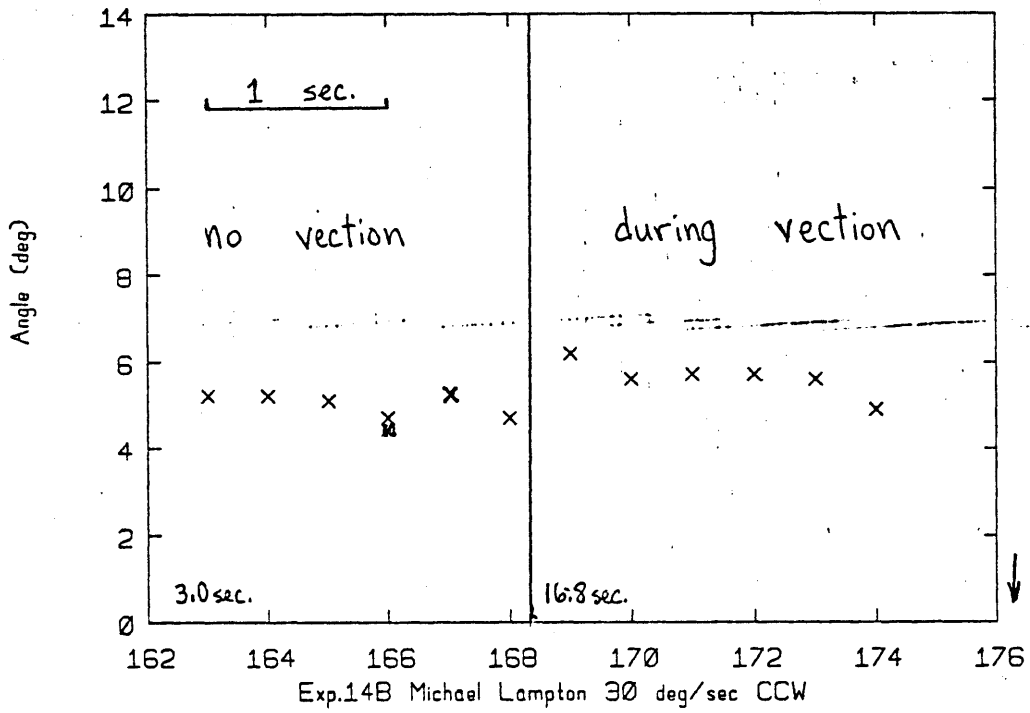
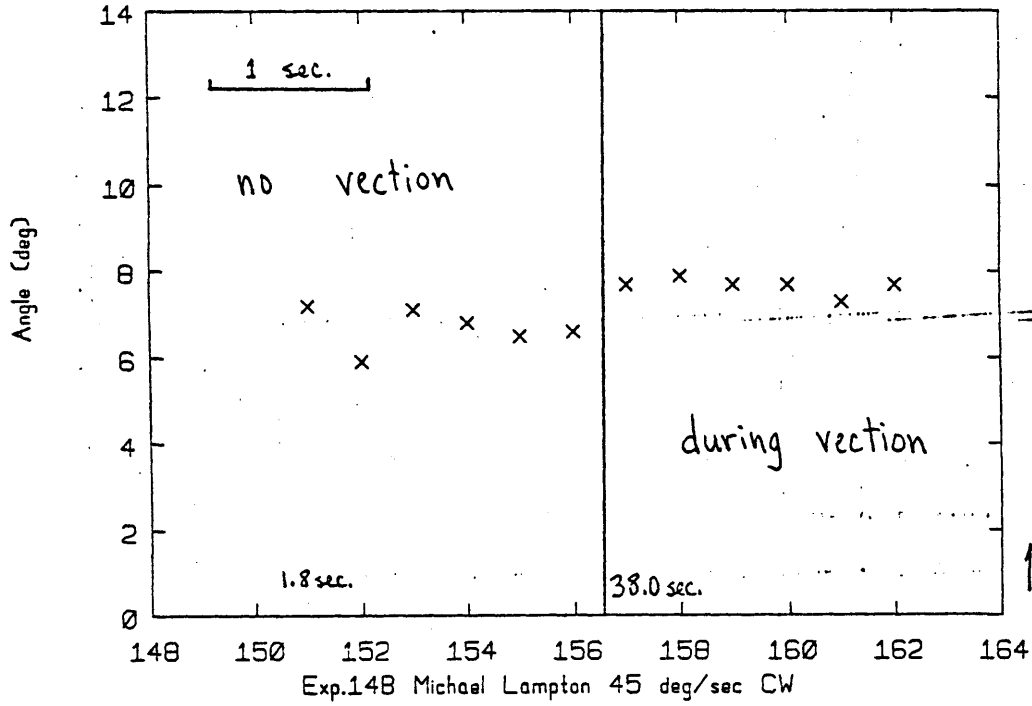


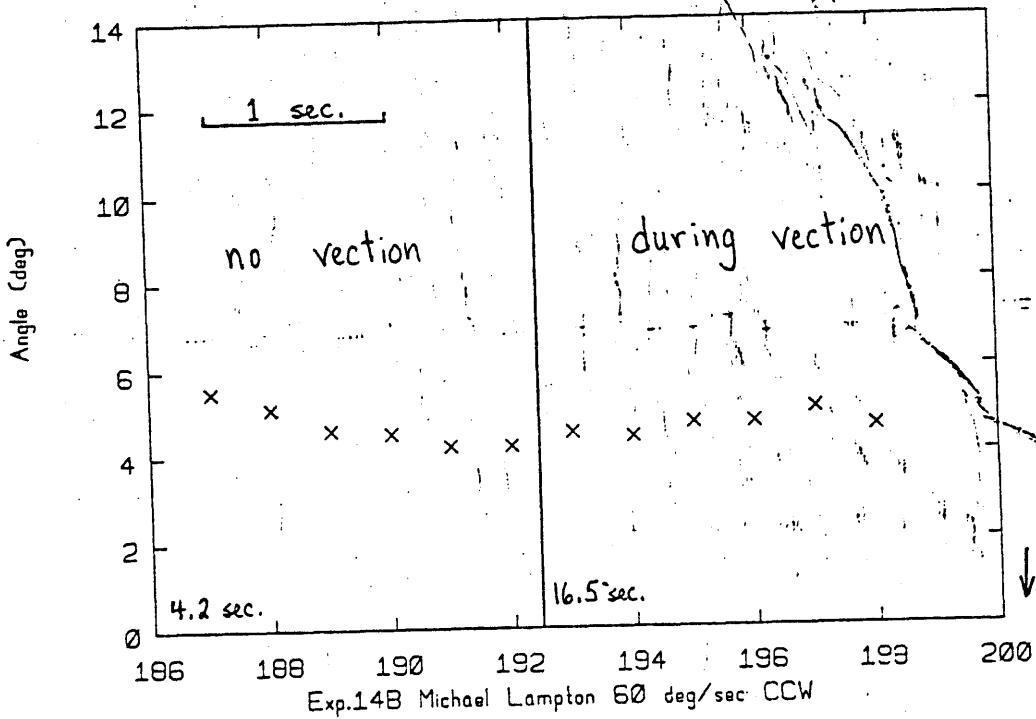
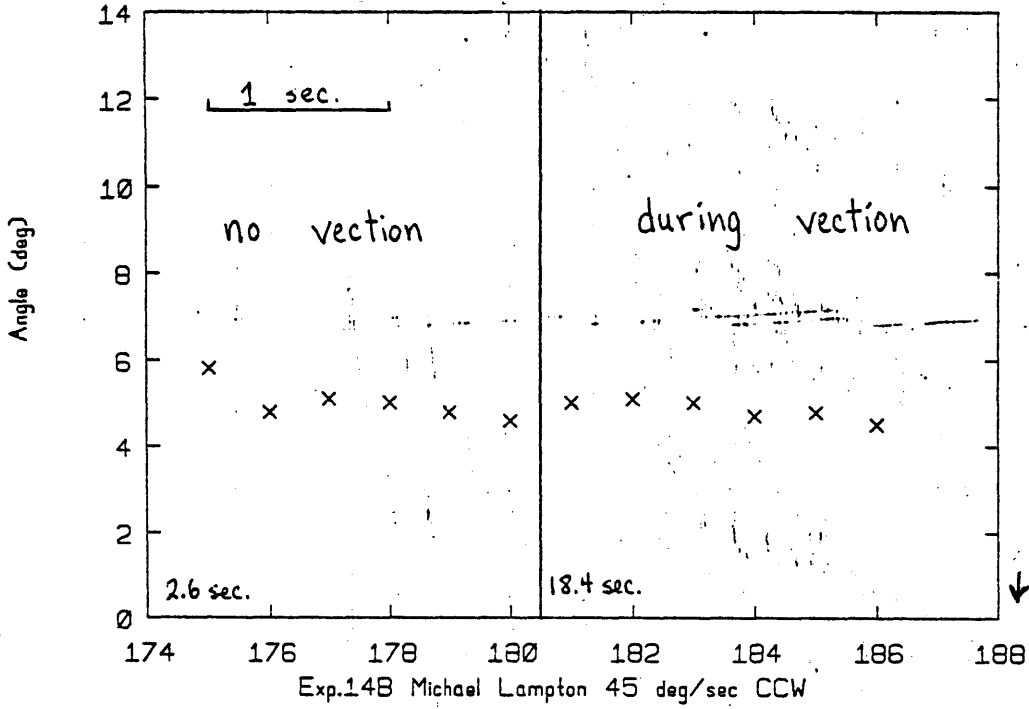


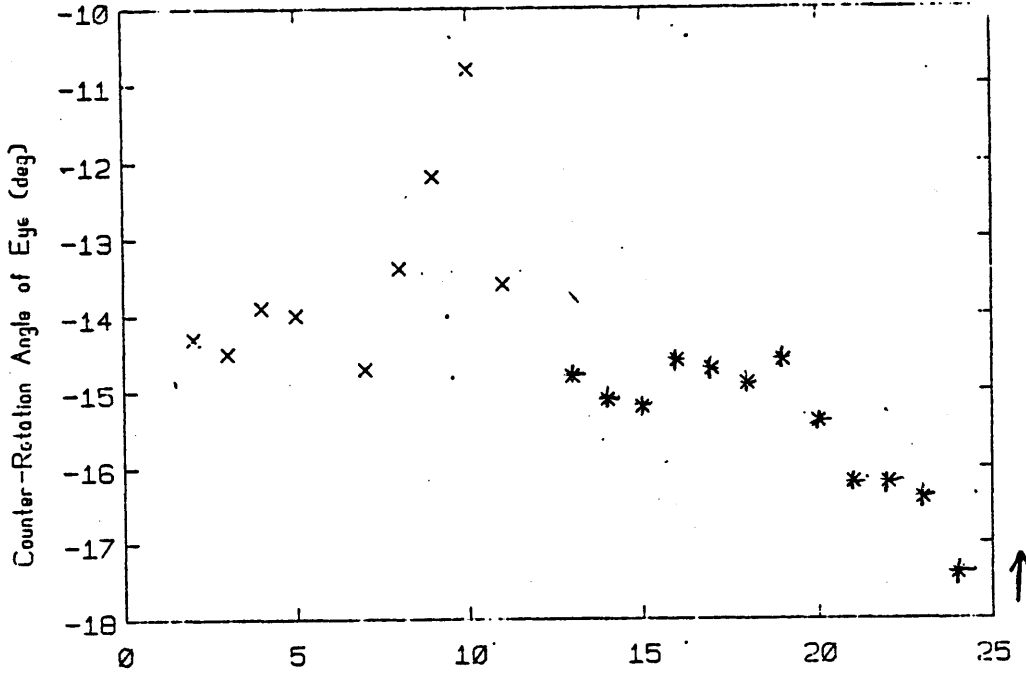






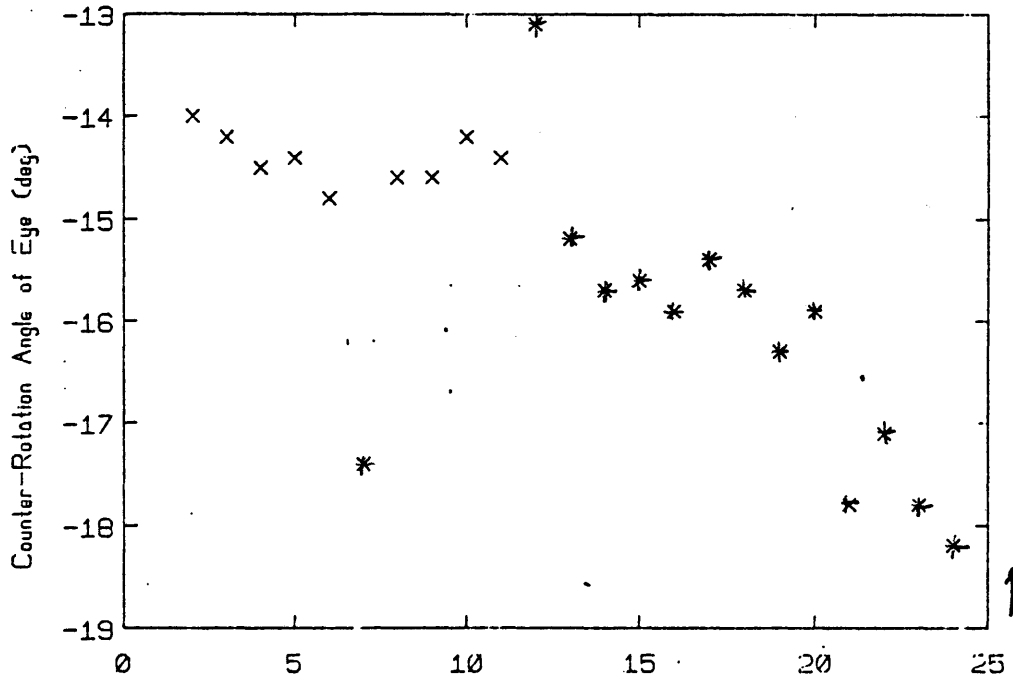






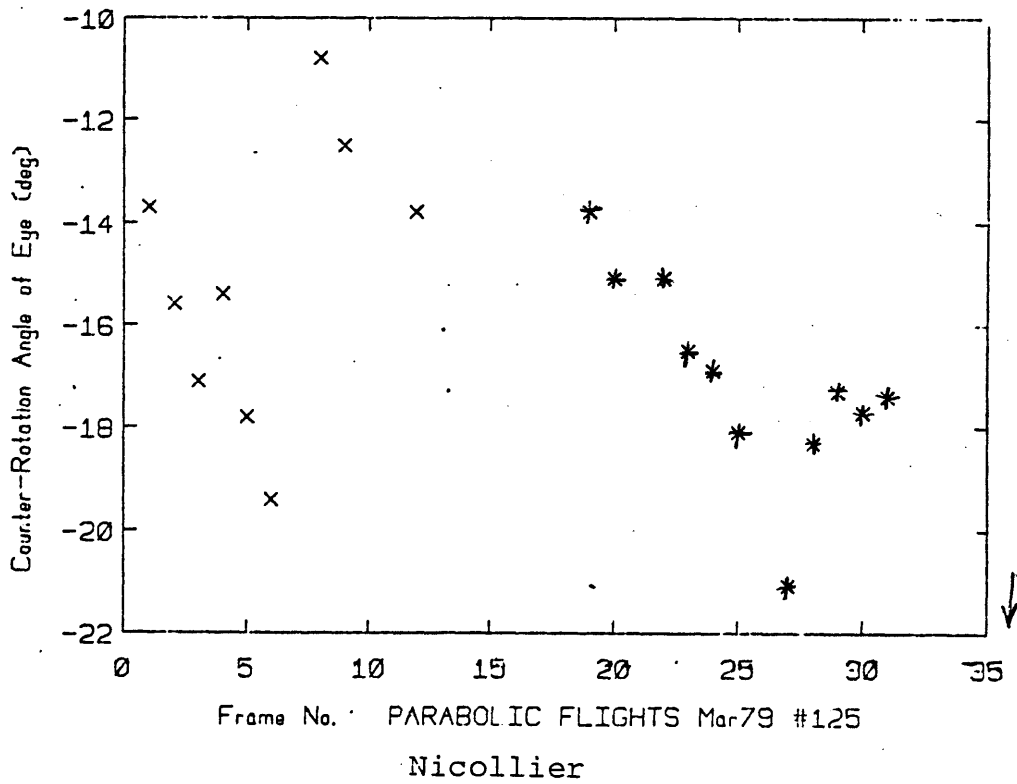
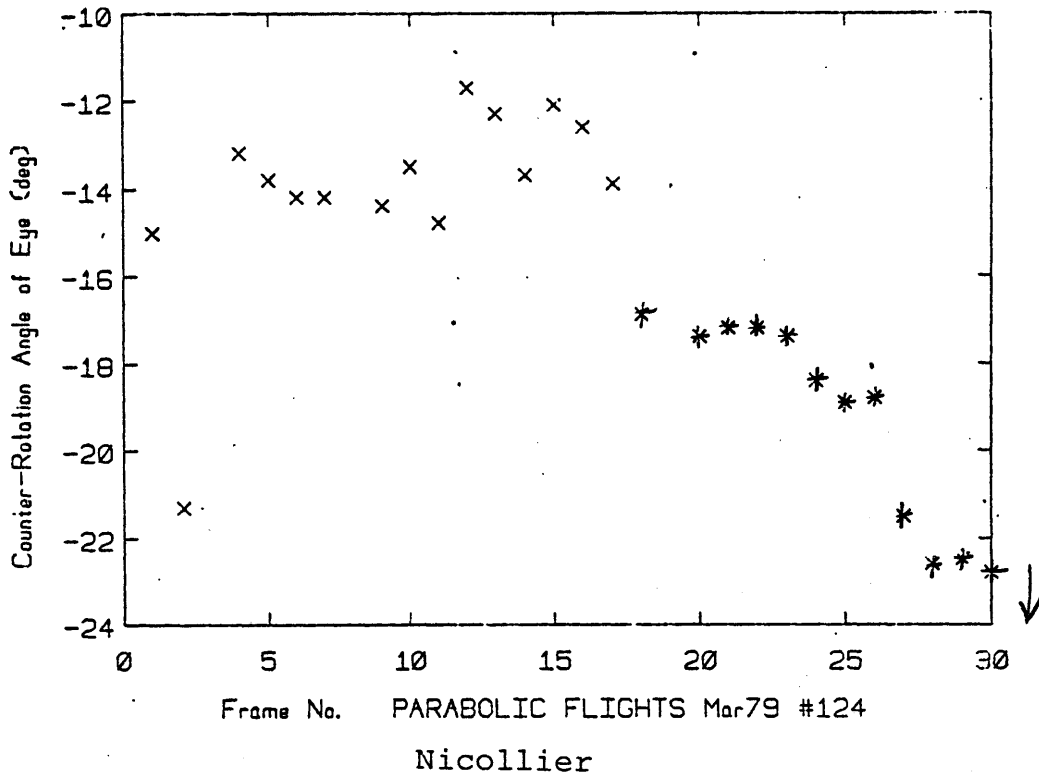
Frame No. PARABOLIC FLIGHTS Mar79 #121

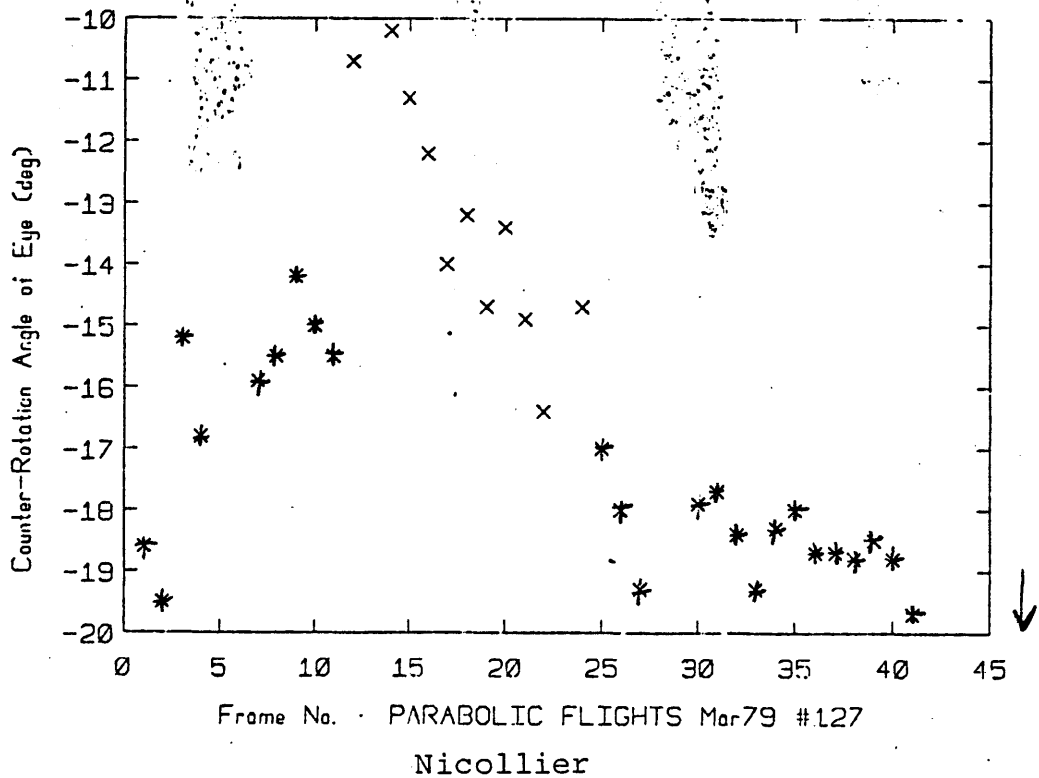
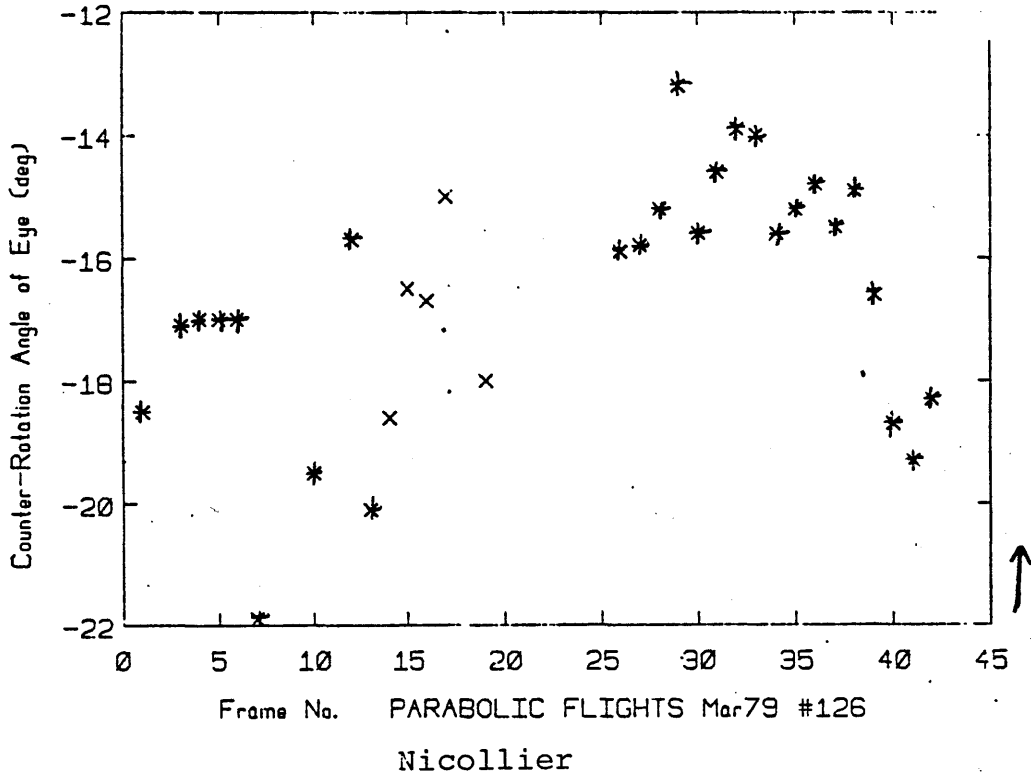
Nicollier

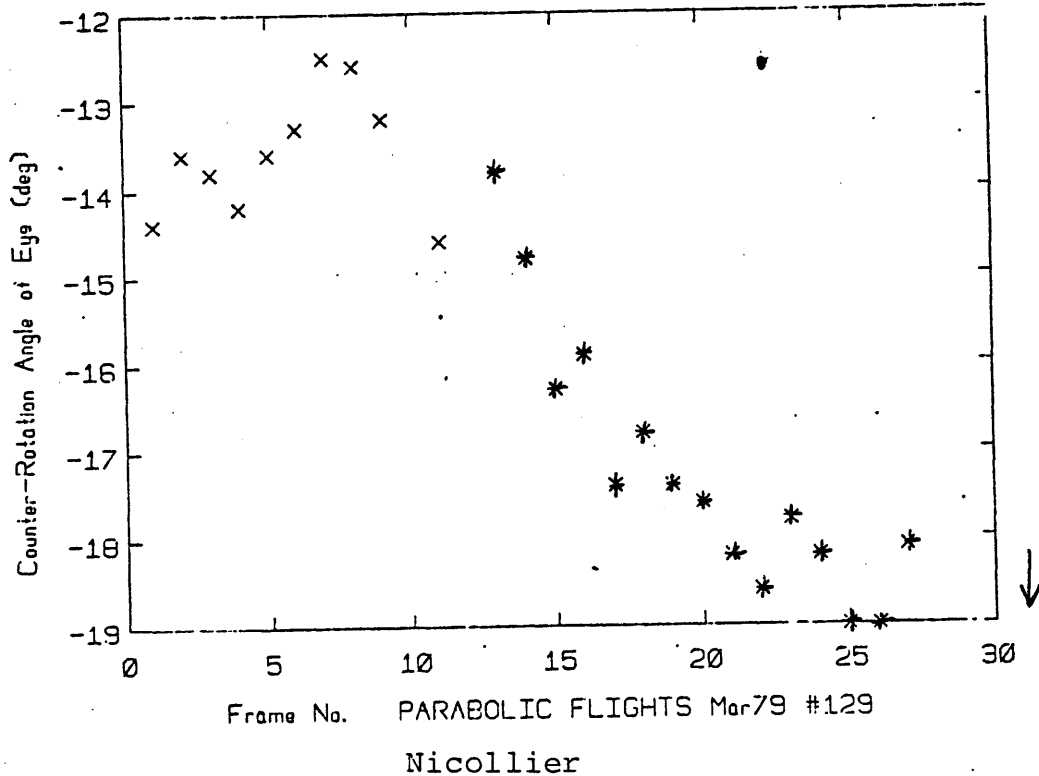
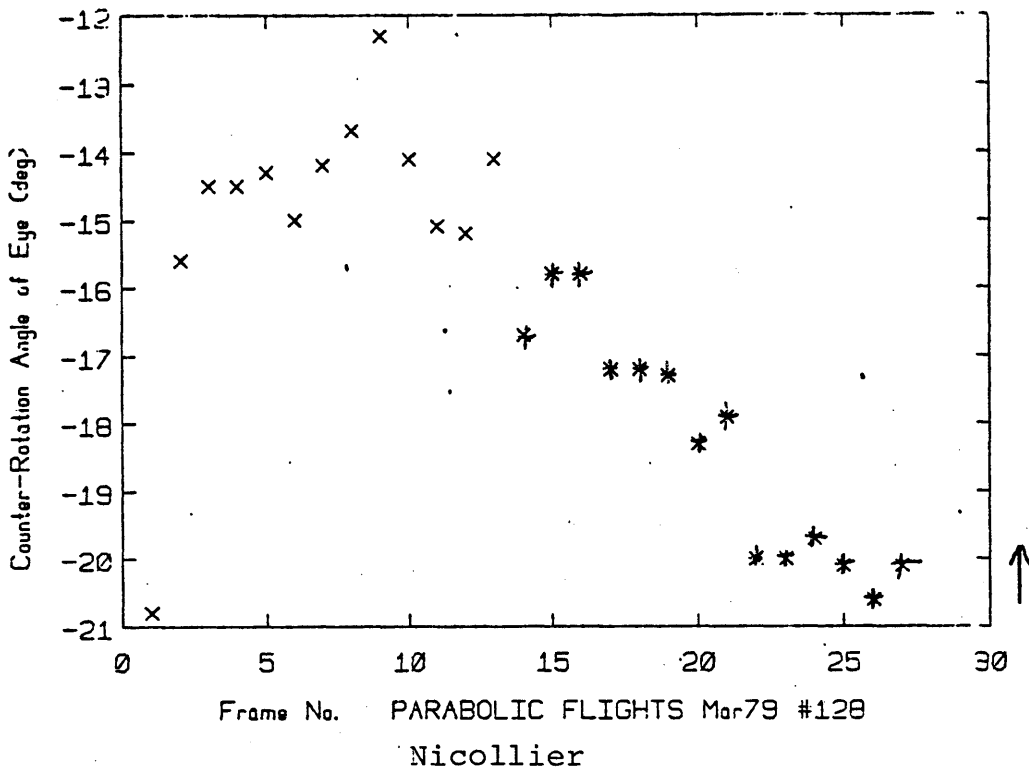


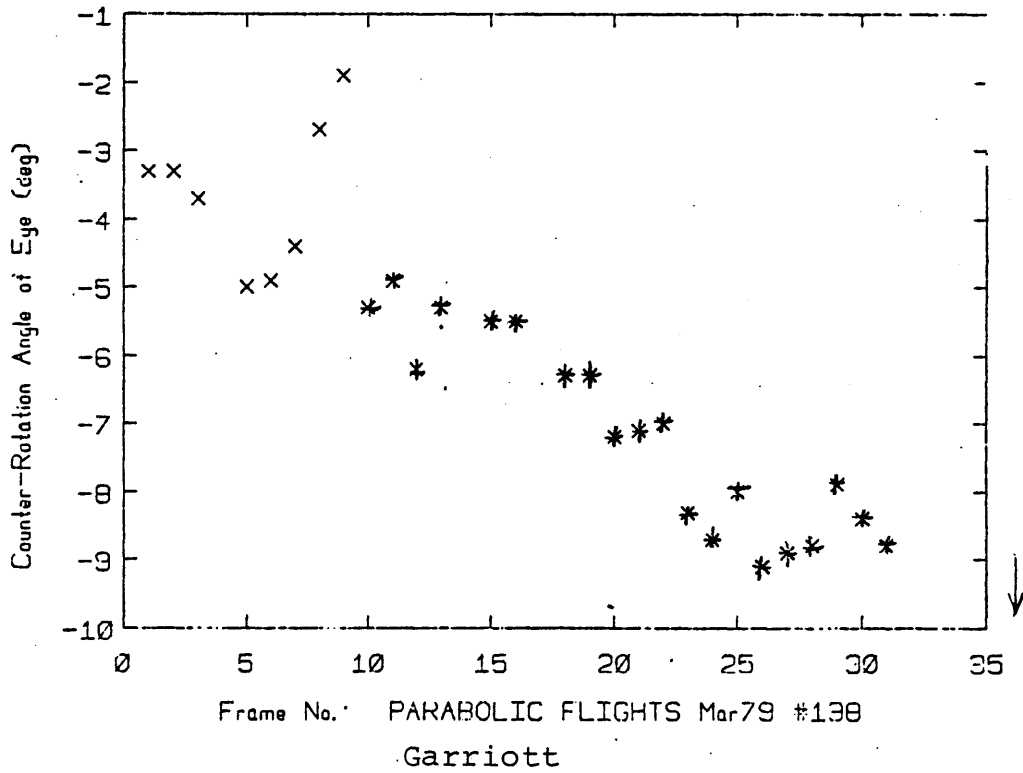
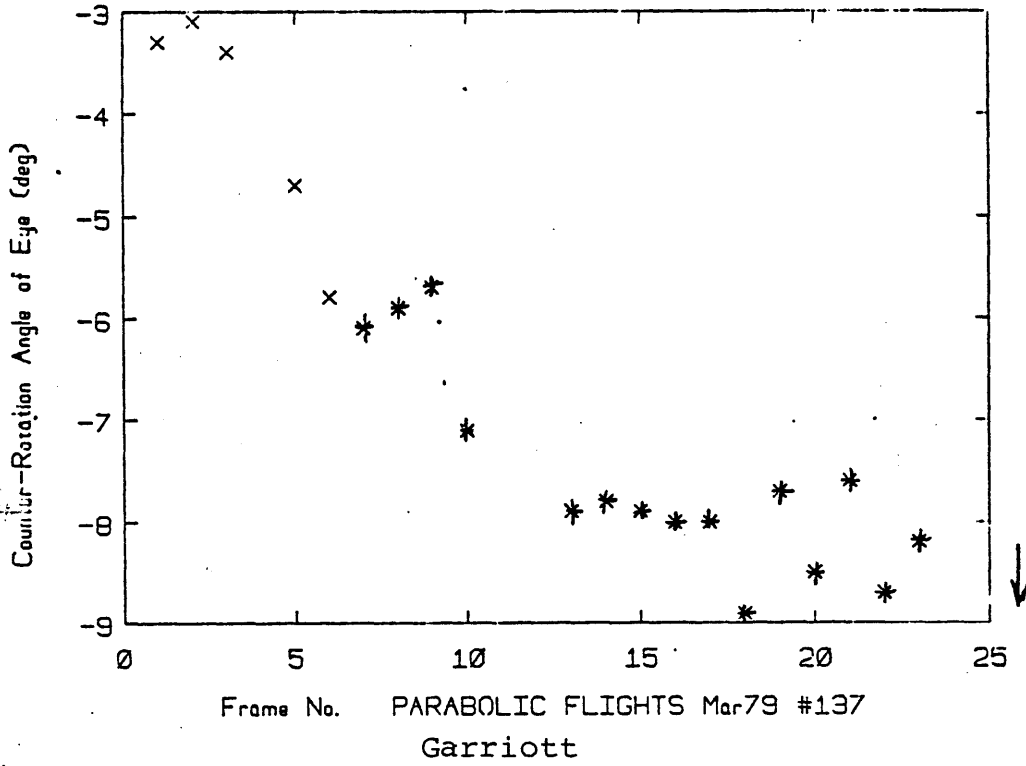
Frame No. PARABOLIC FLIGHTS Mar79 #123

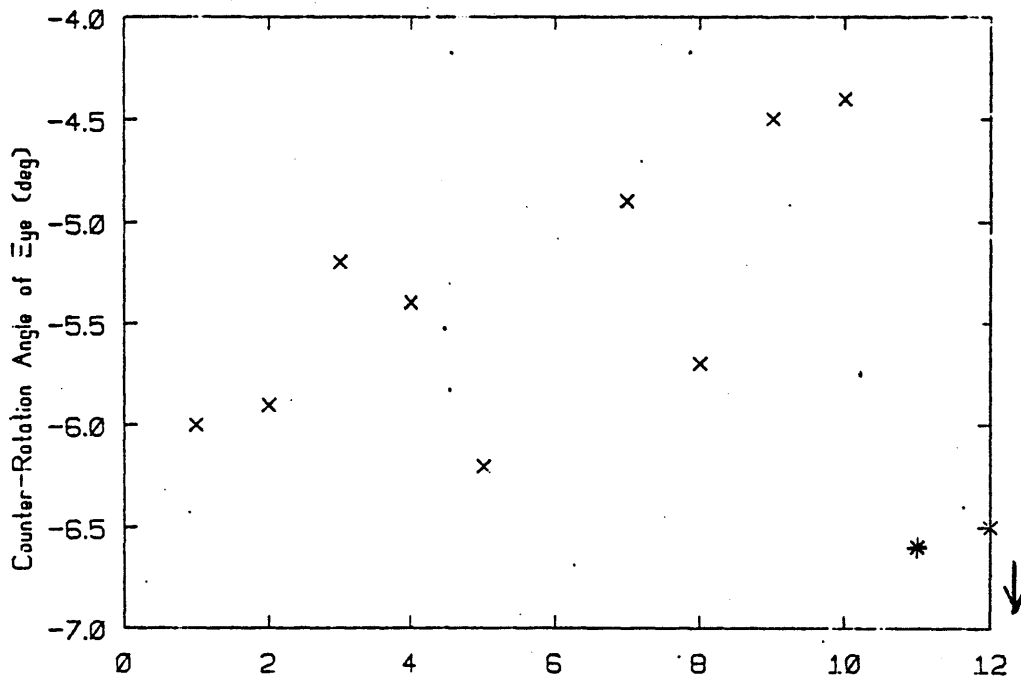
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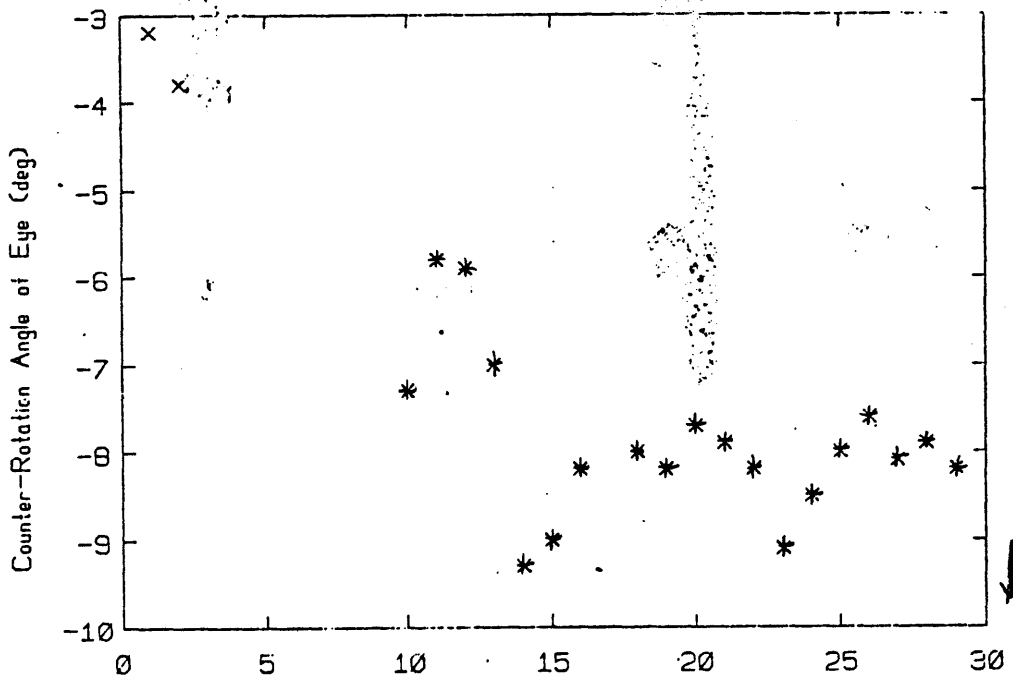




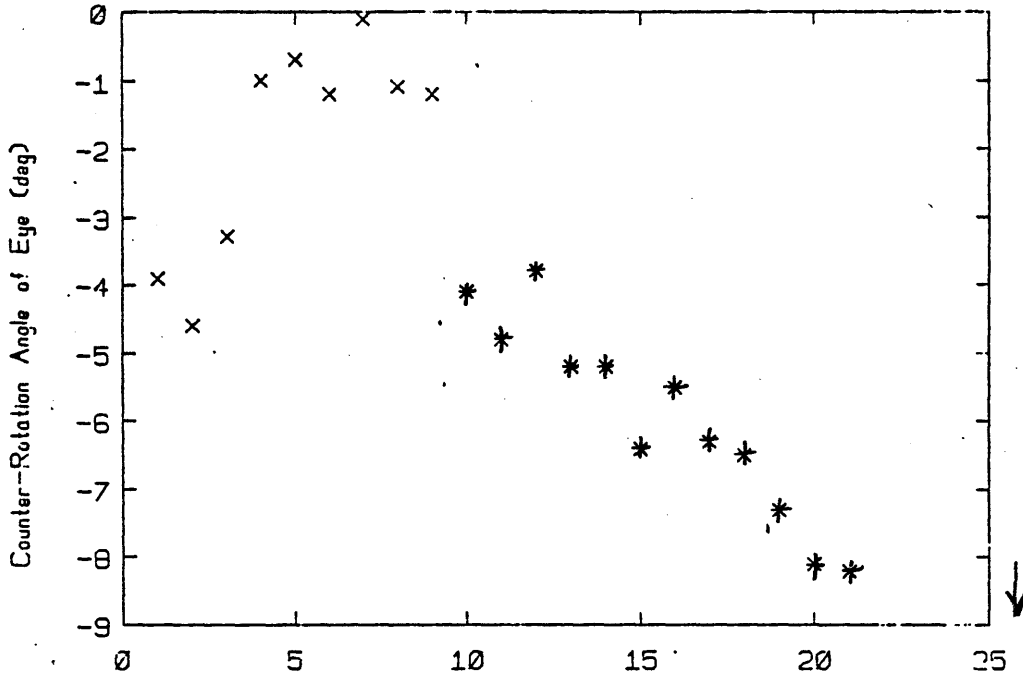




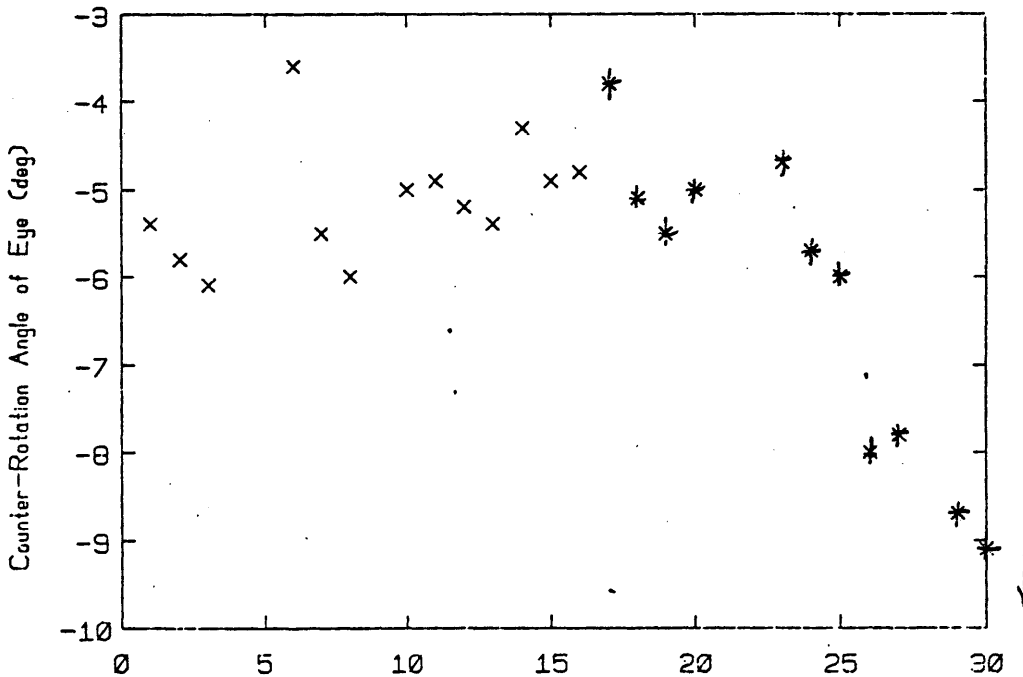
Frame No. PARABOLIC FLIGHTS Mar79 #139
Garriott



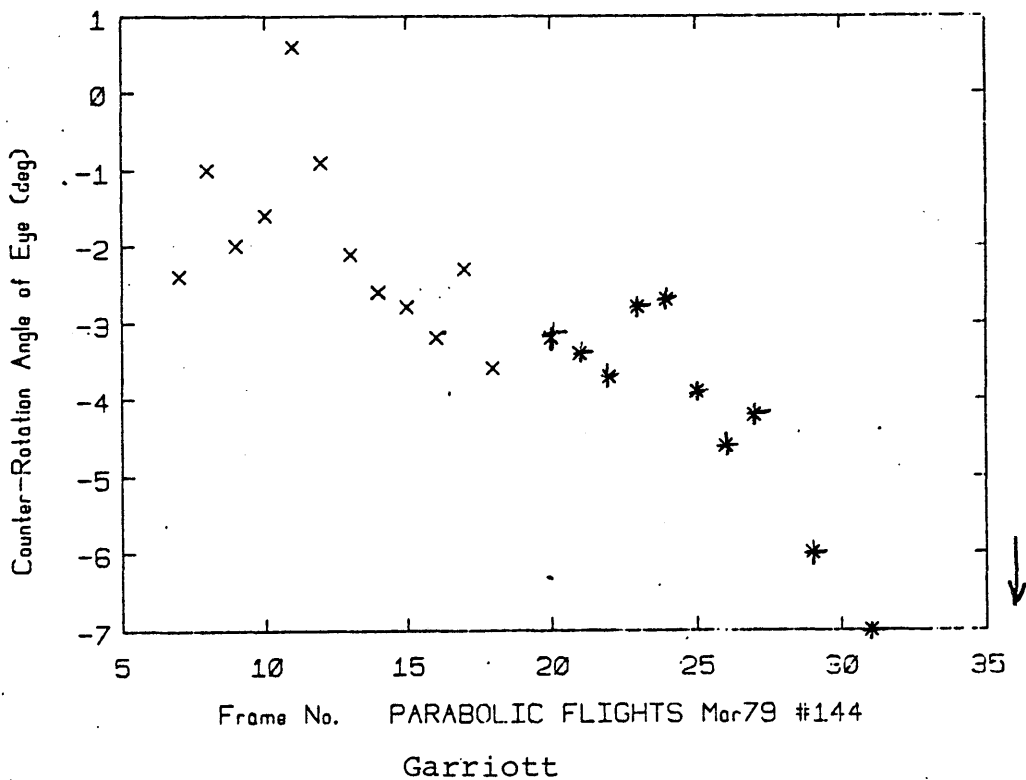
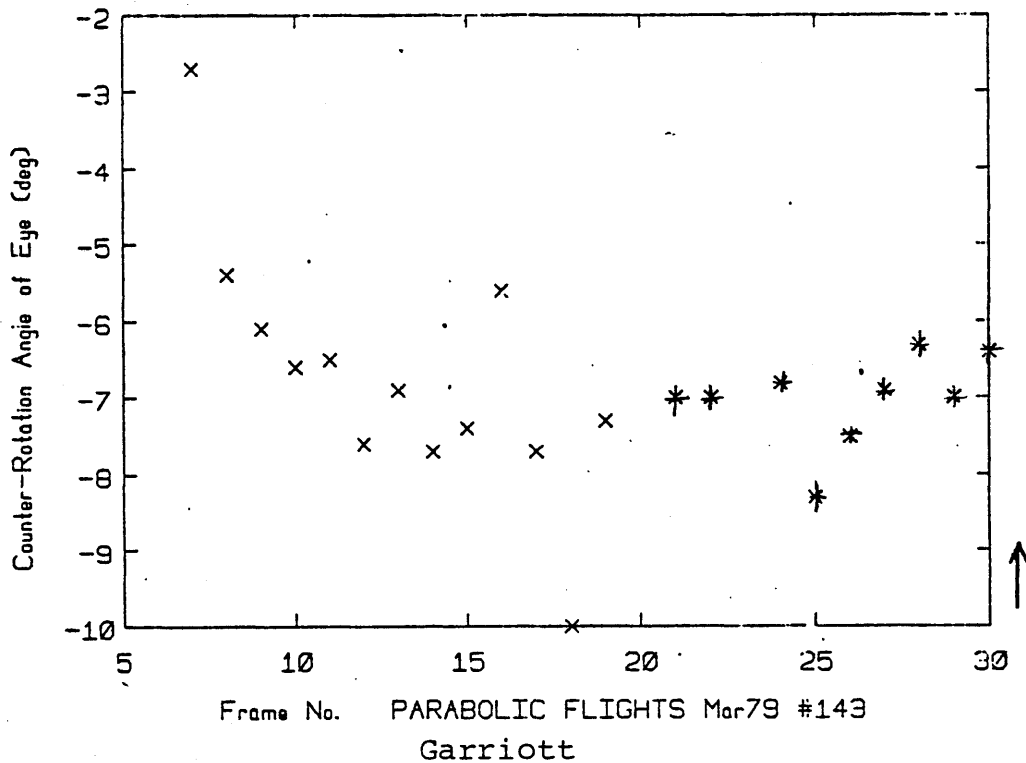
Frame No. PARABOLIC FLIGHTS Mar79 #140
Garriott

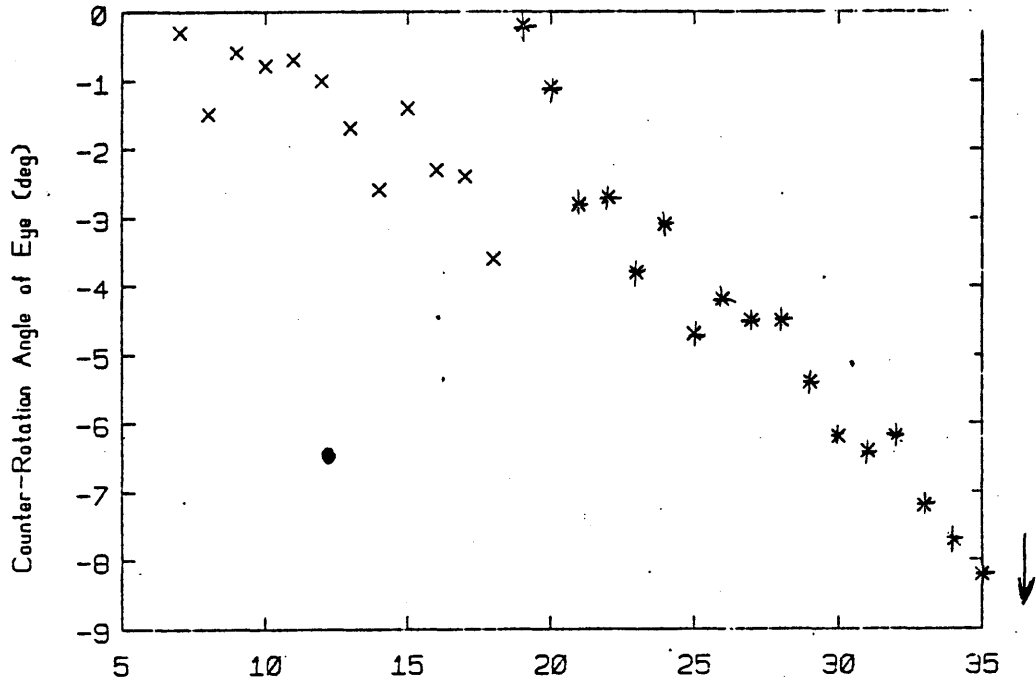


Frame No. PARABOLIC FLIGHTS Mar79 #141
Garriott



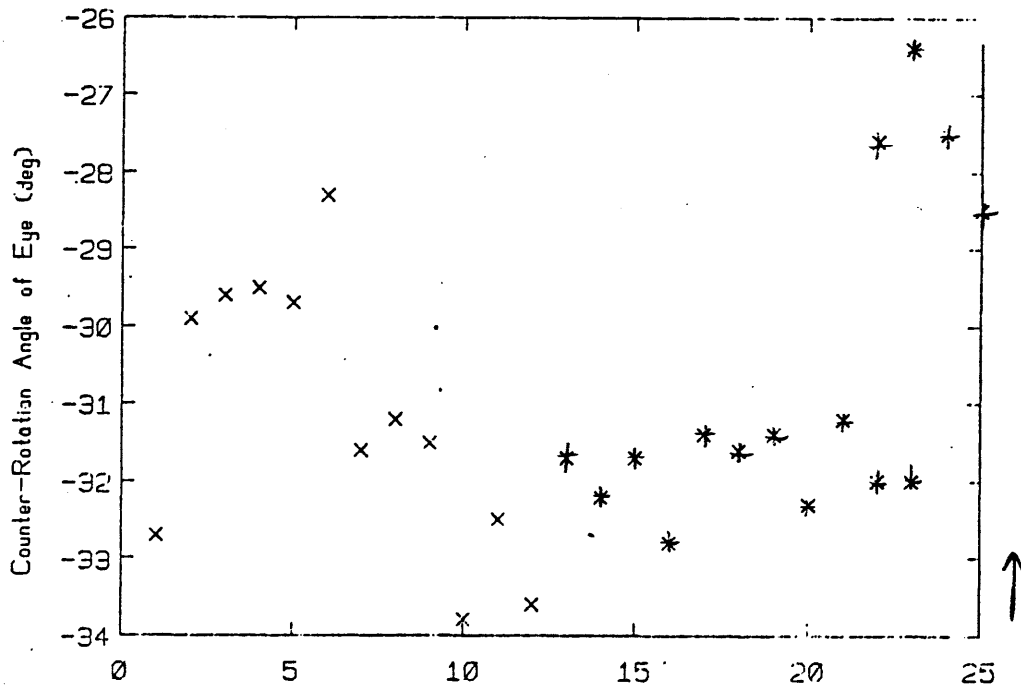
Frame No. PARABOLIC FLIGHTS Mar79 #142
Garriott





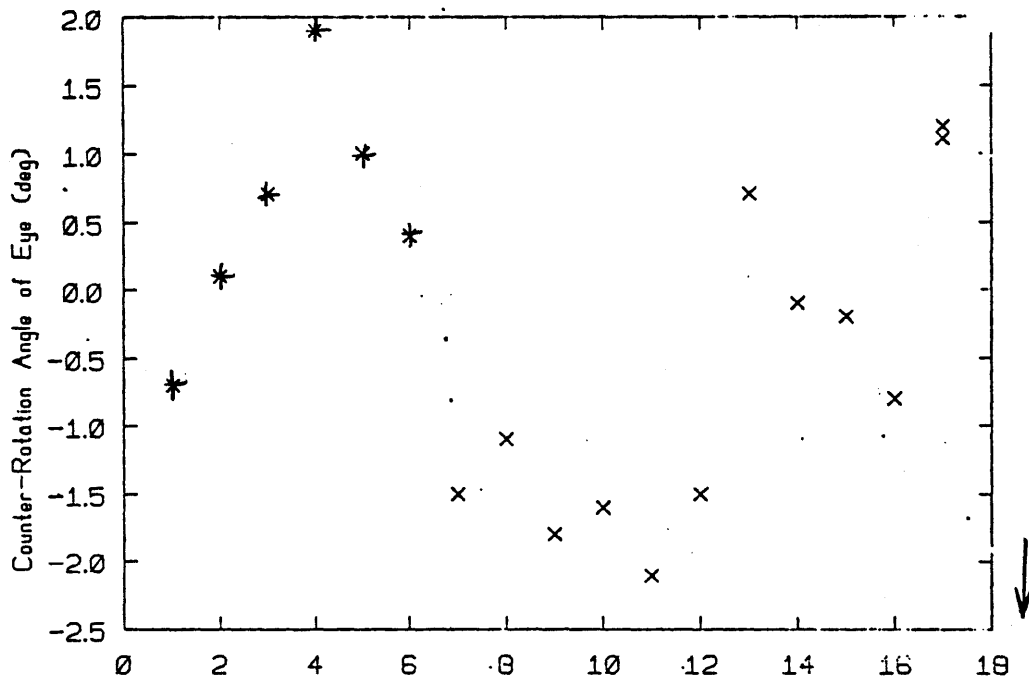
Frame No. PARABOLIC FLIGHTS Mar79 #145

Garriott

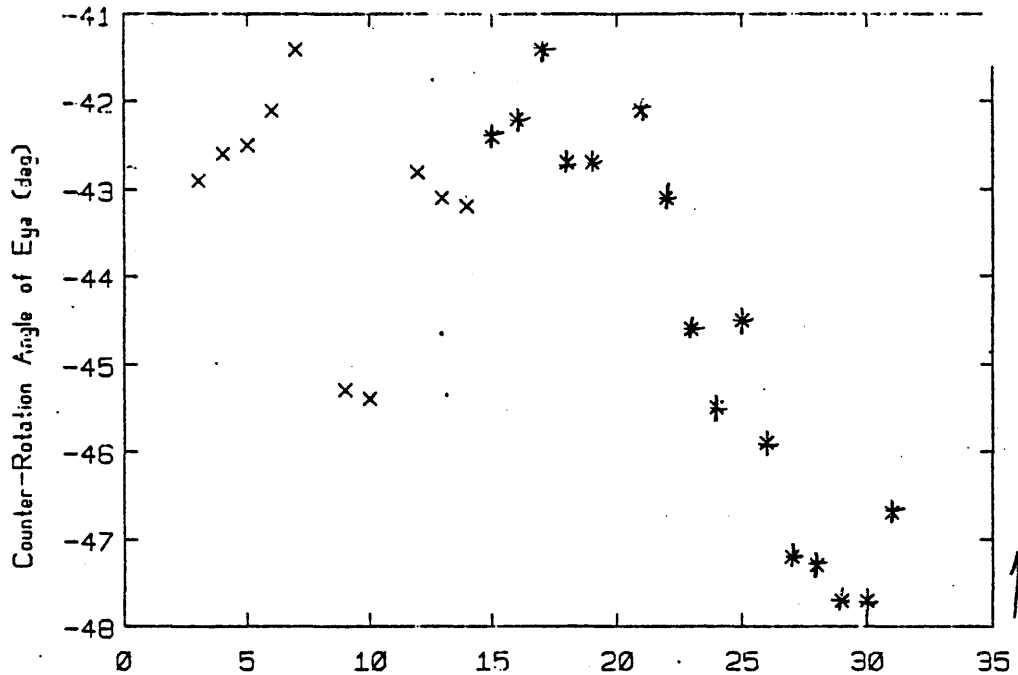


Frame No. PARABOLIC FLIGHTS Mar79 #145

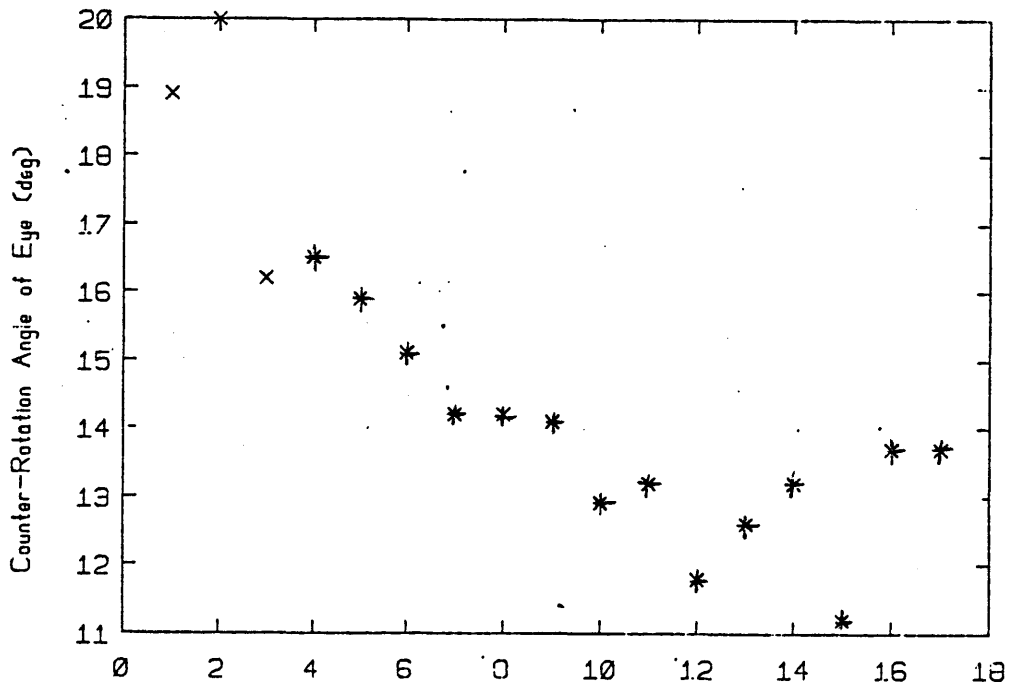
Garriott



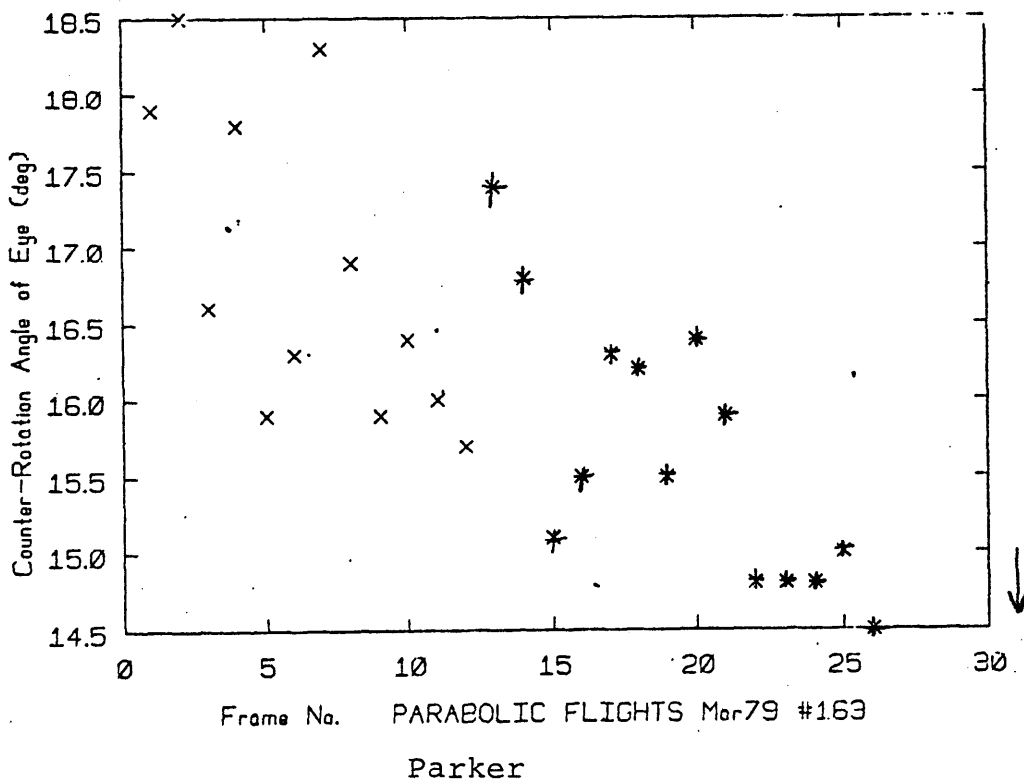
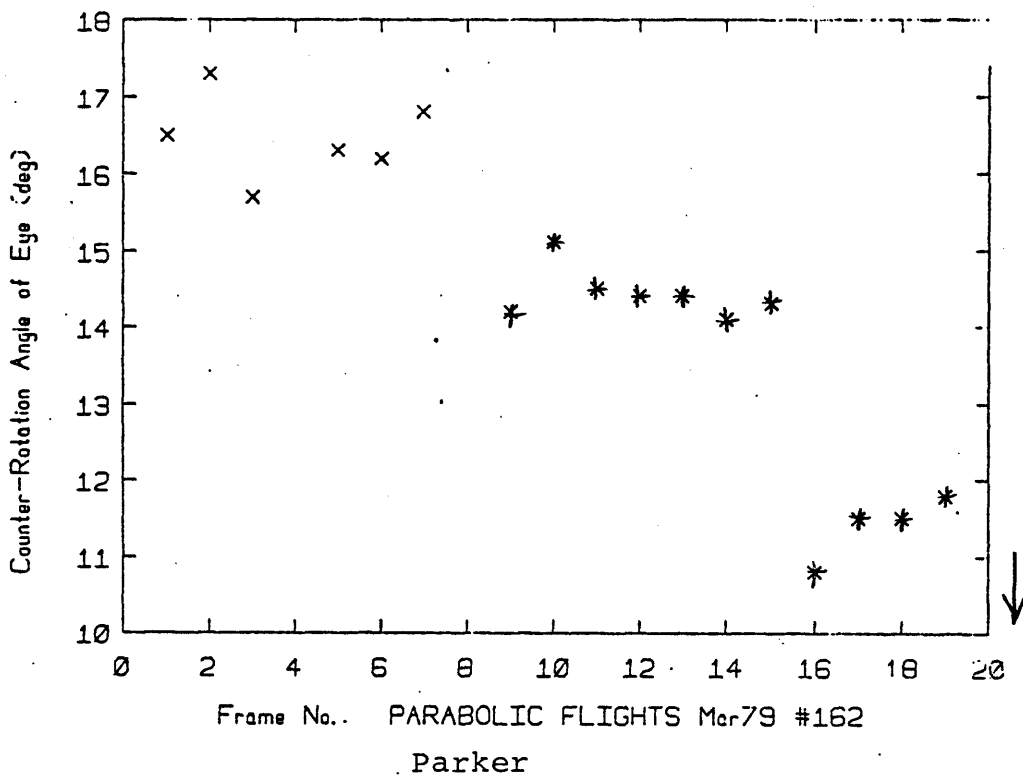
Frame No. PARABOLIC FLIGHTS Mar79 #147
Garriott

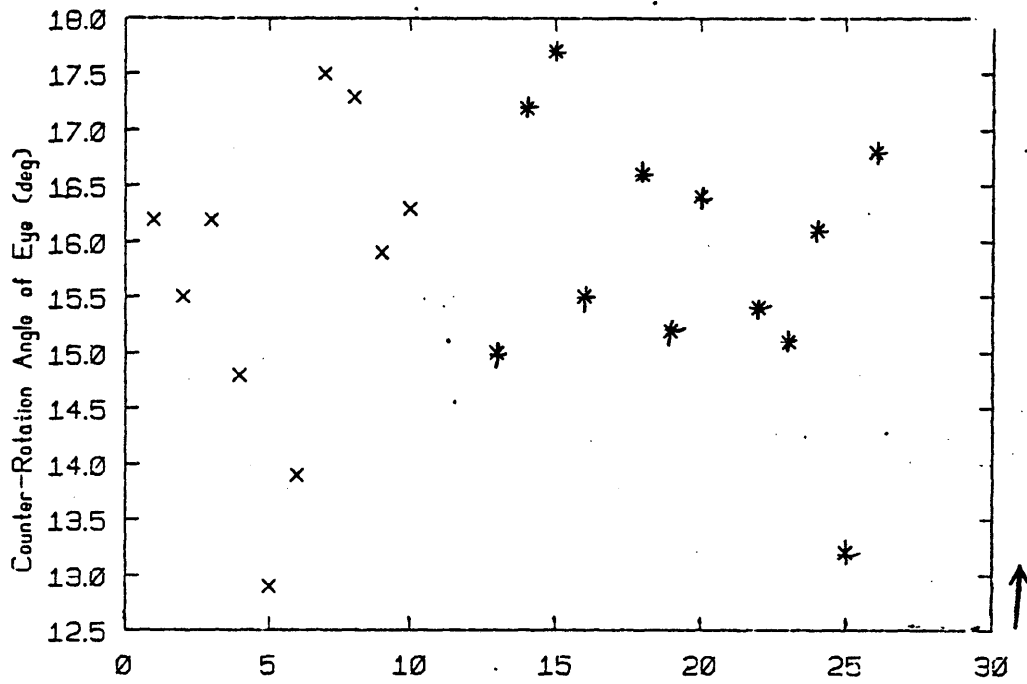


Frames No. PARABOLIC FLIGHTS Mar79 #160
Parker



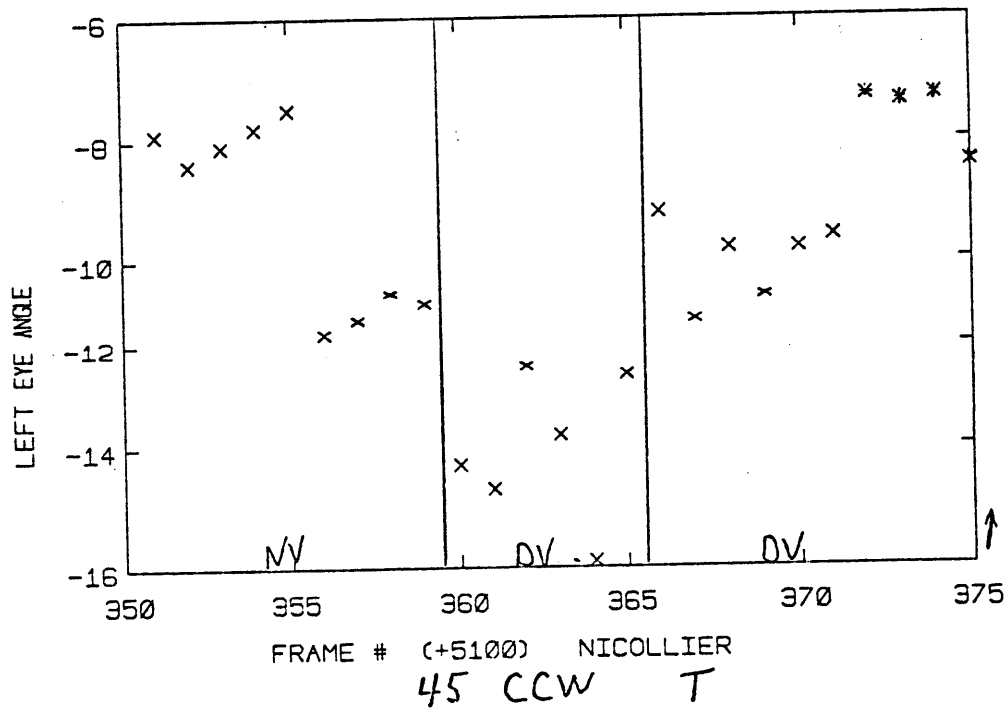
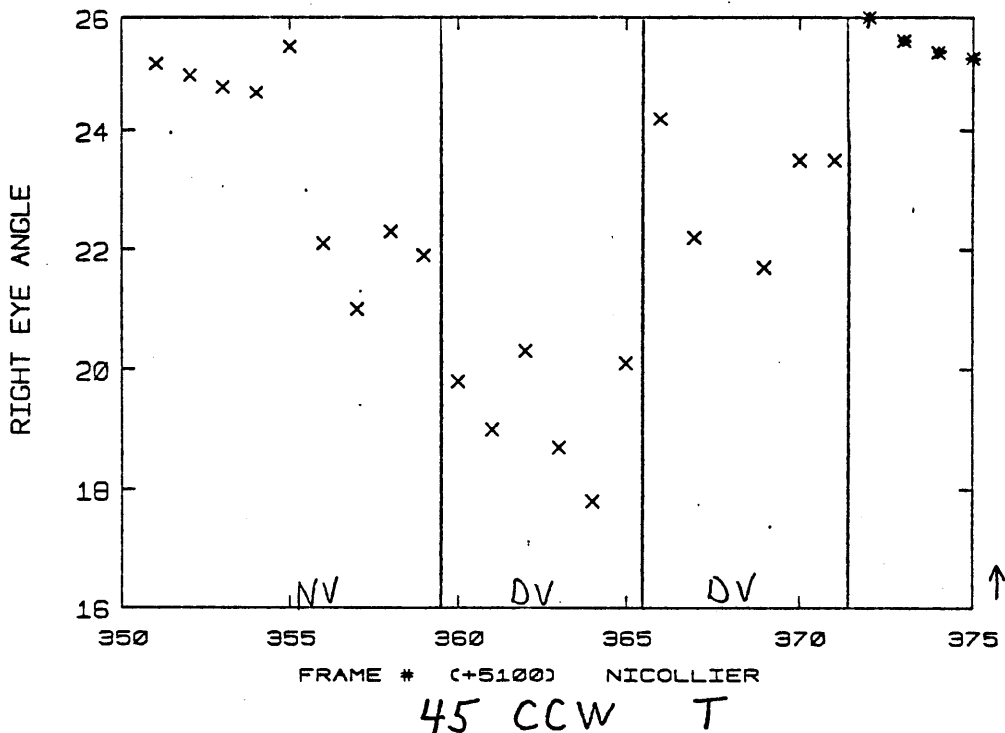
Frame No. PARABOLIC FLIGHTS Mar79 #161
Parker

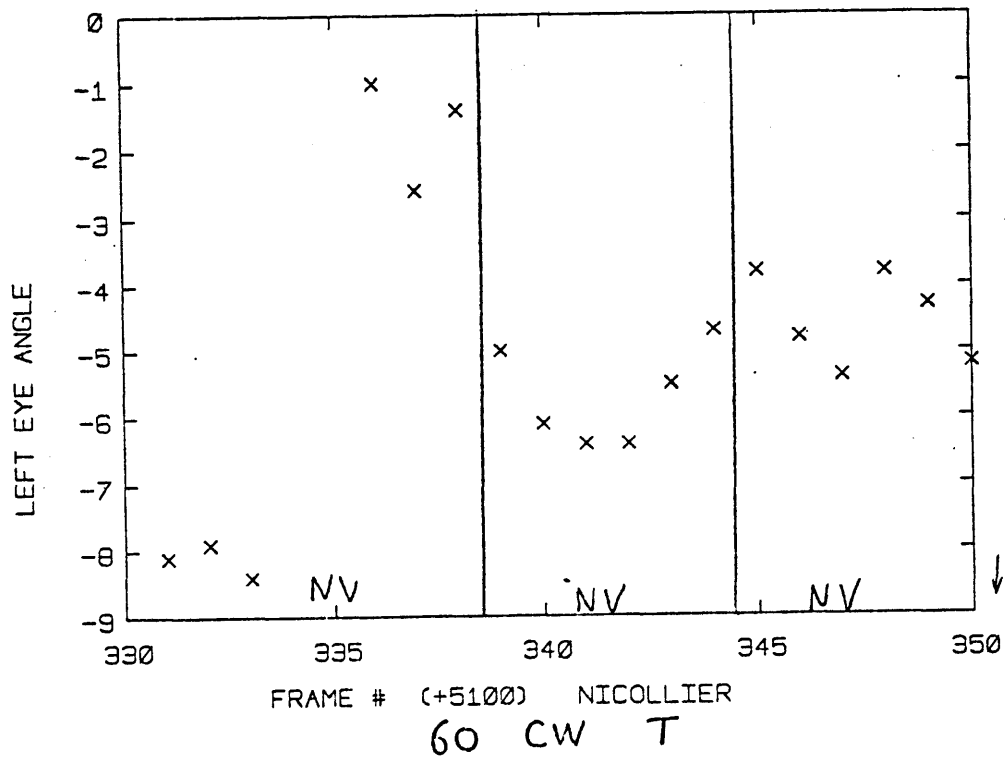
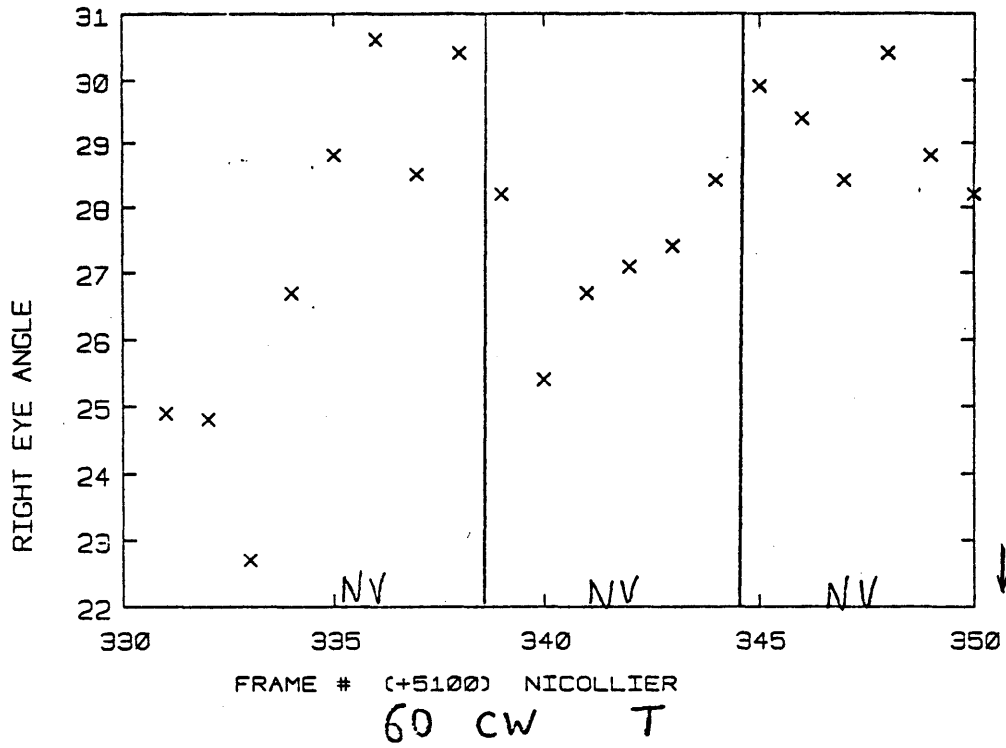


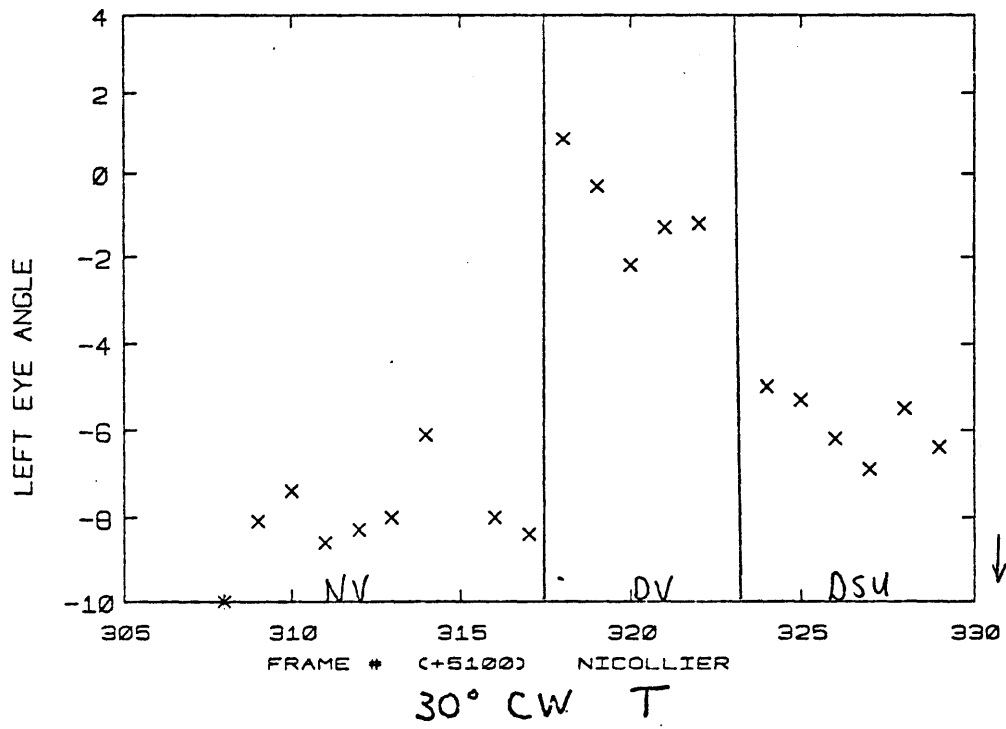
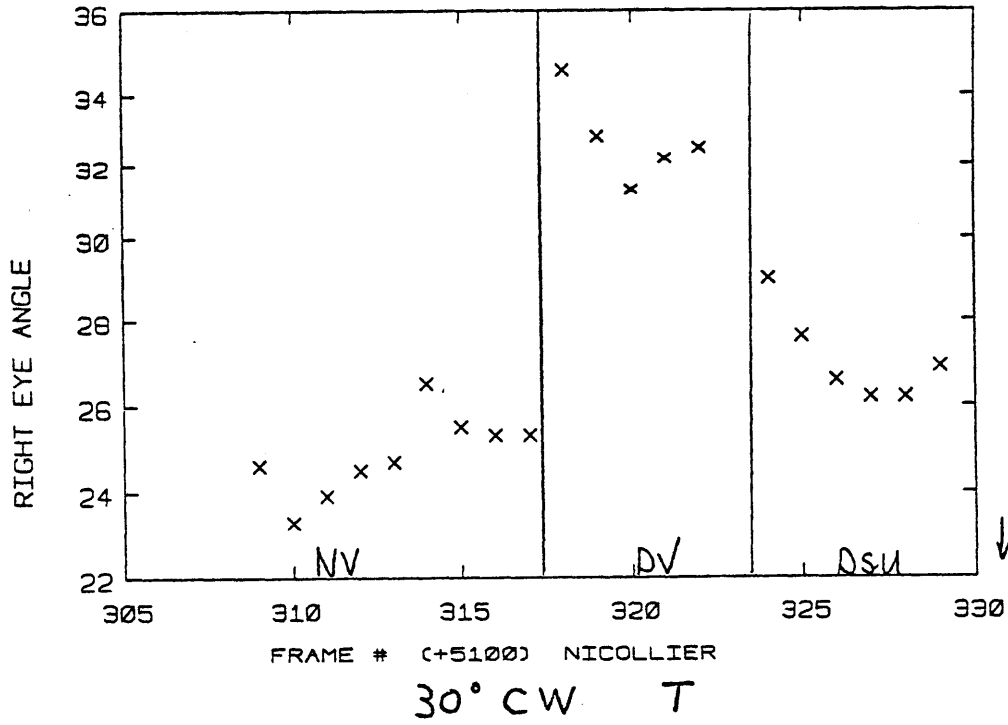


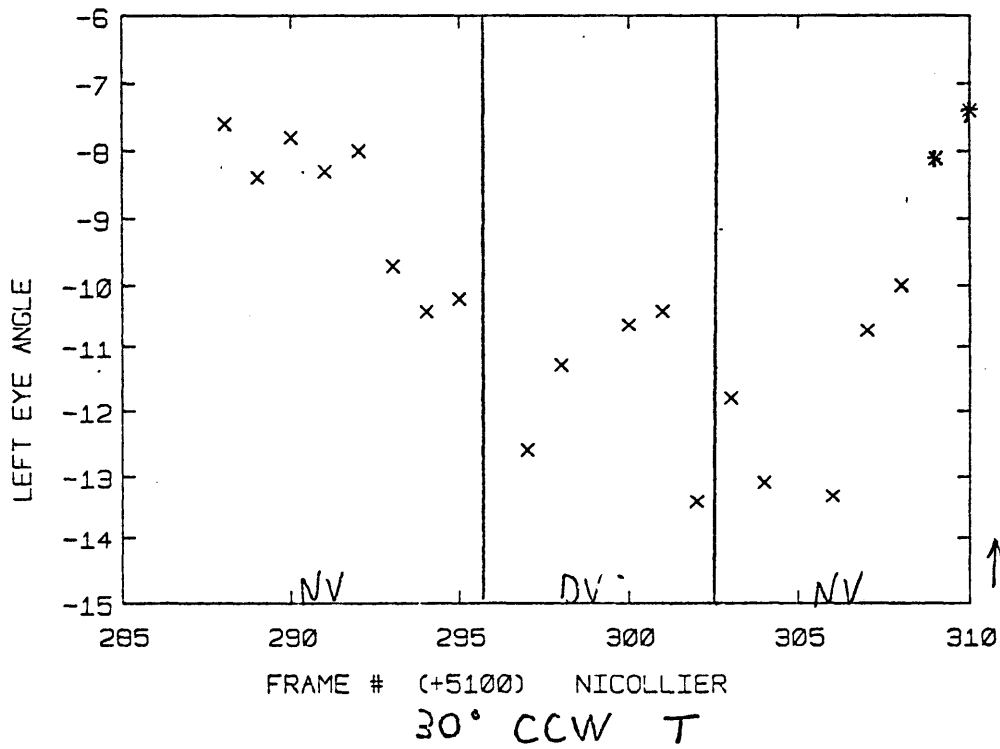
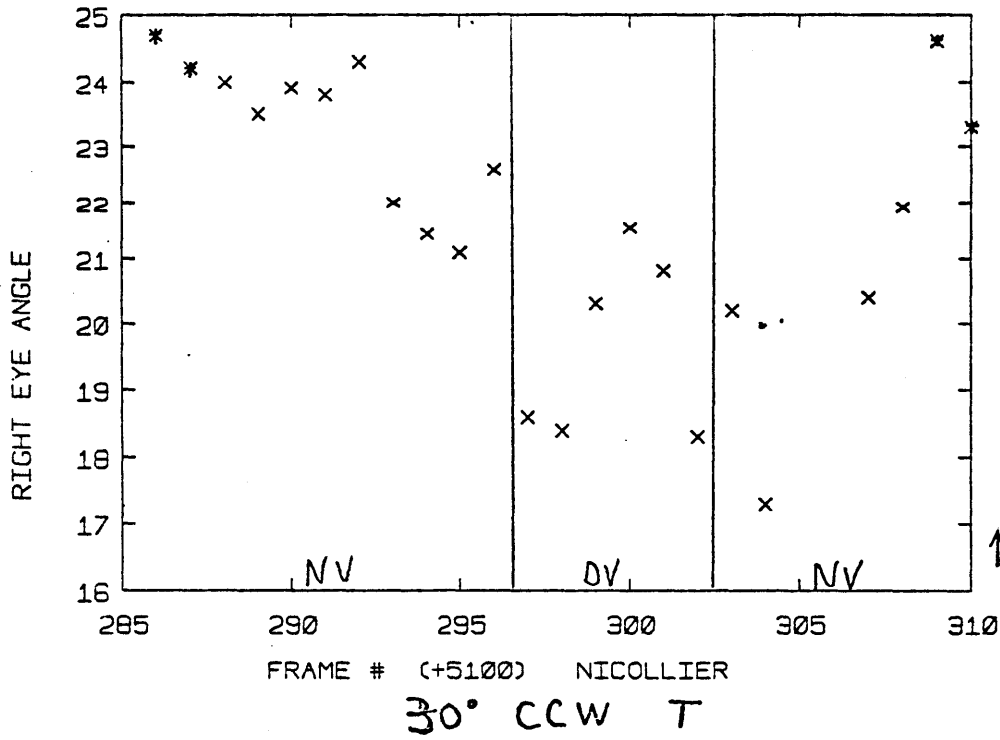
Frame No. PARABOLIC FLIGHTS Mar79 #164

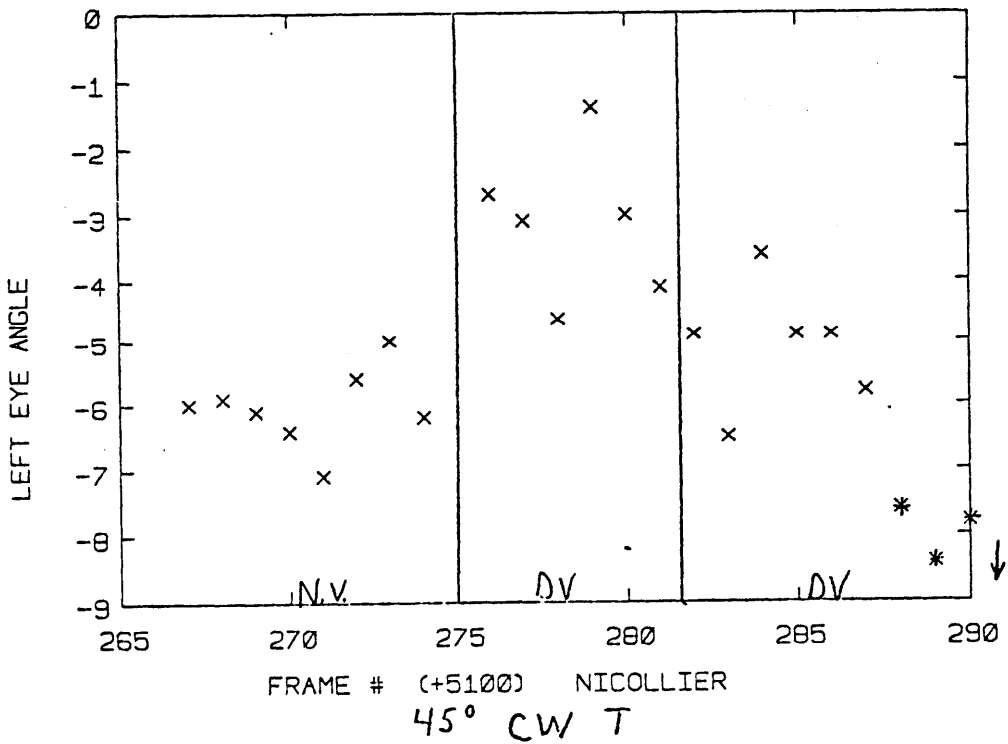
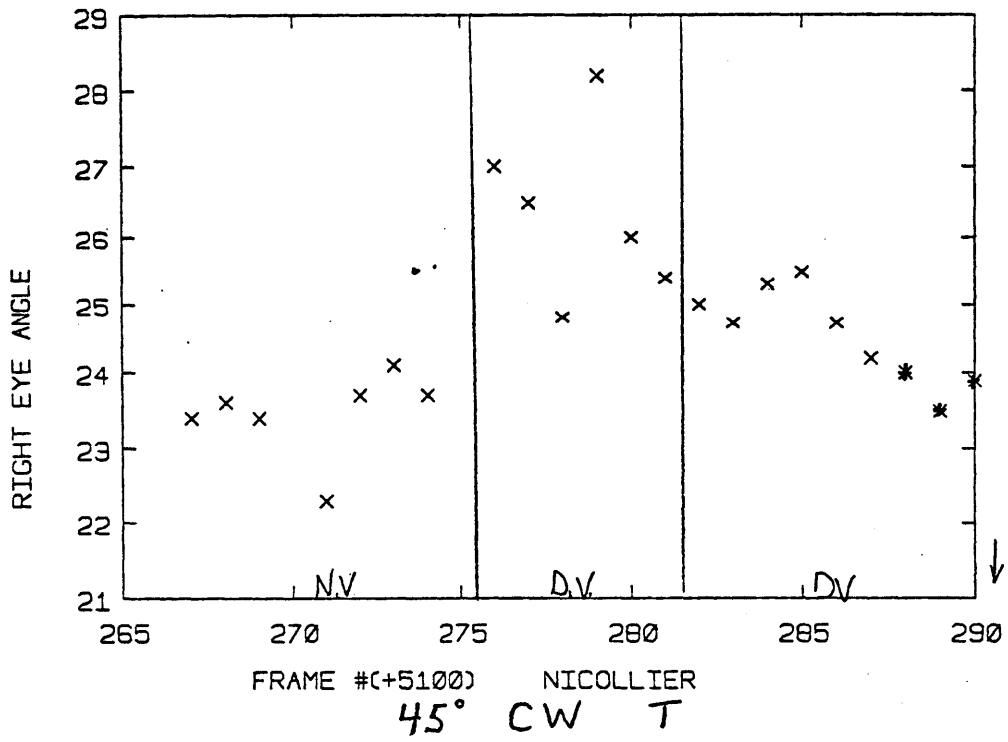
Parker

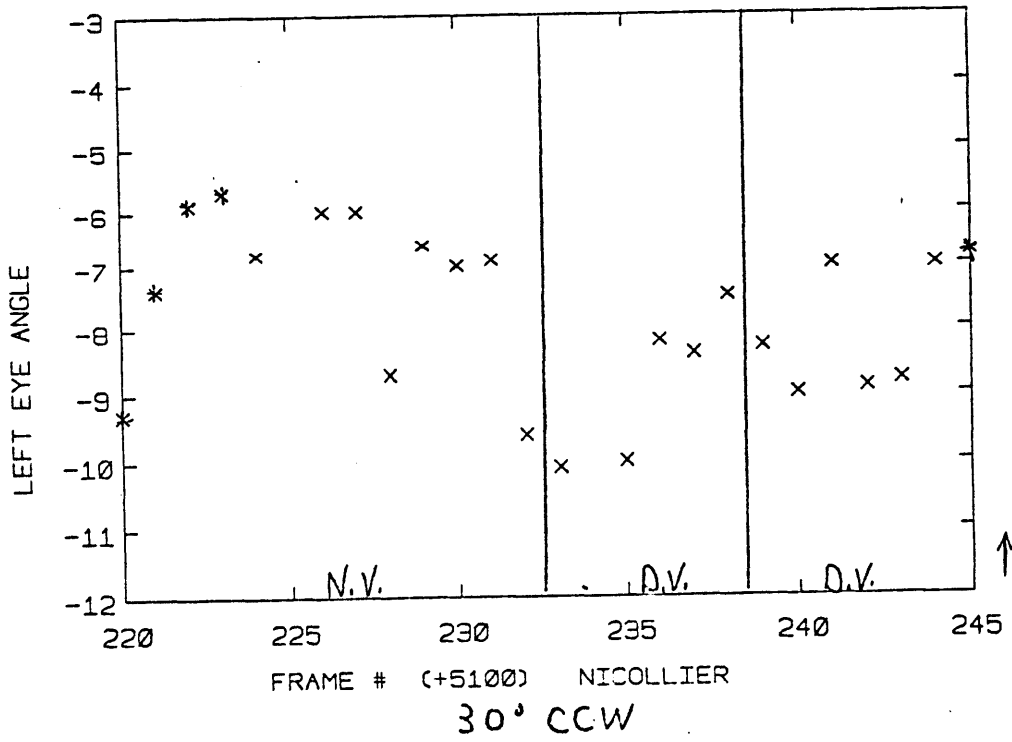
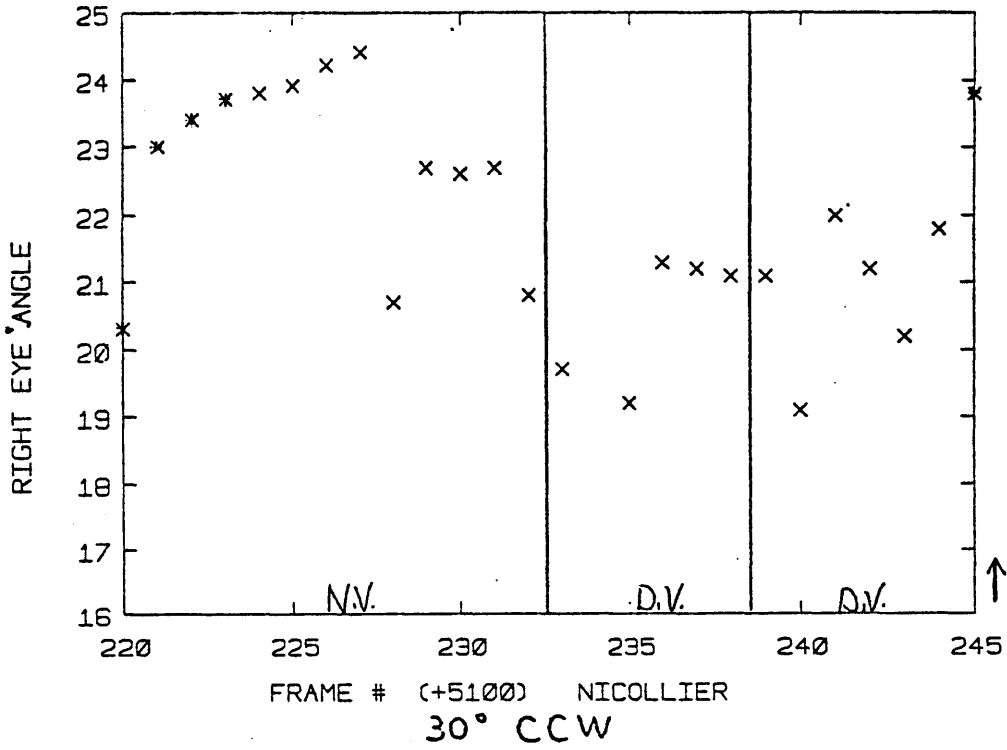


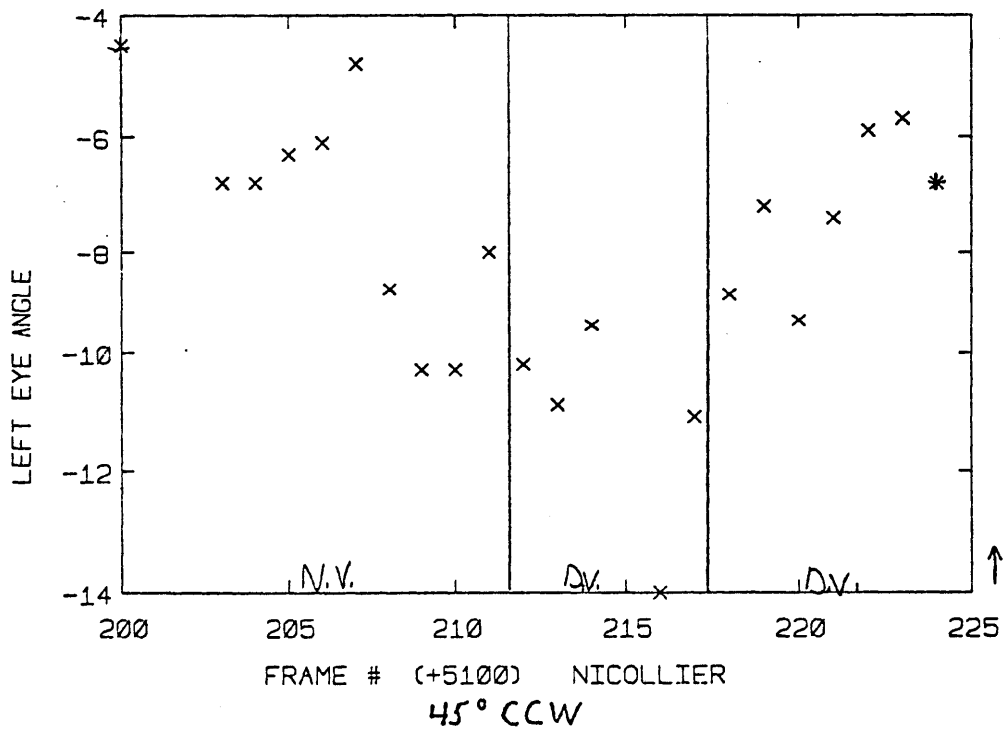
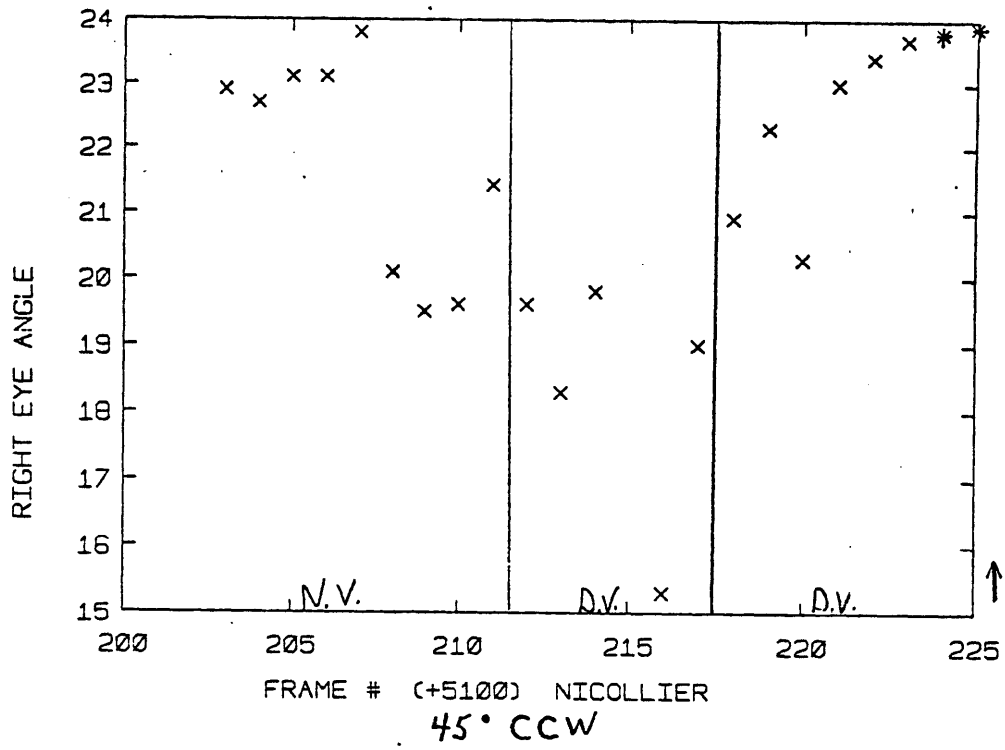


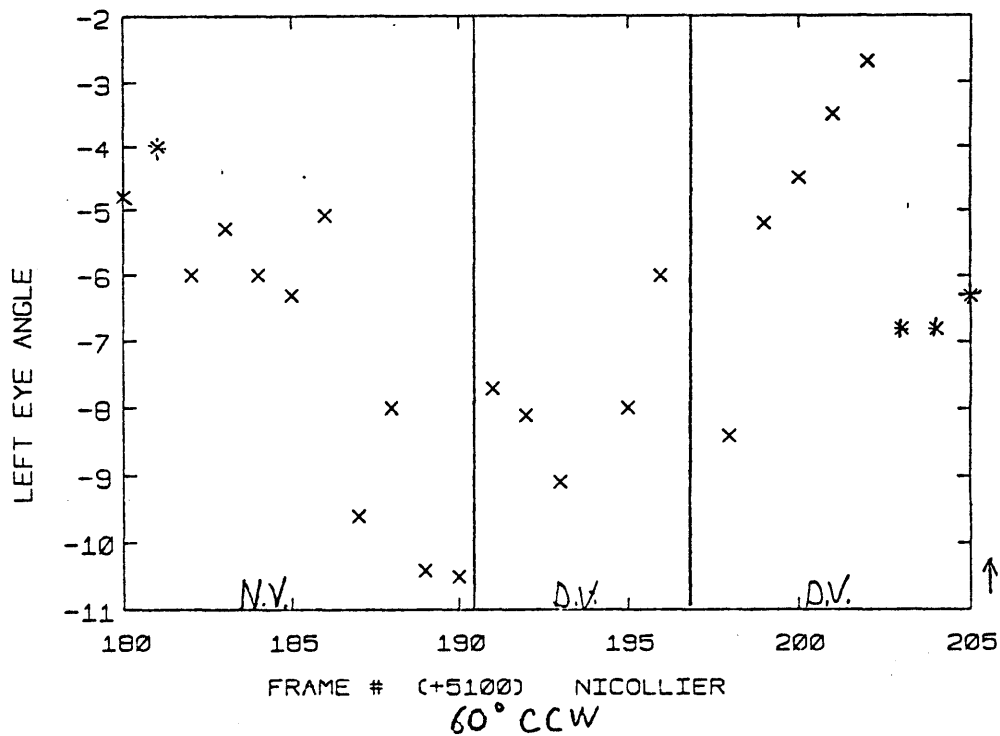
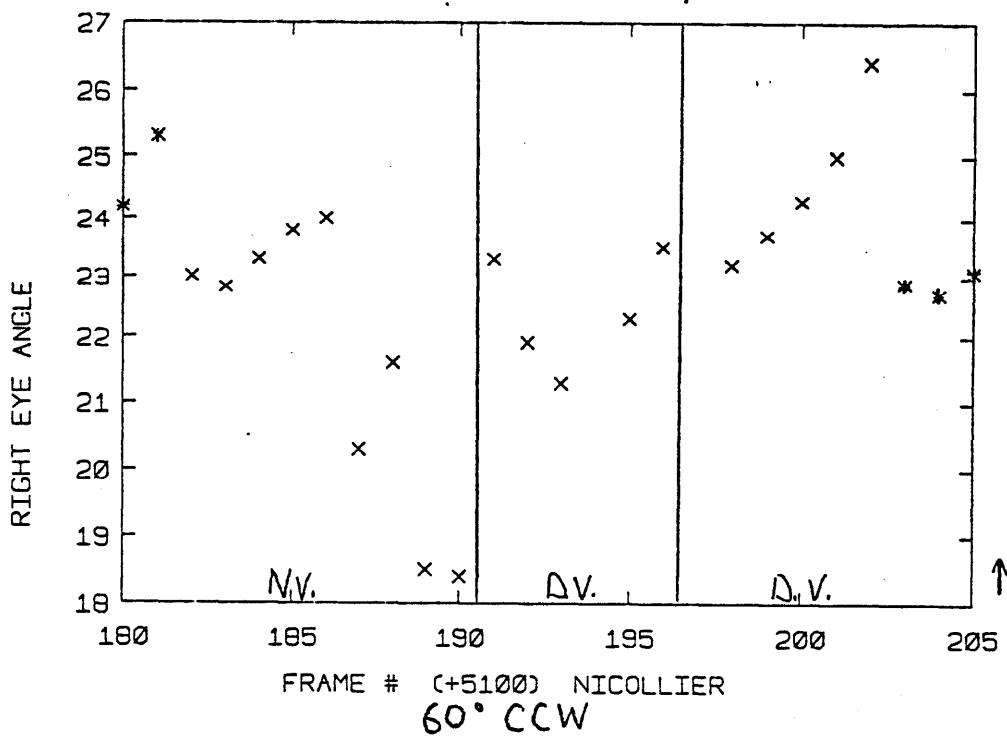


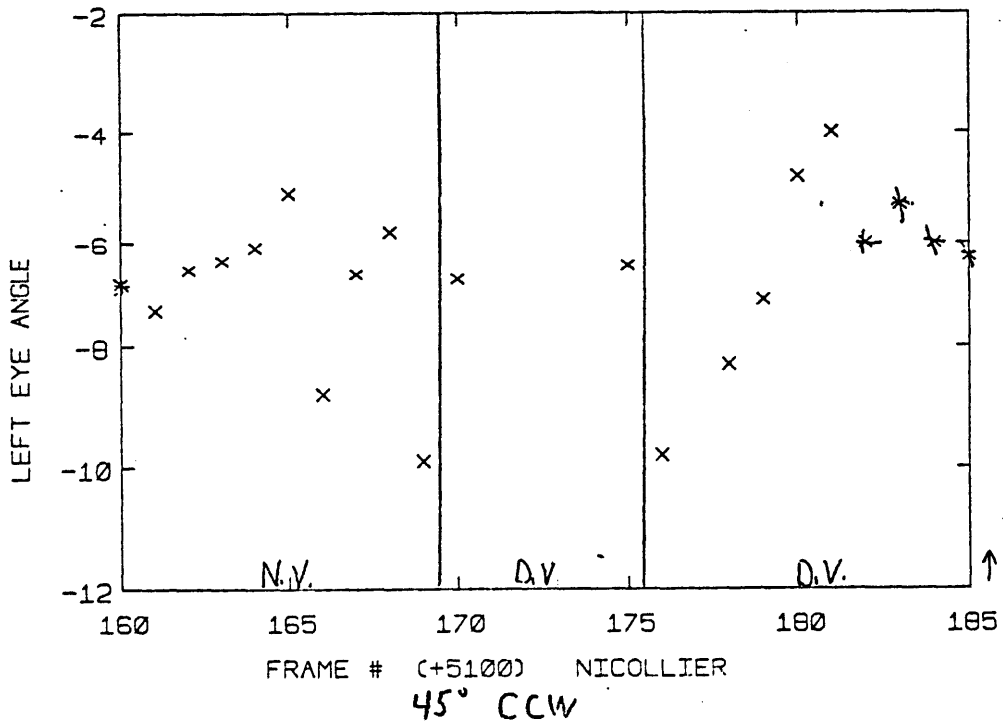
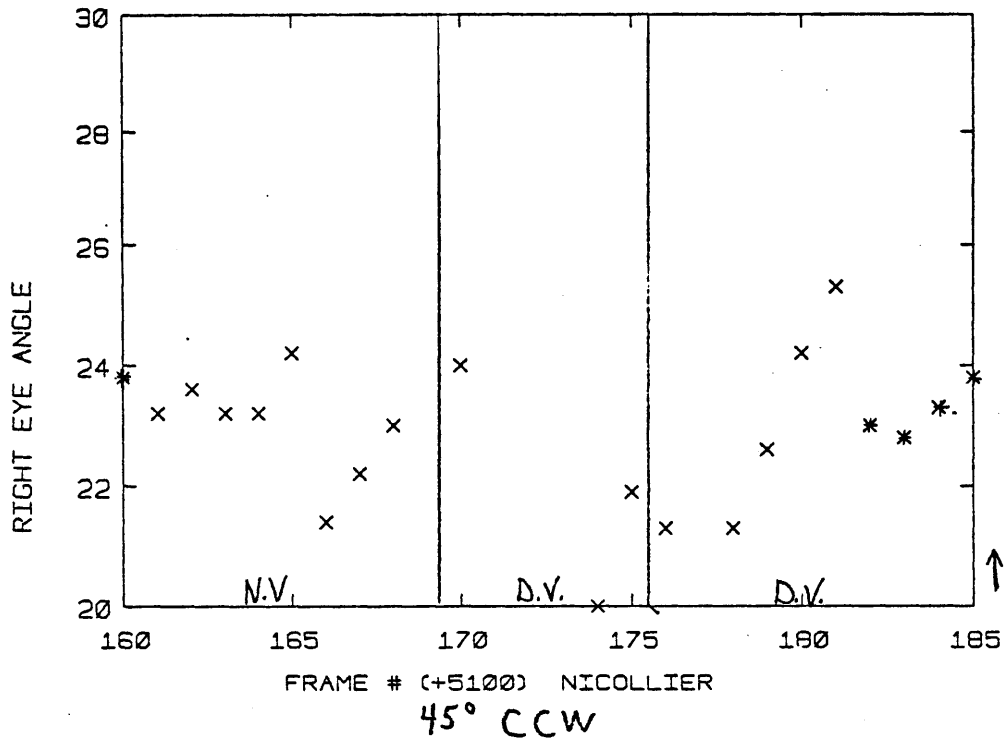


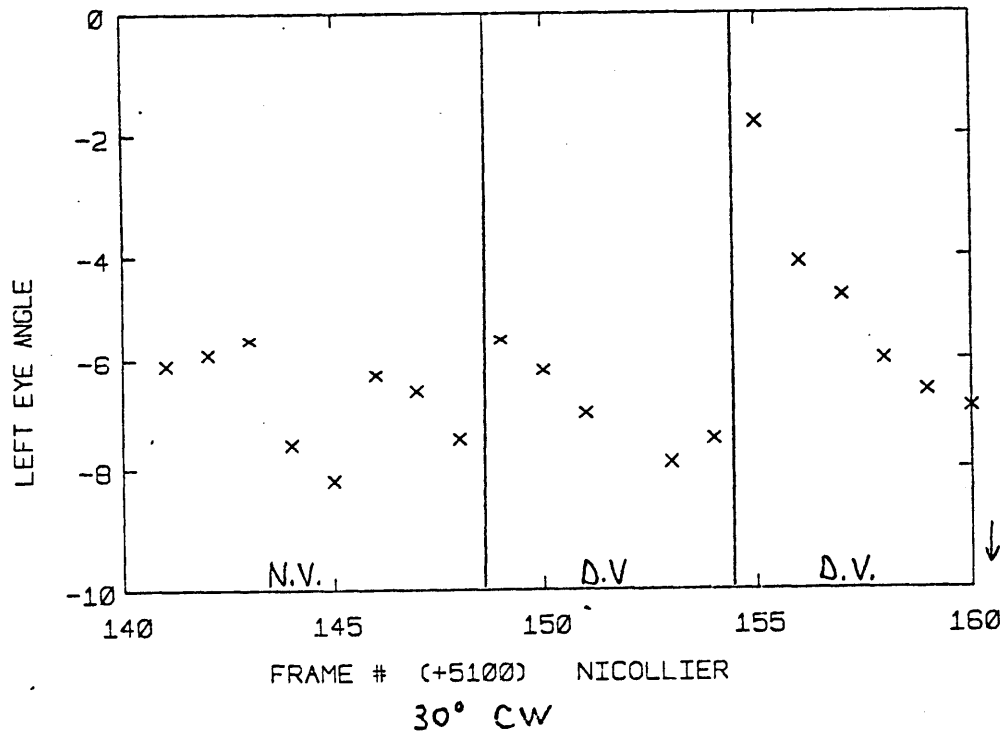
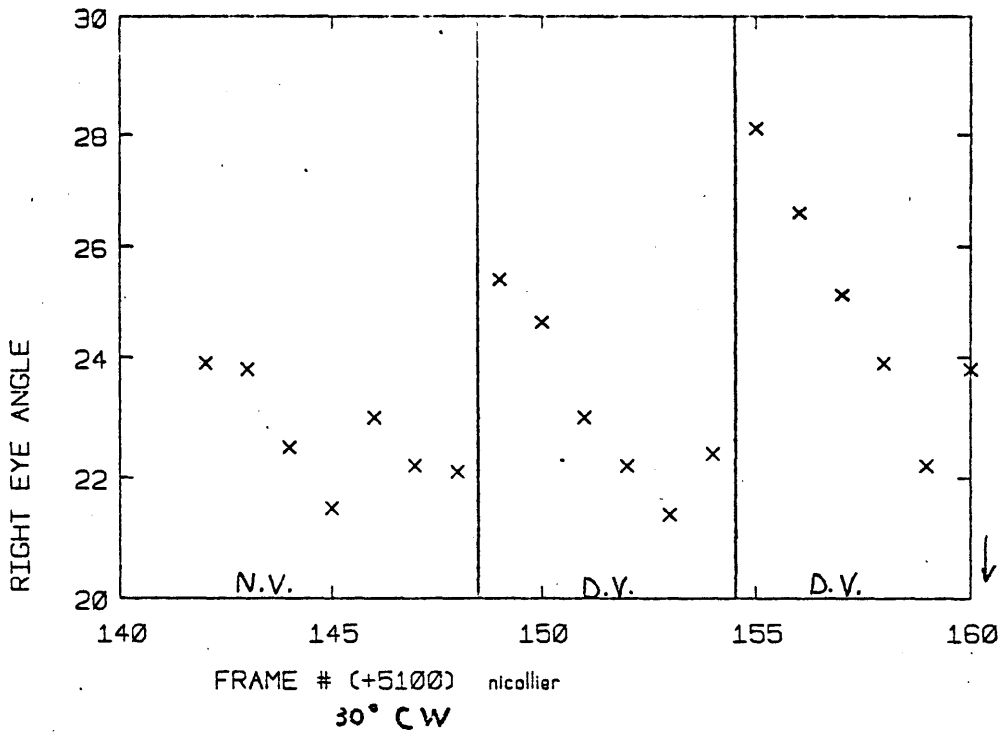


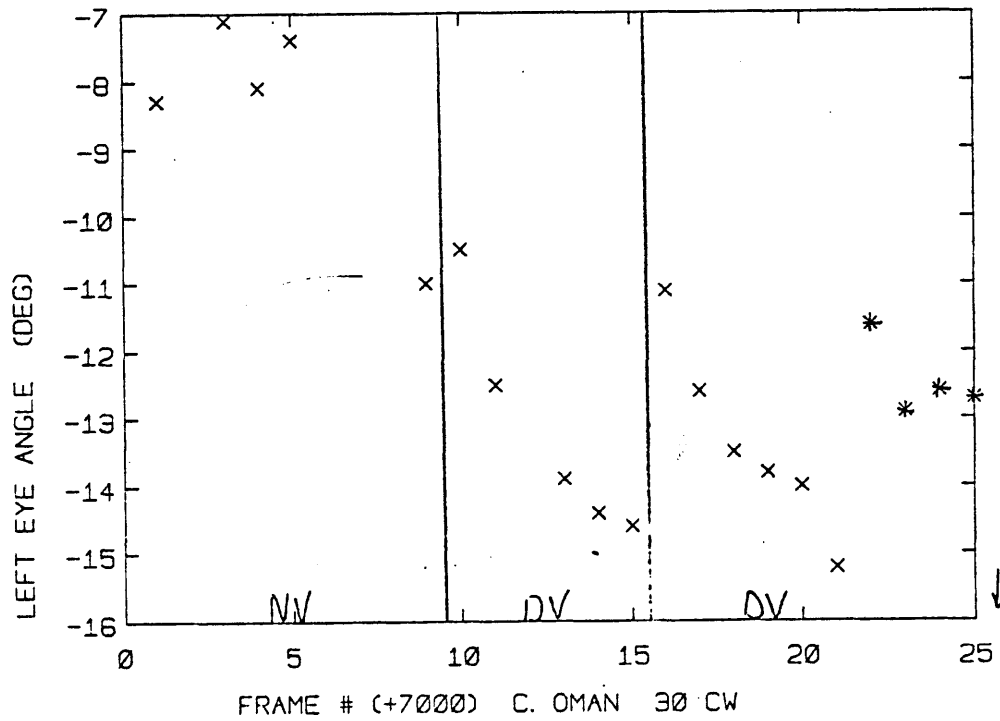
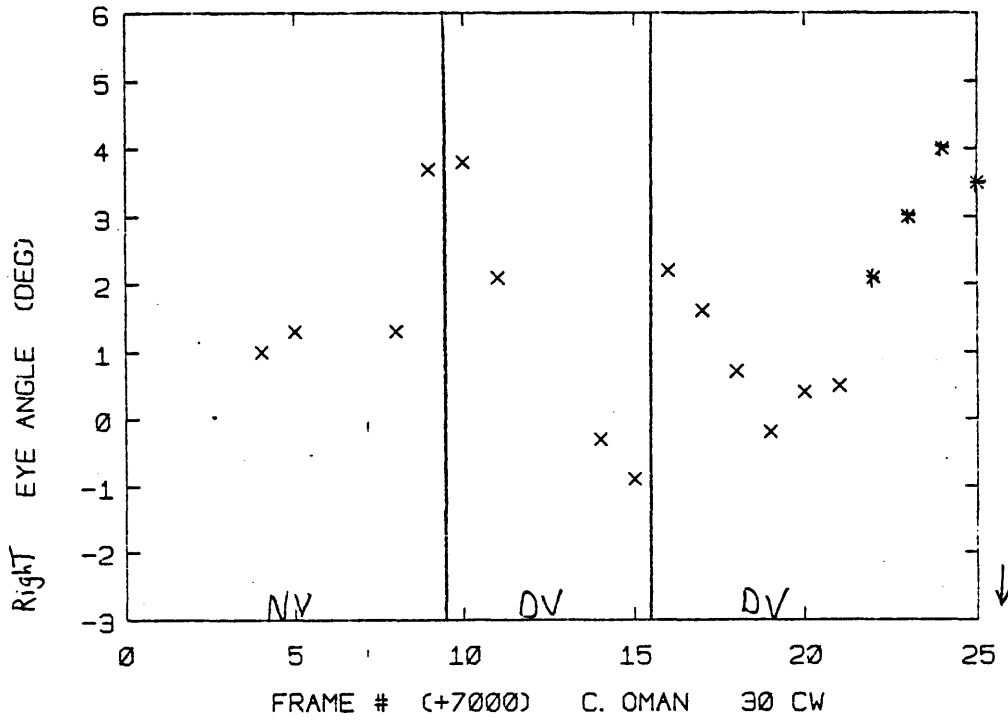


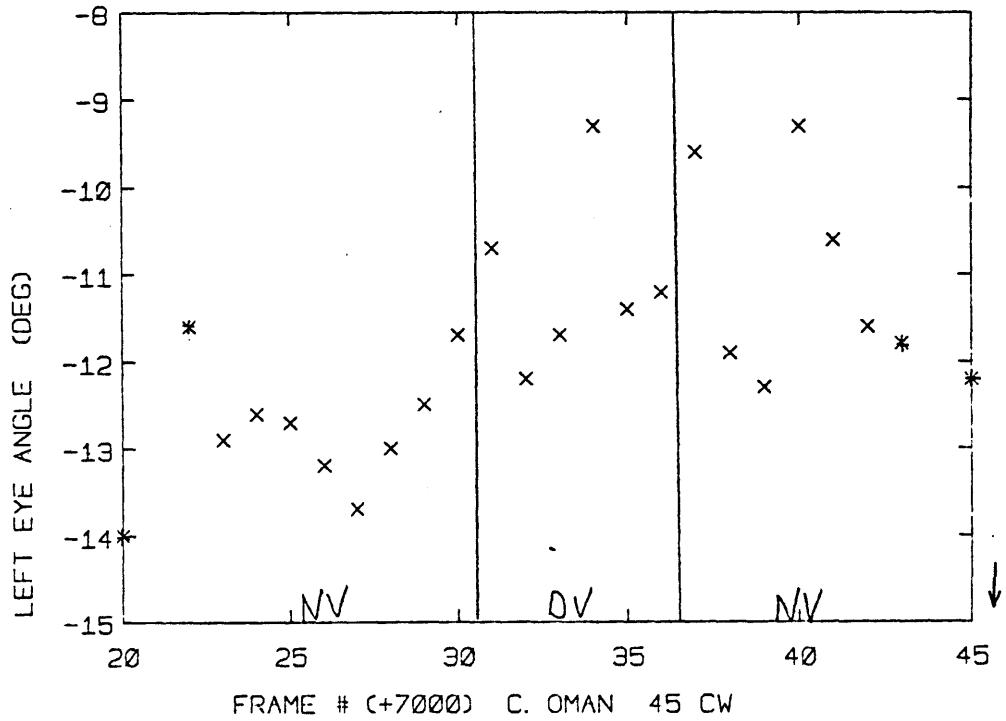
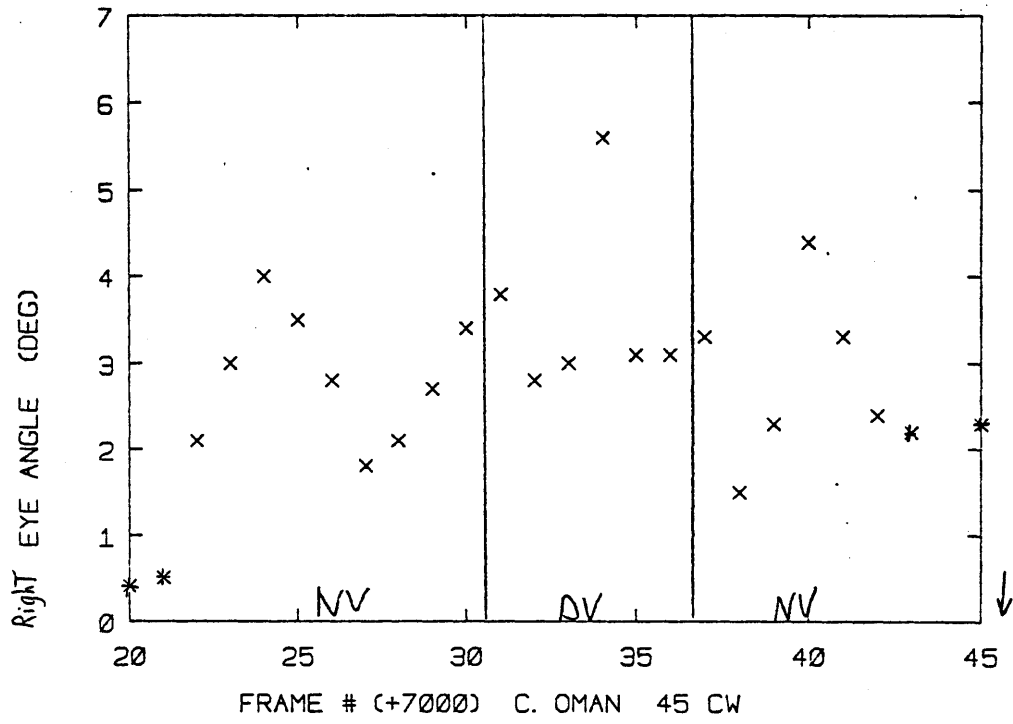


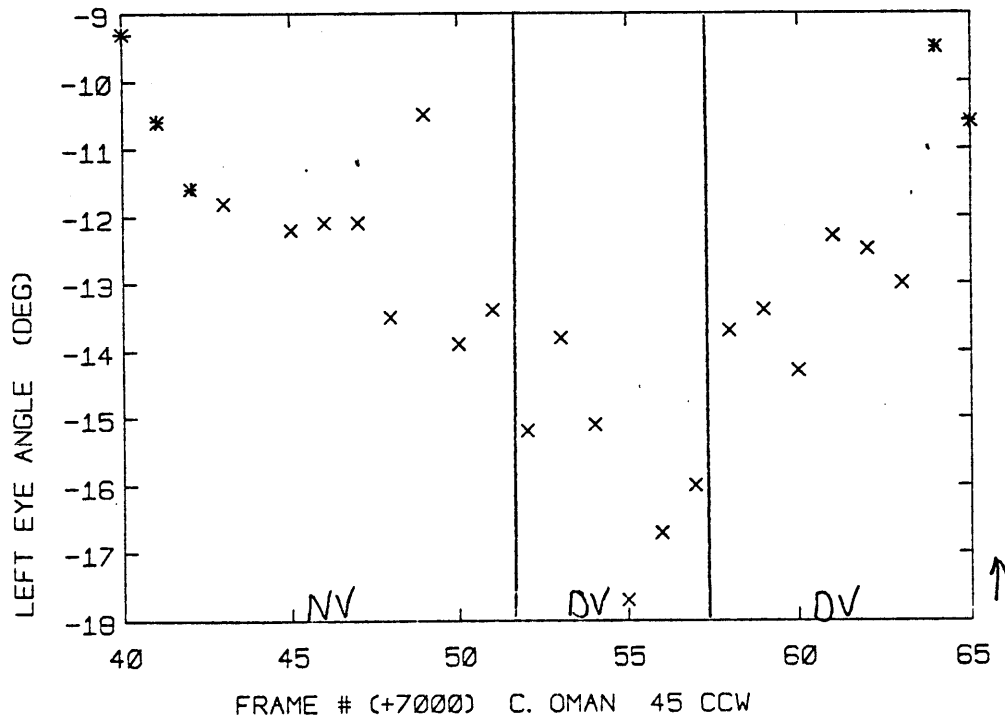
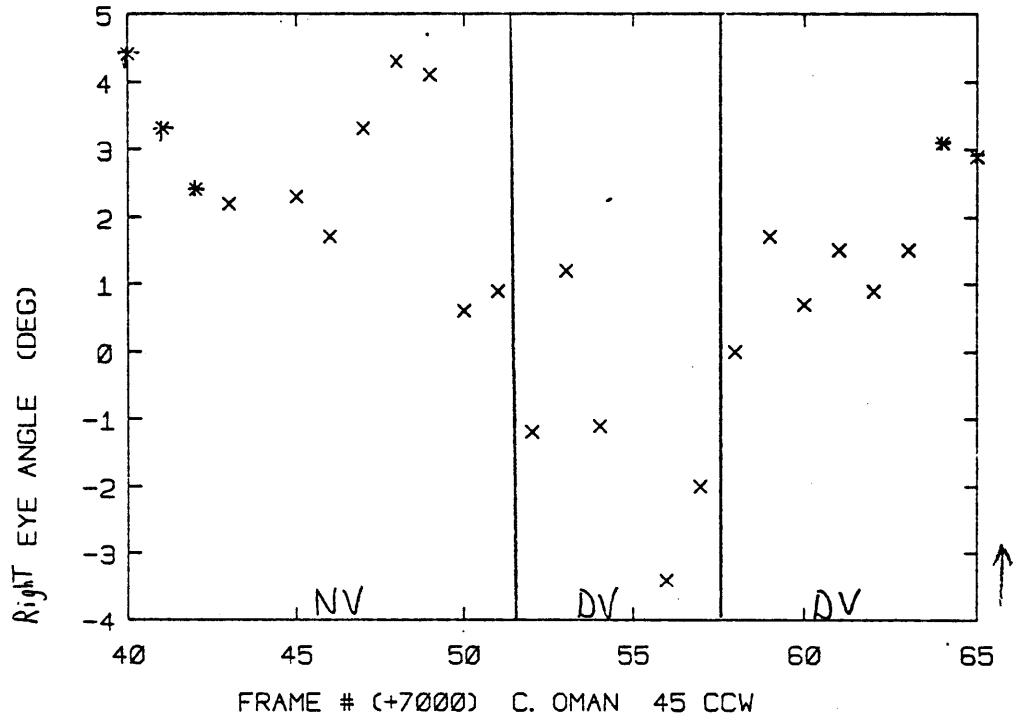


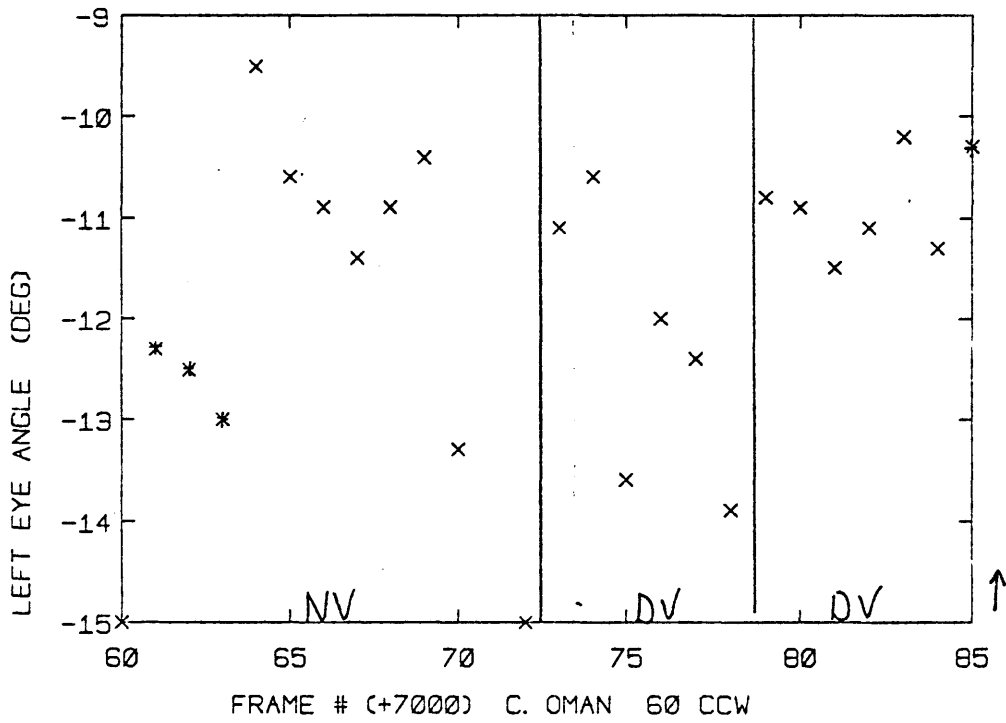
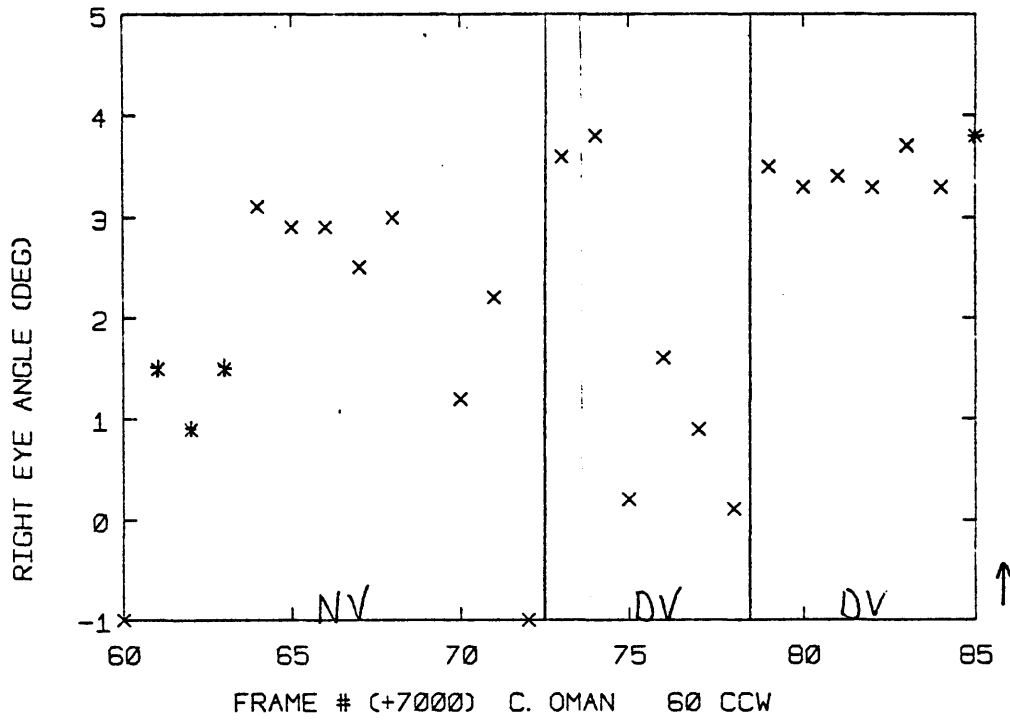


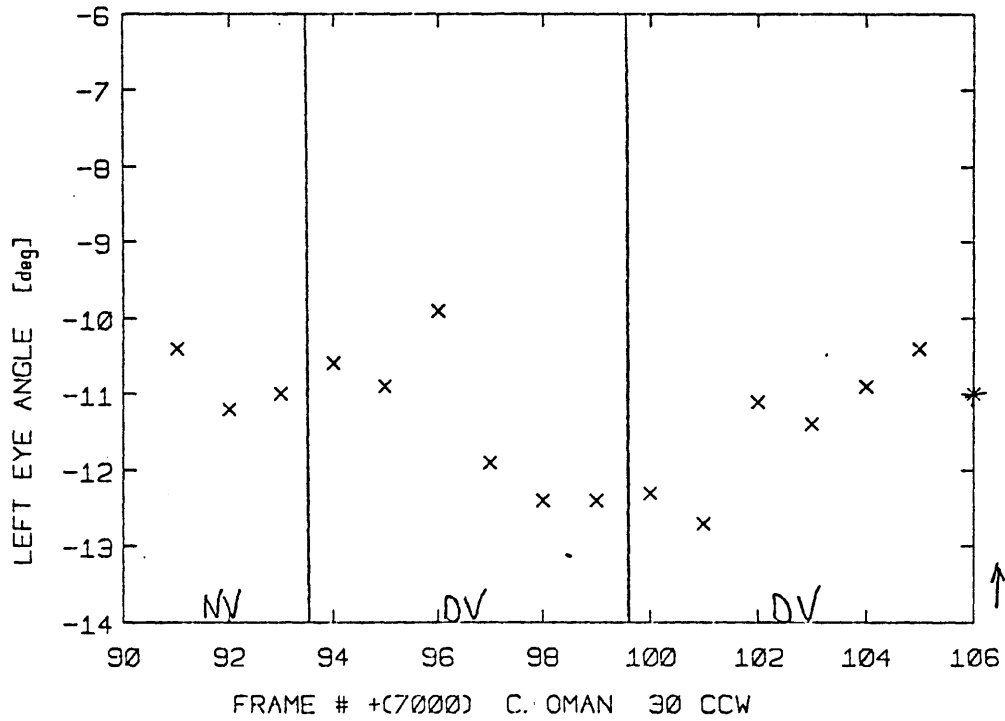
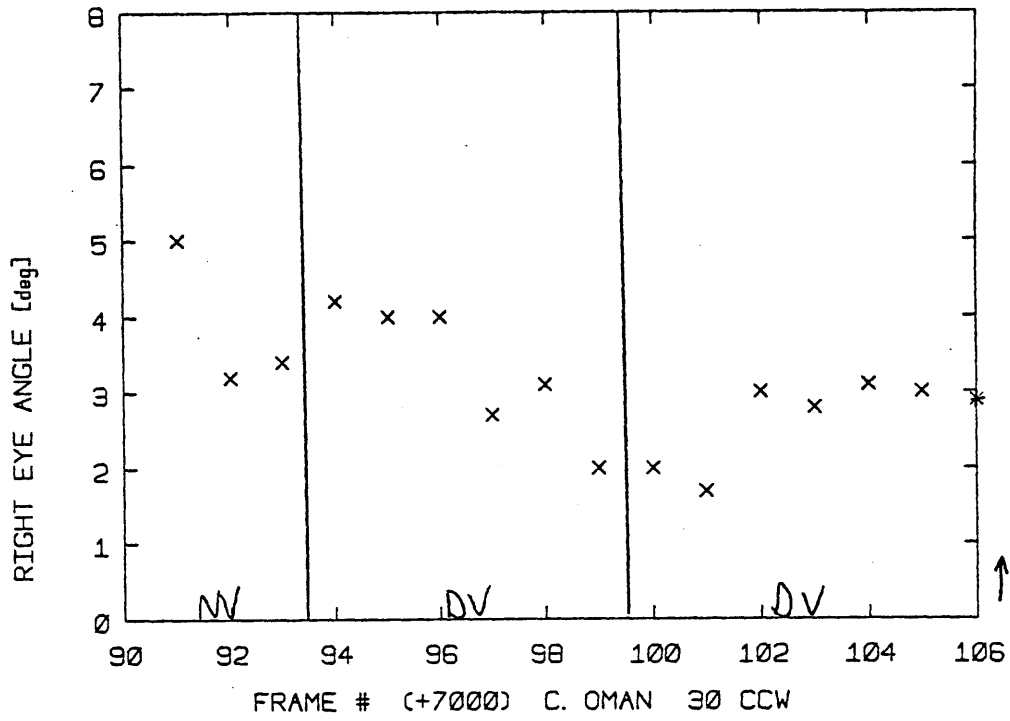


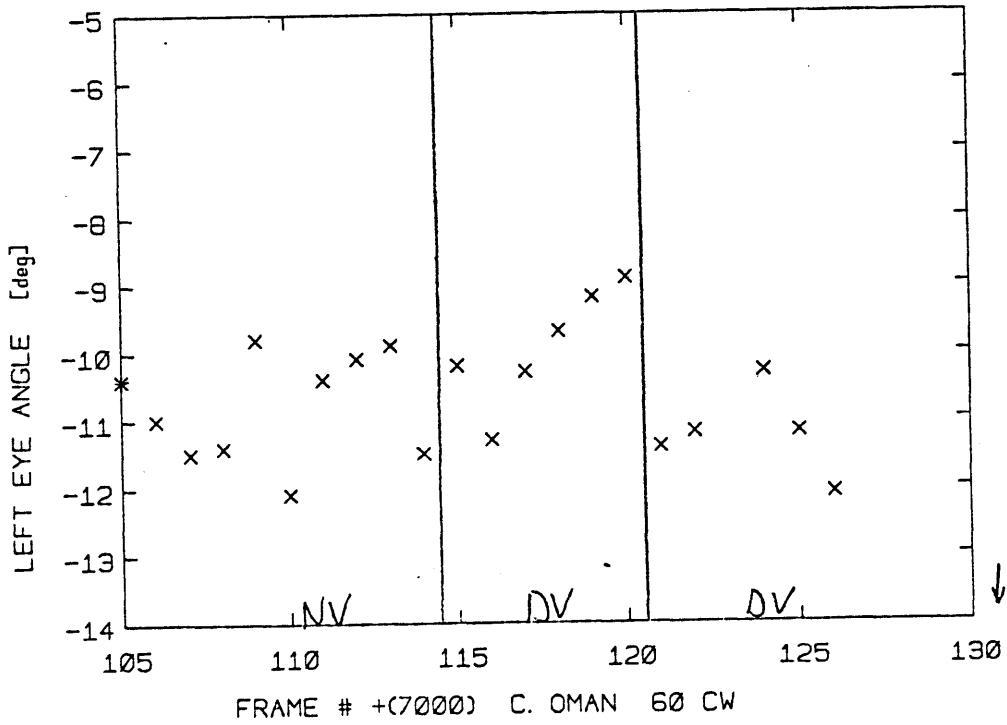
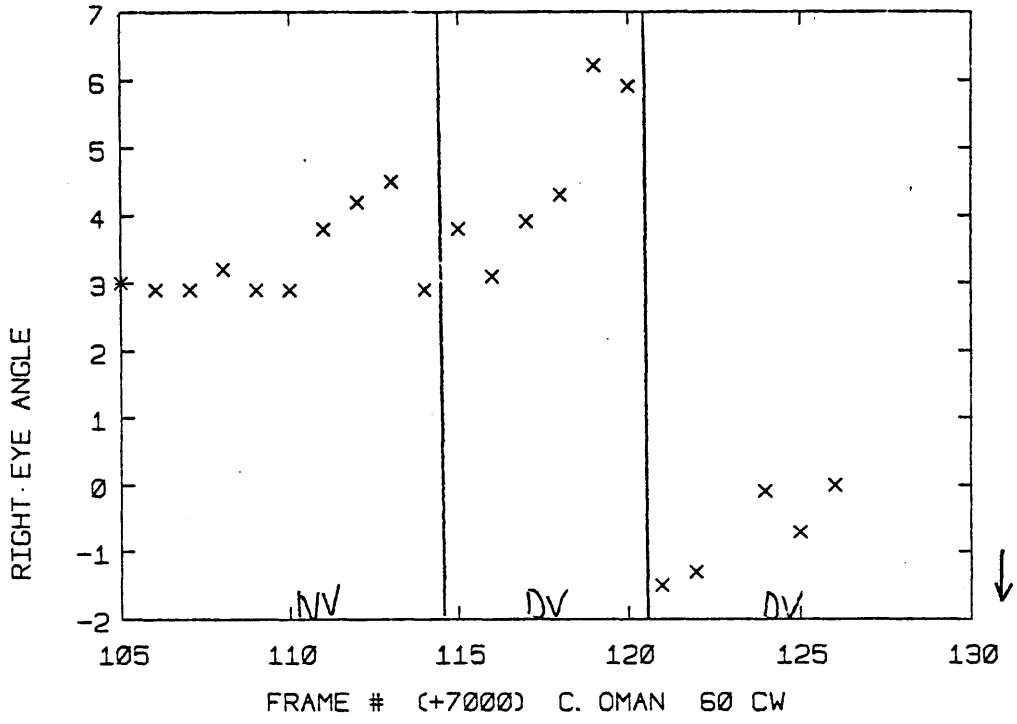


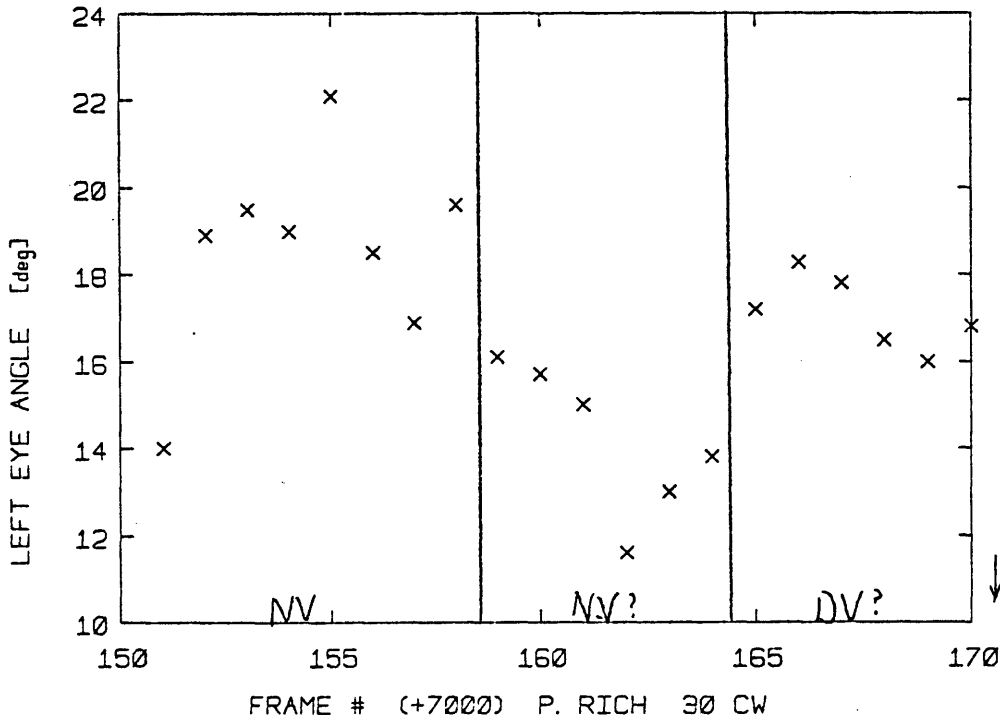
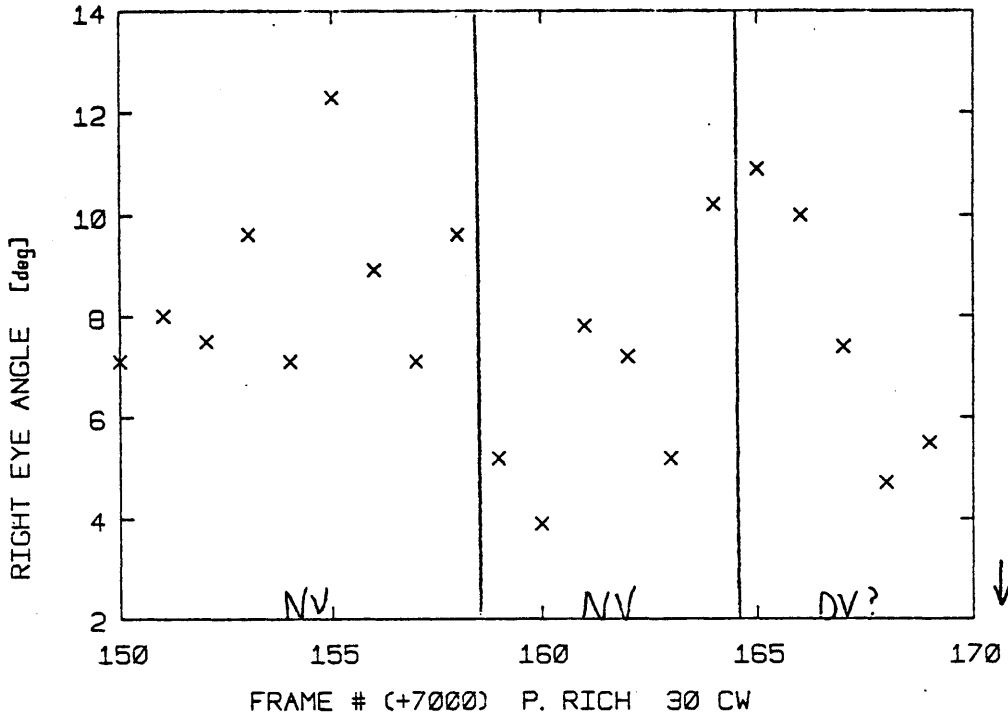


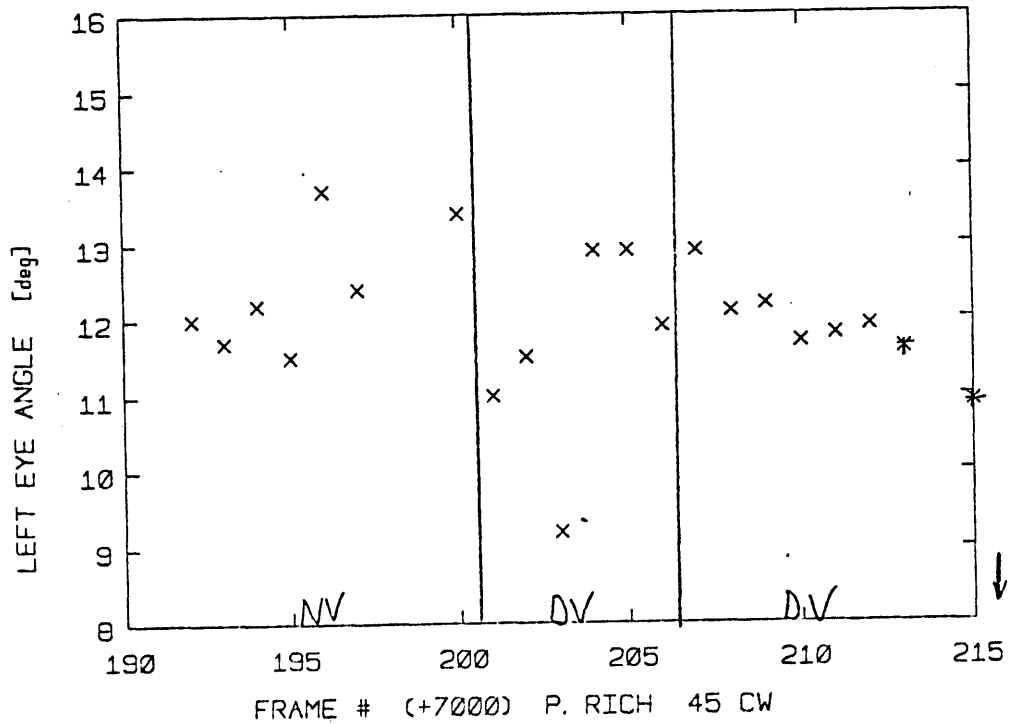
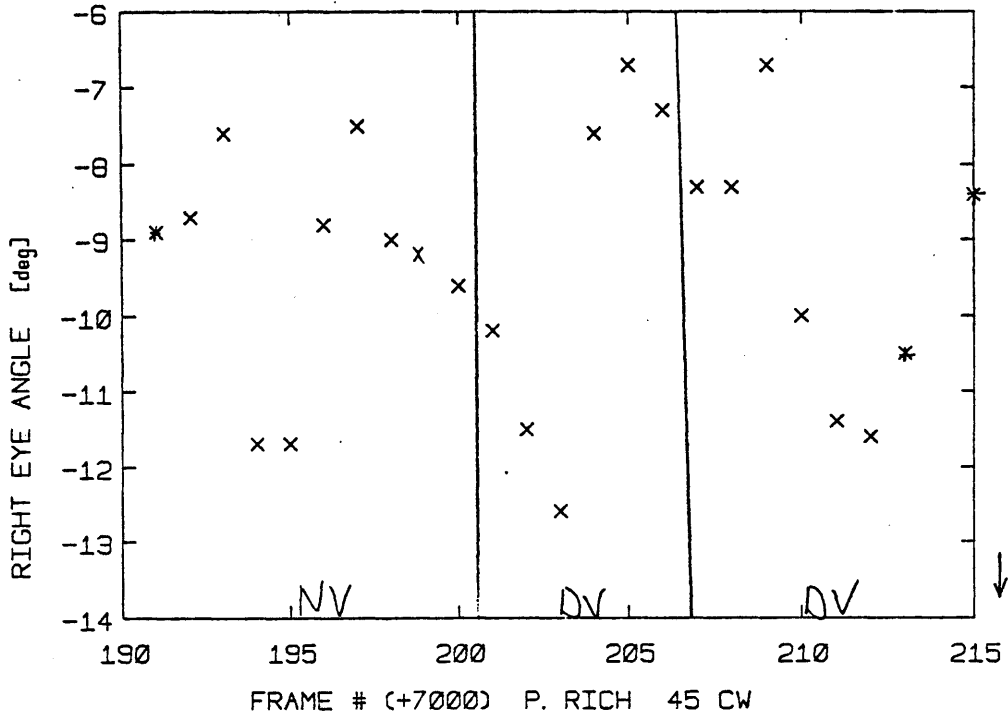


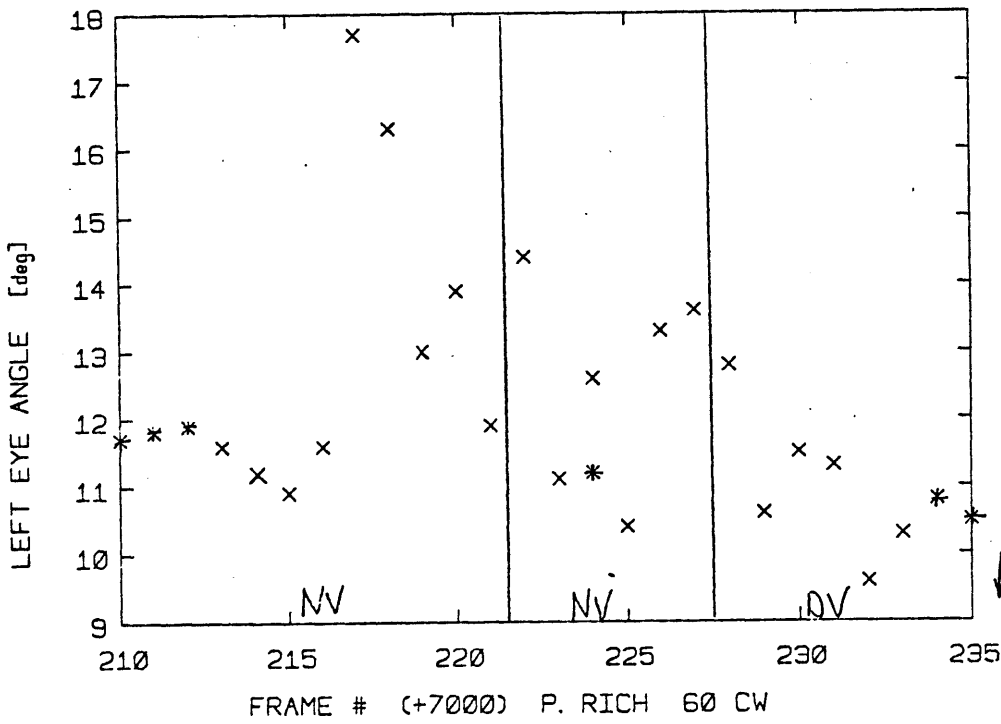
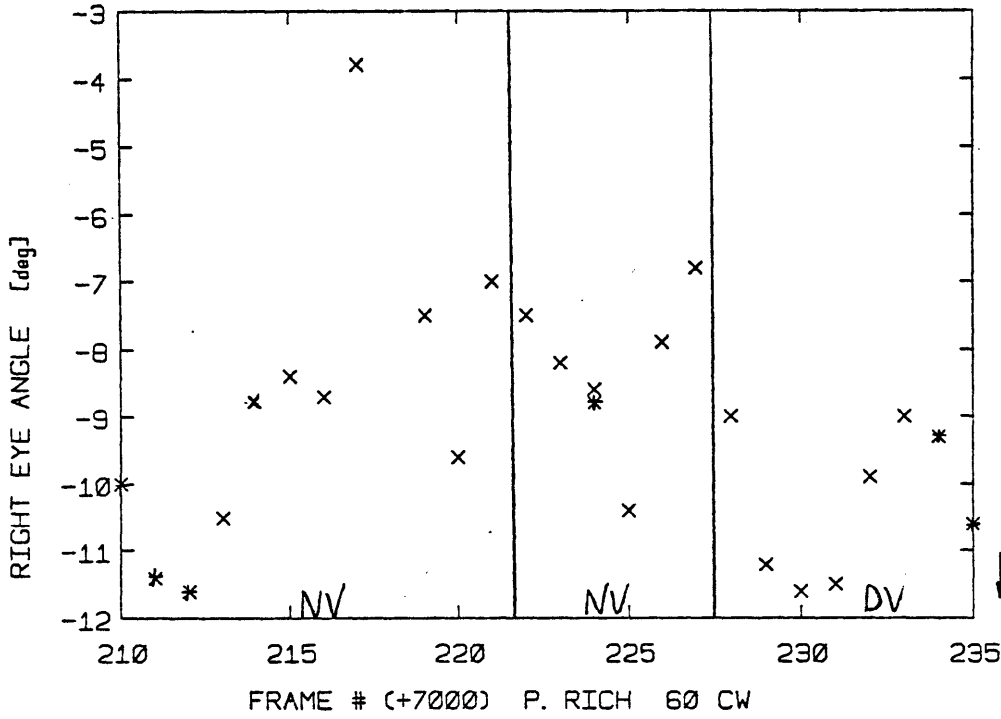


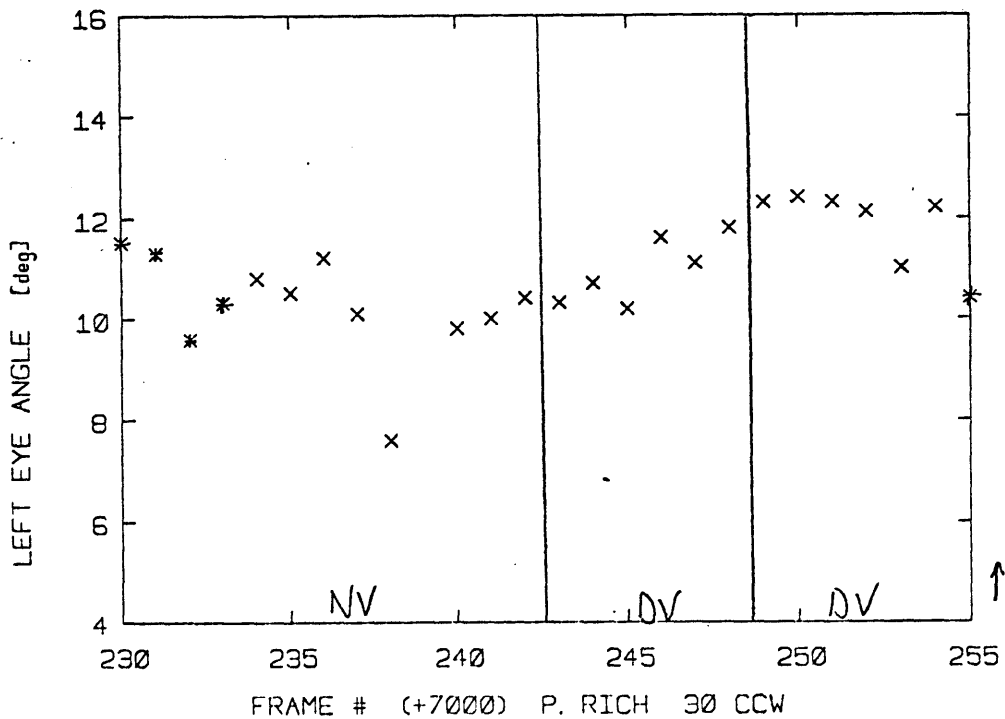
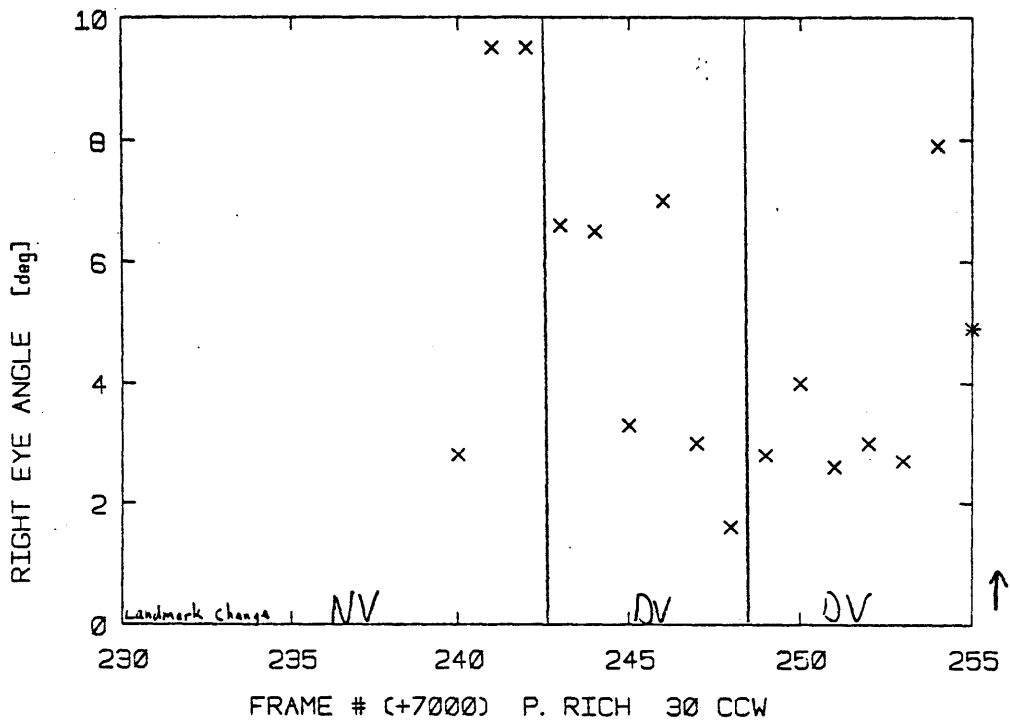


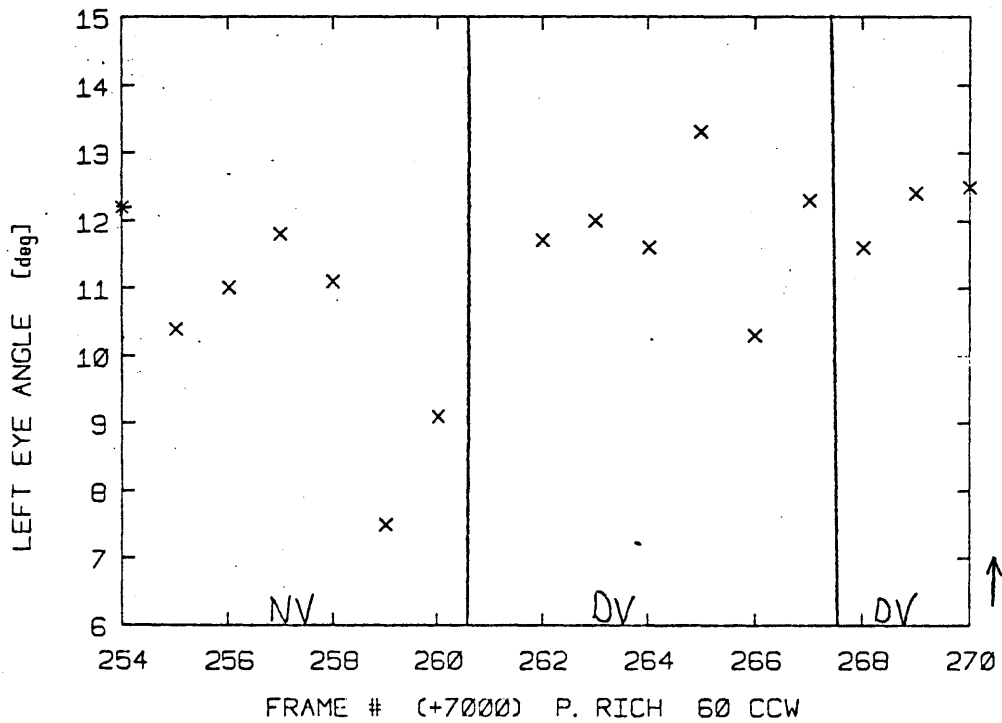
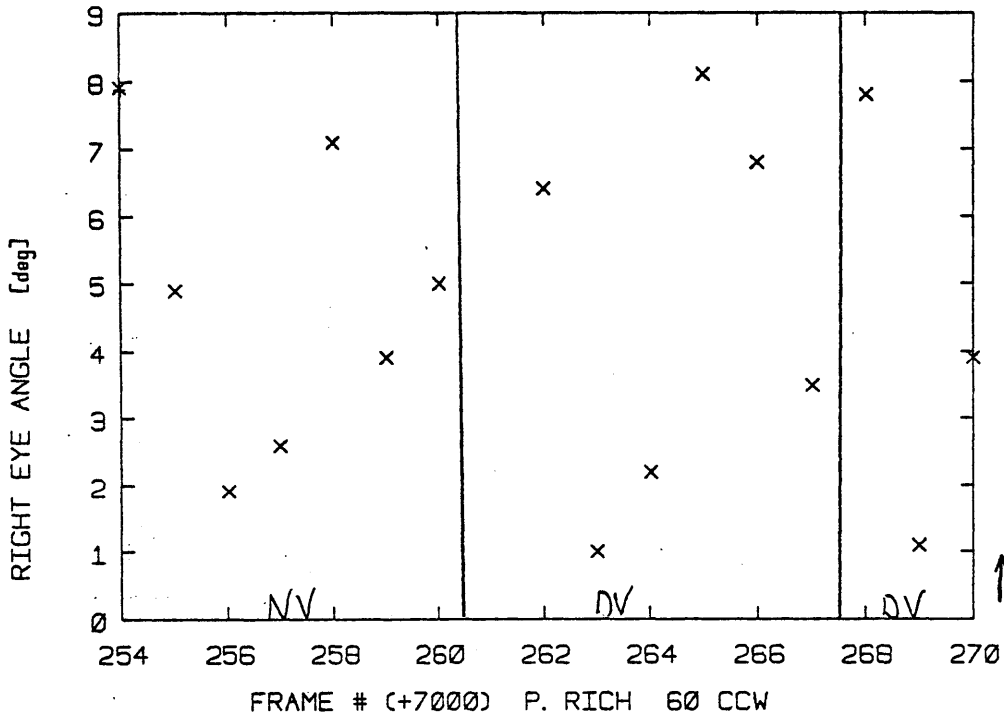




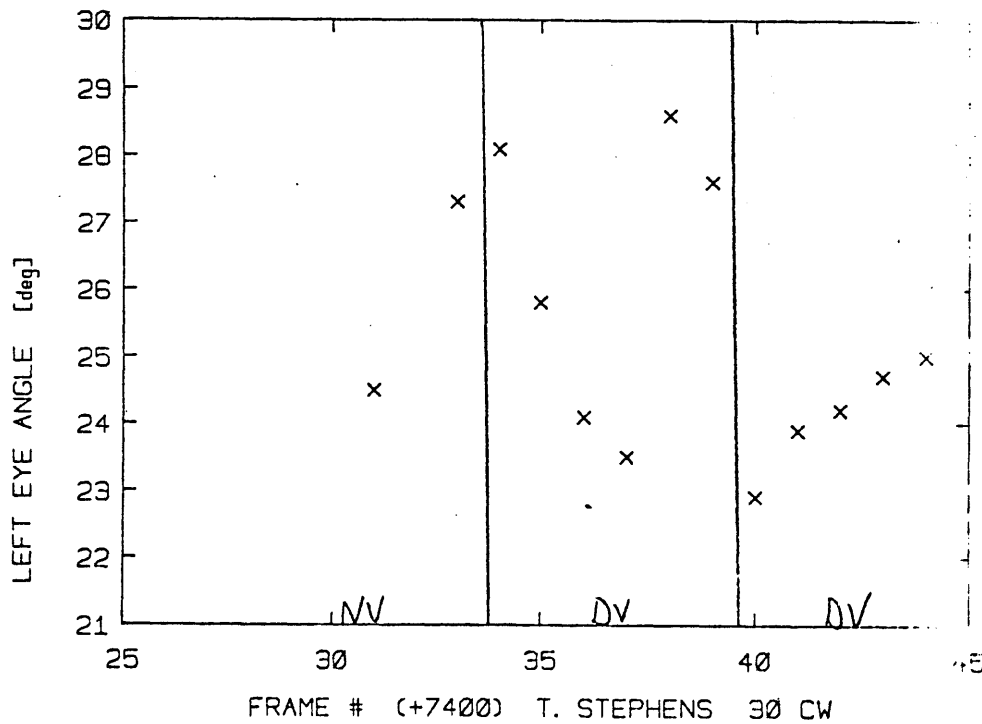
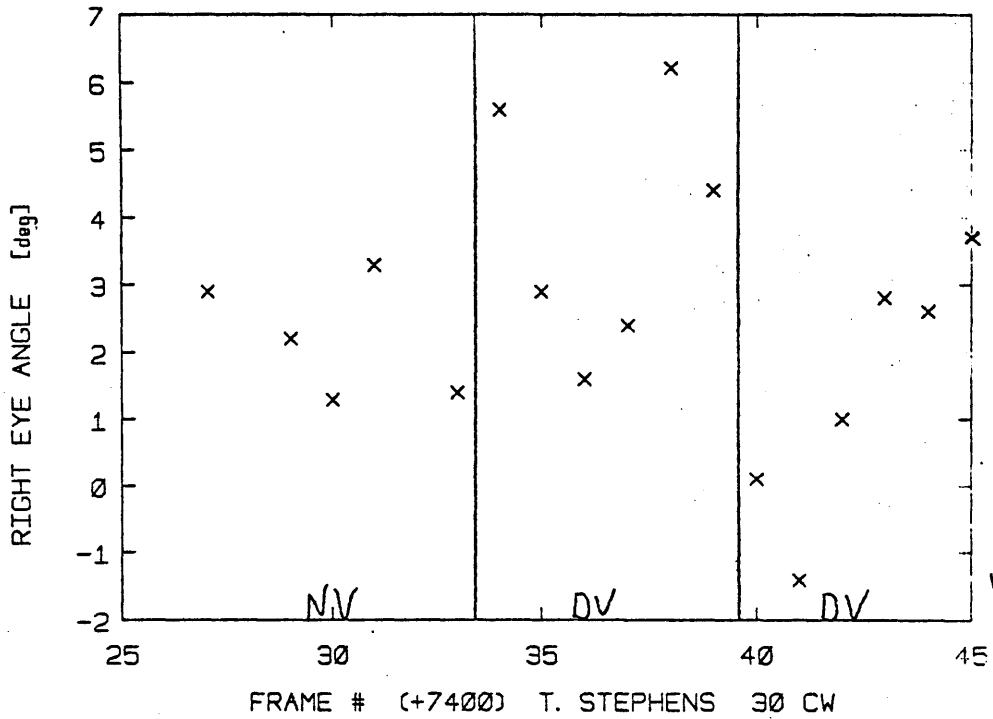


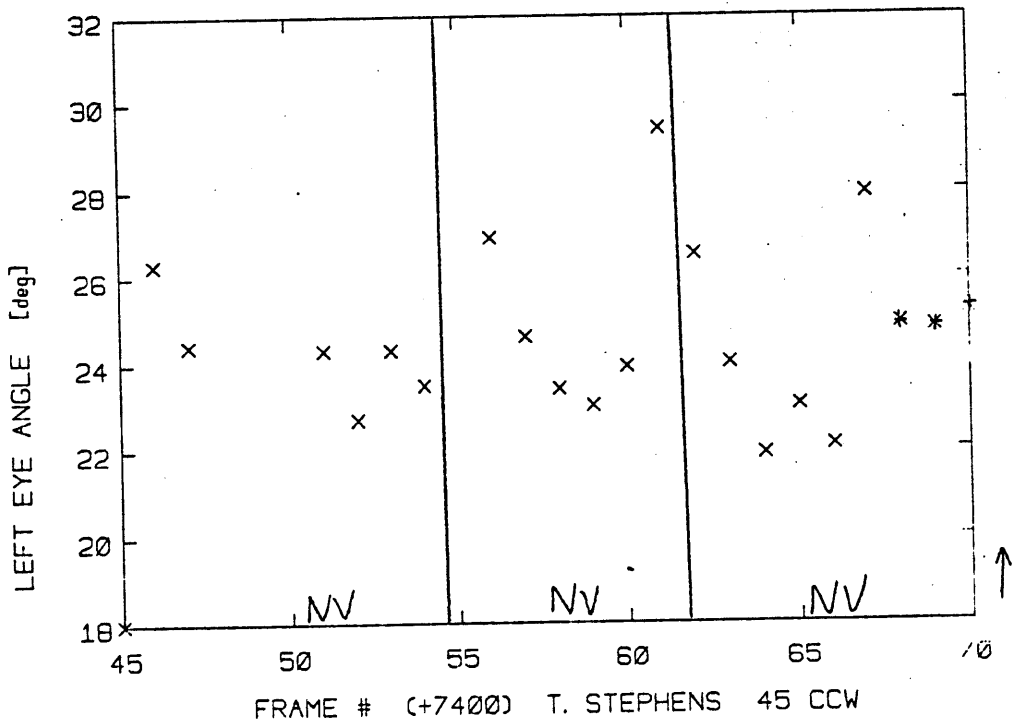
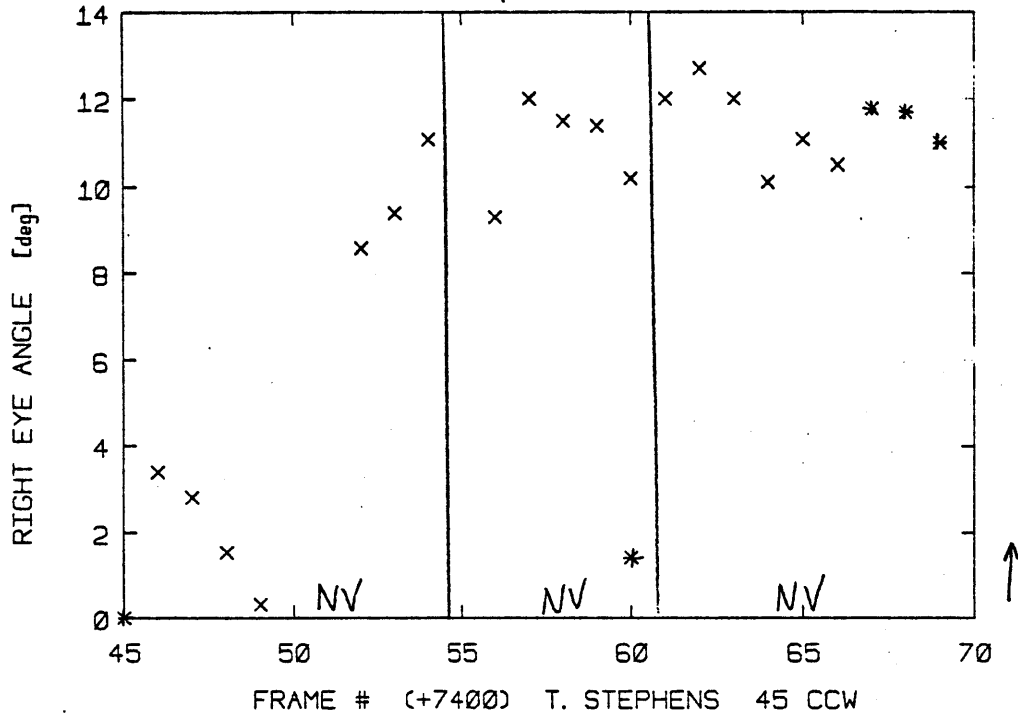


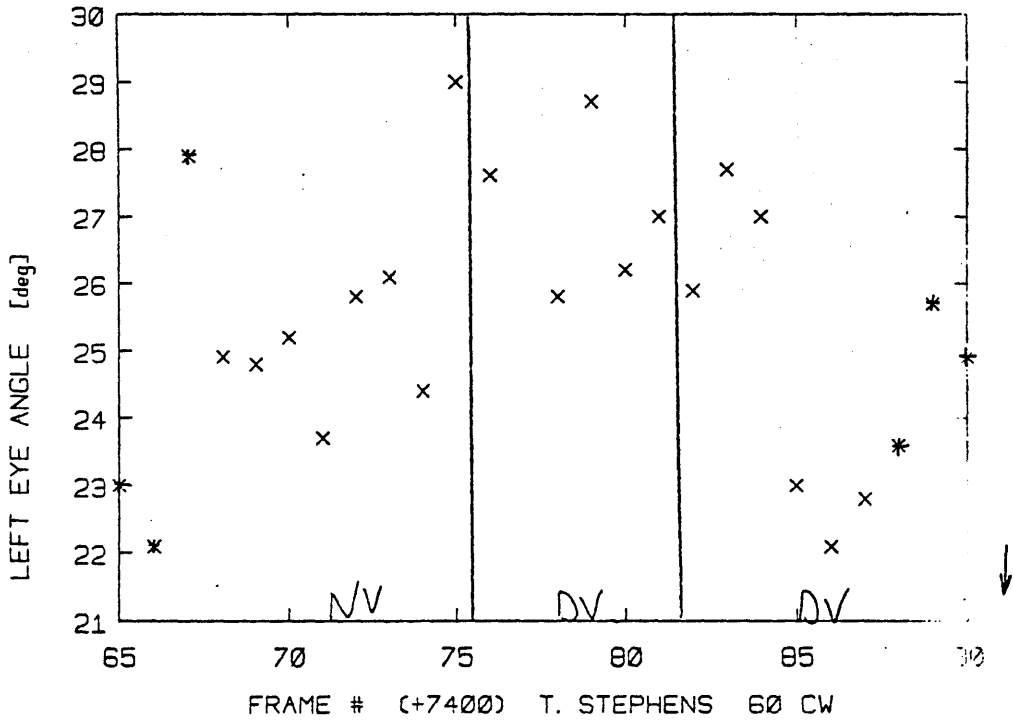
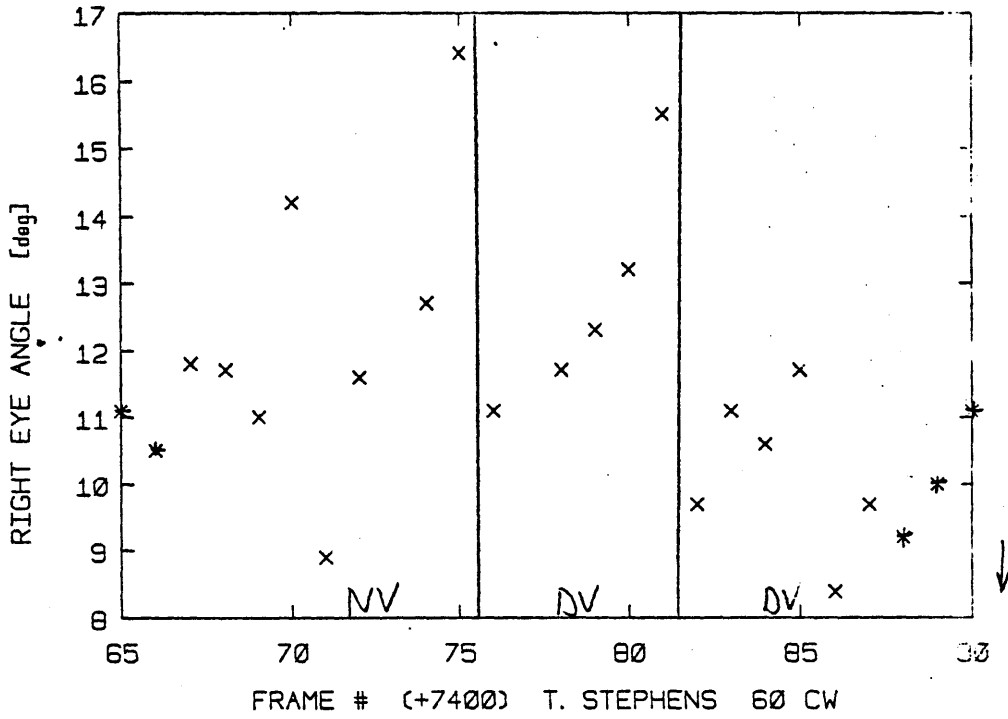


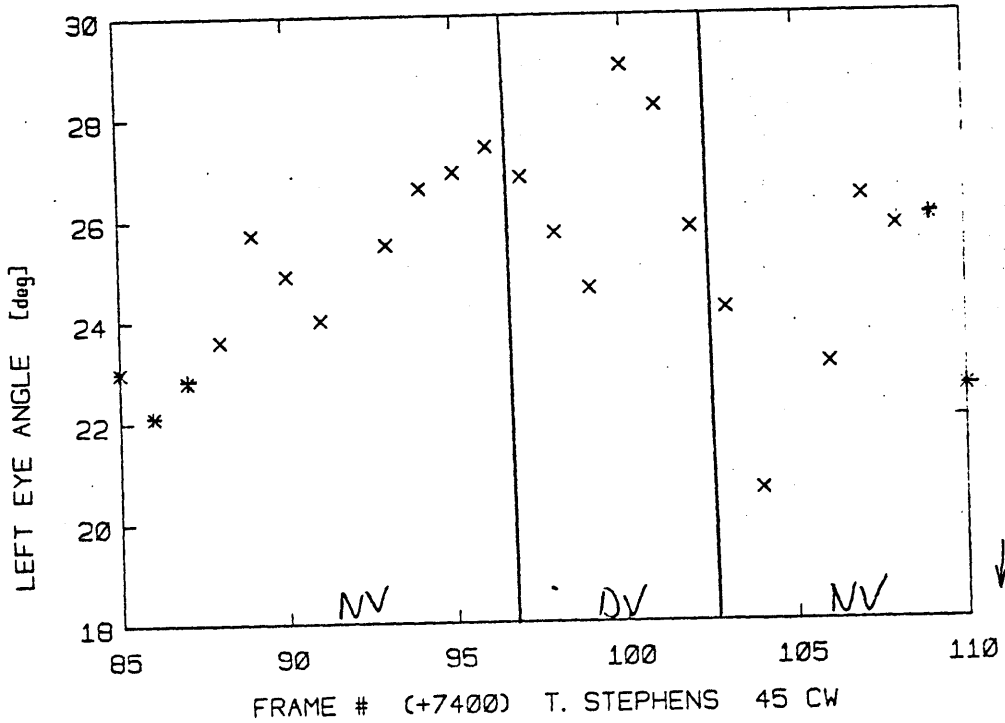
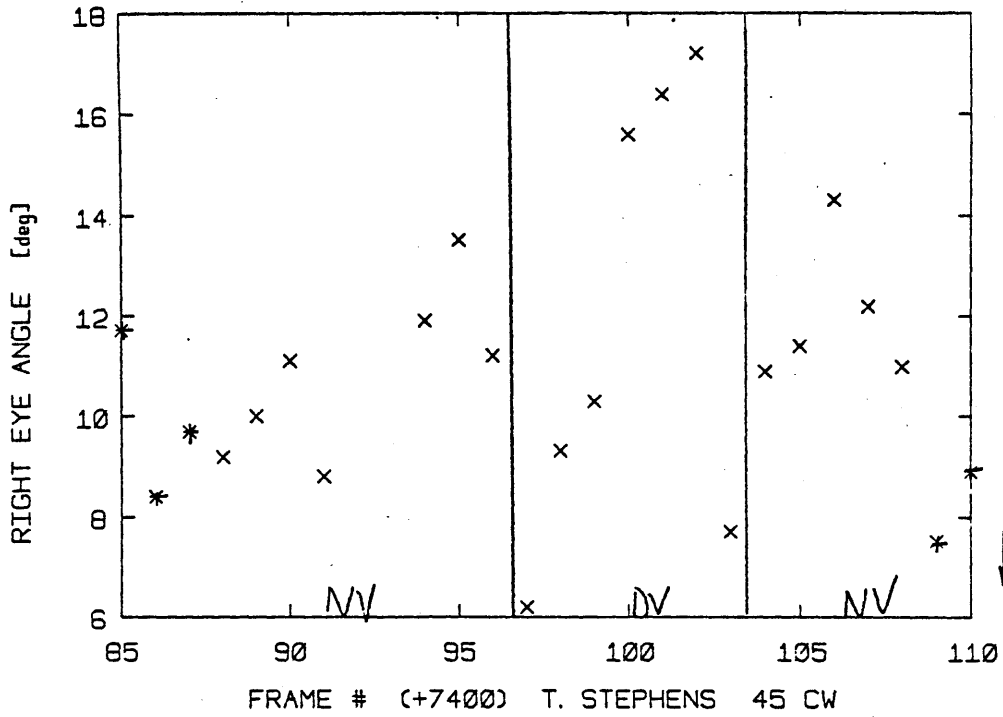


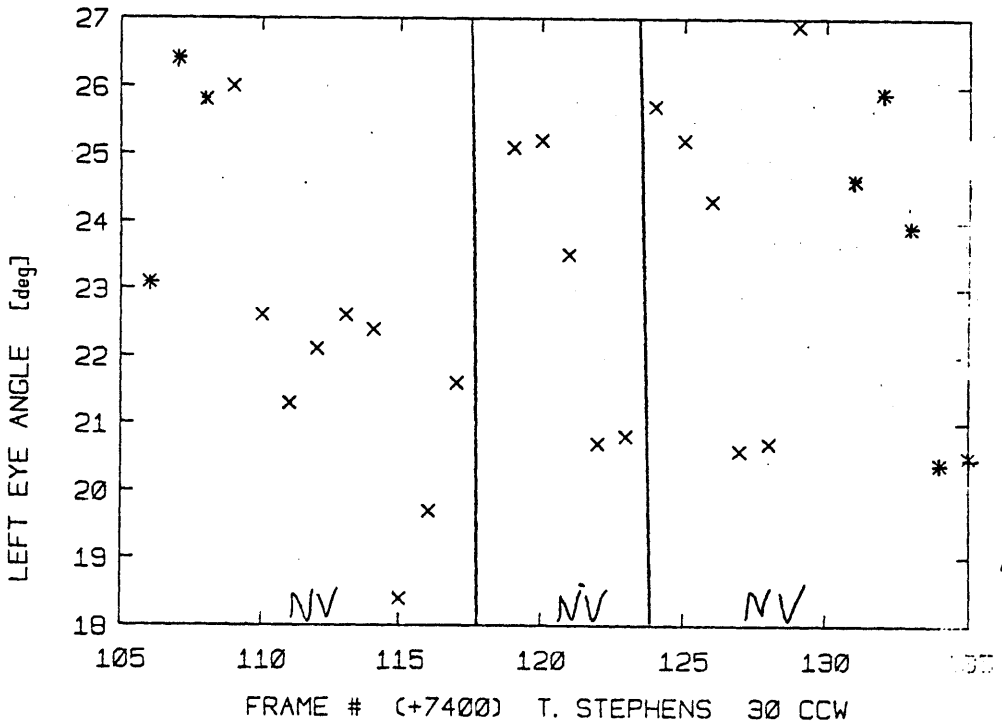
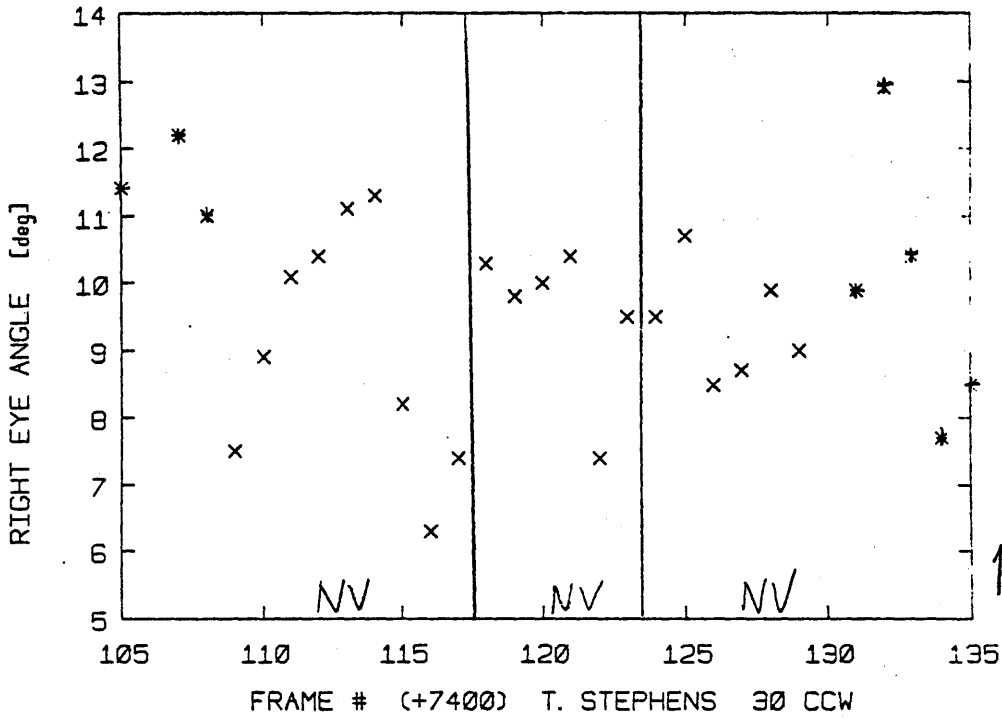
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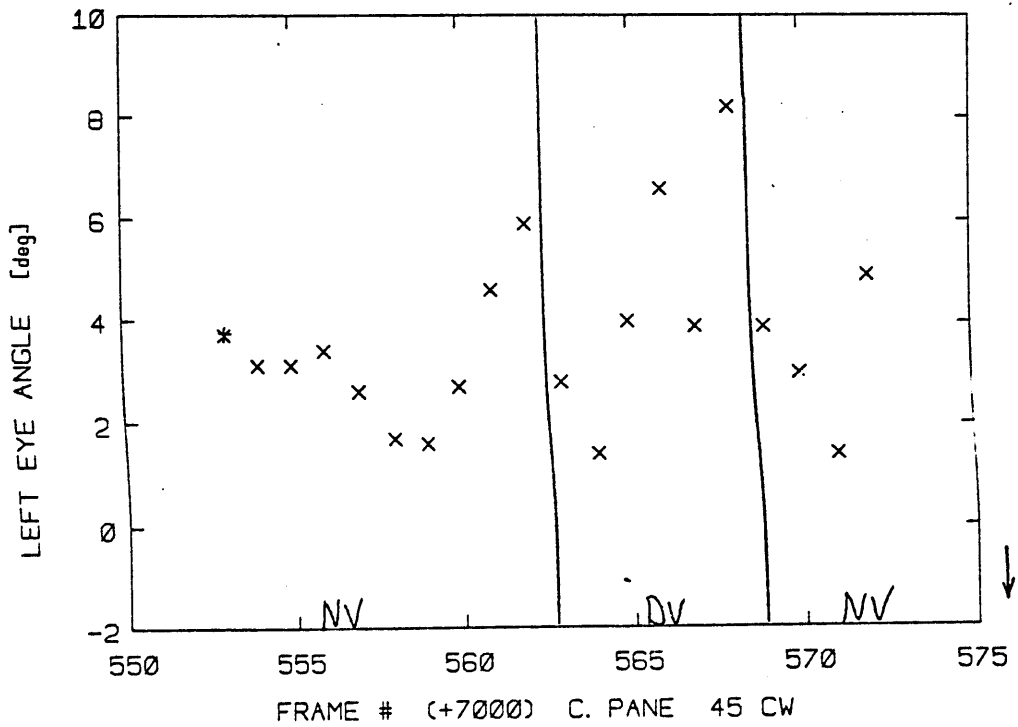
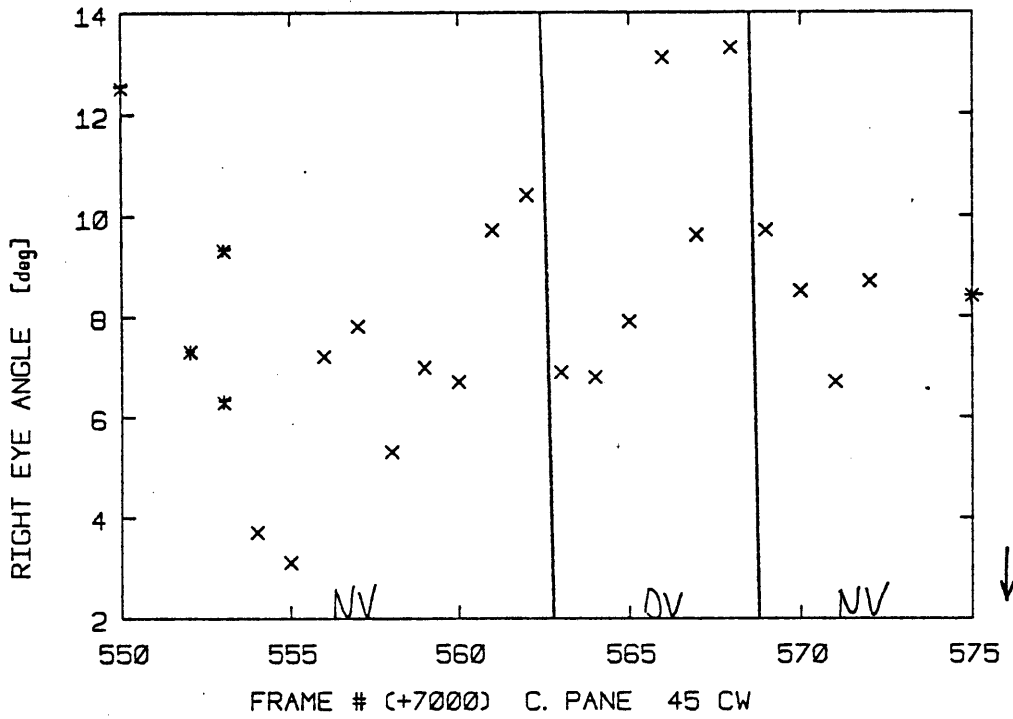


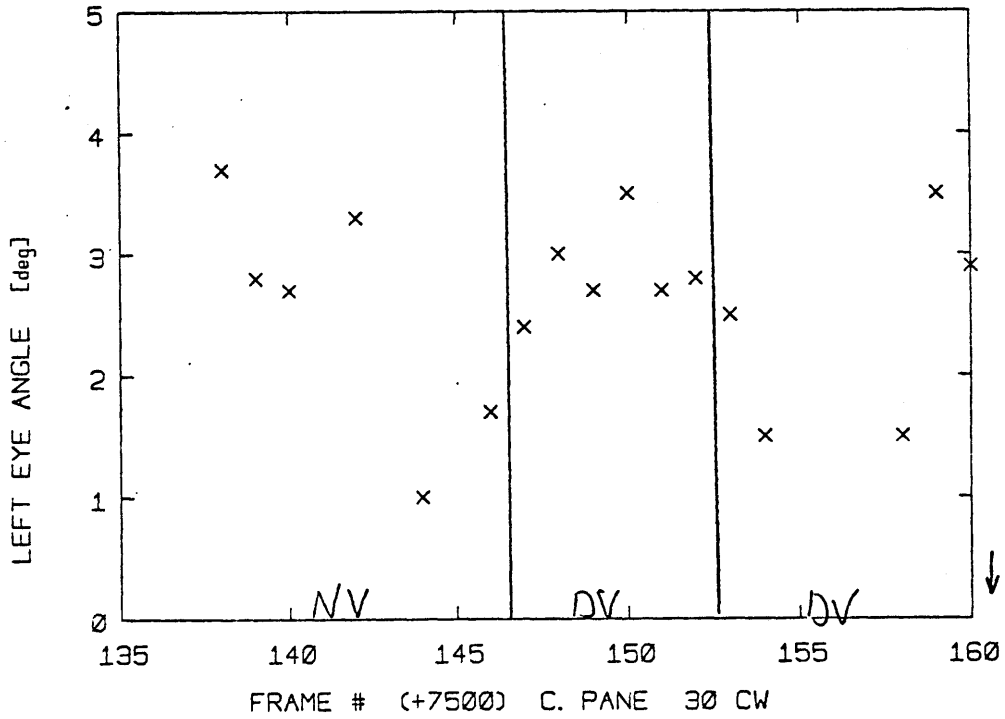
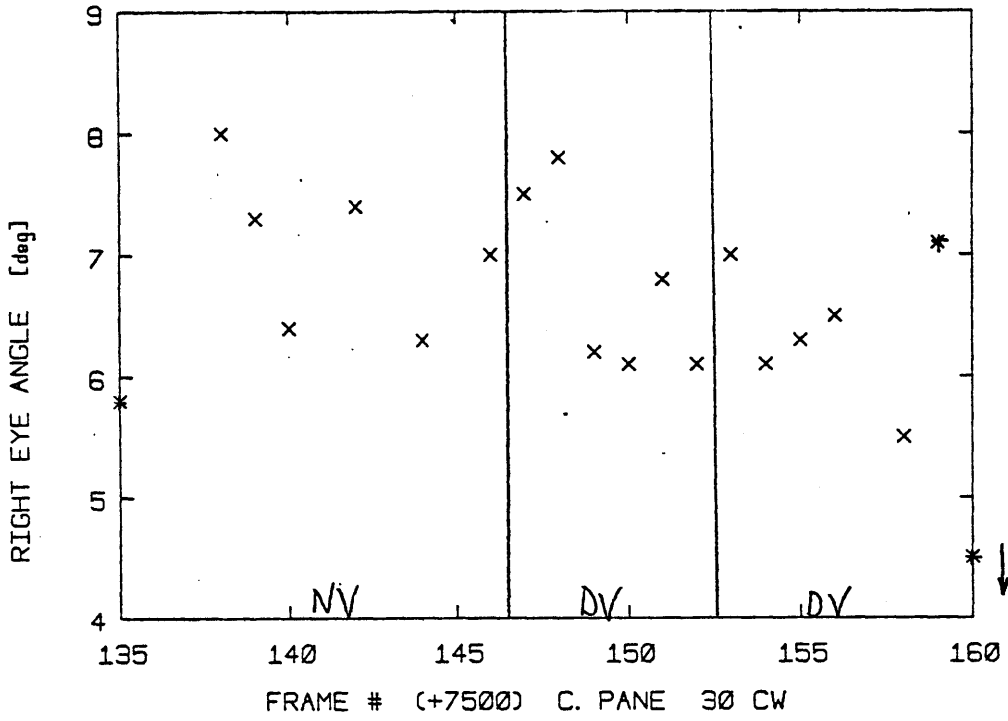


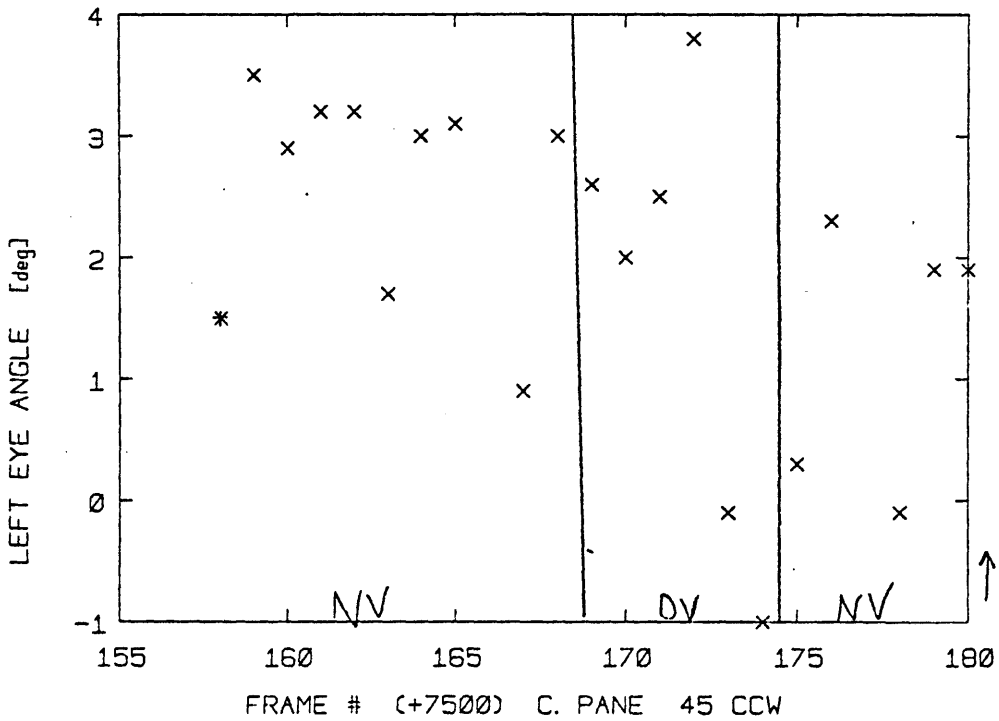
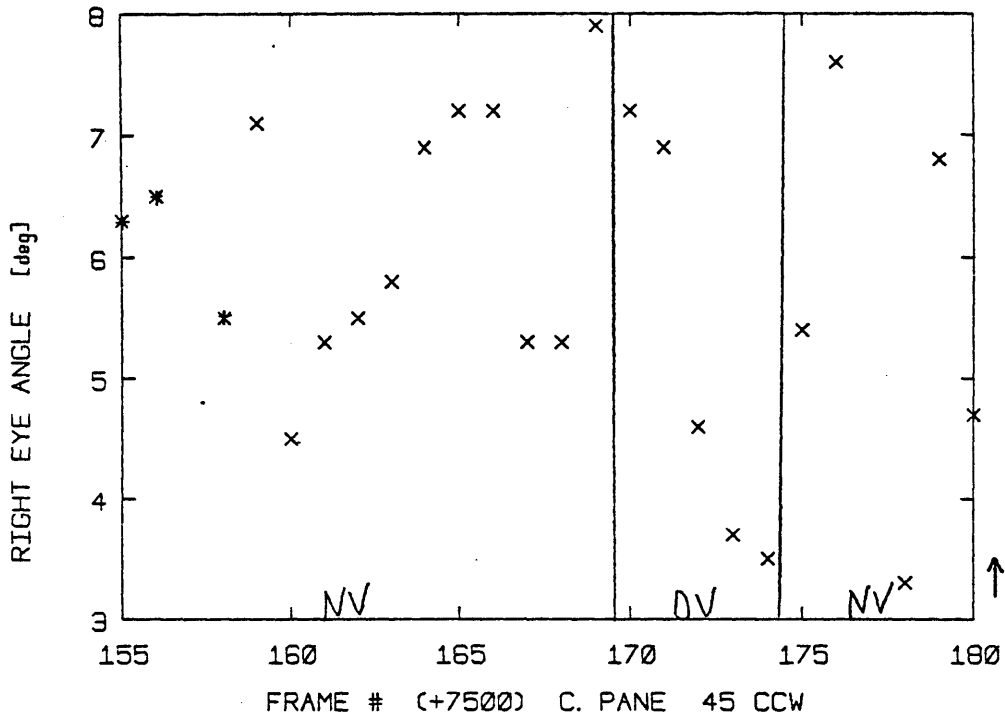


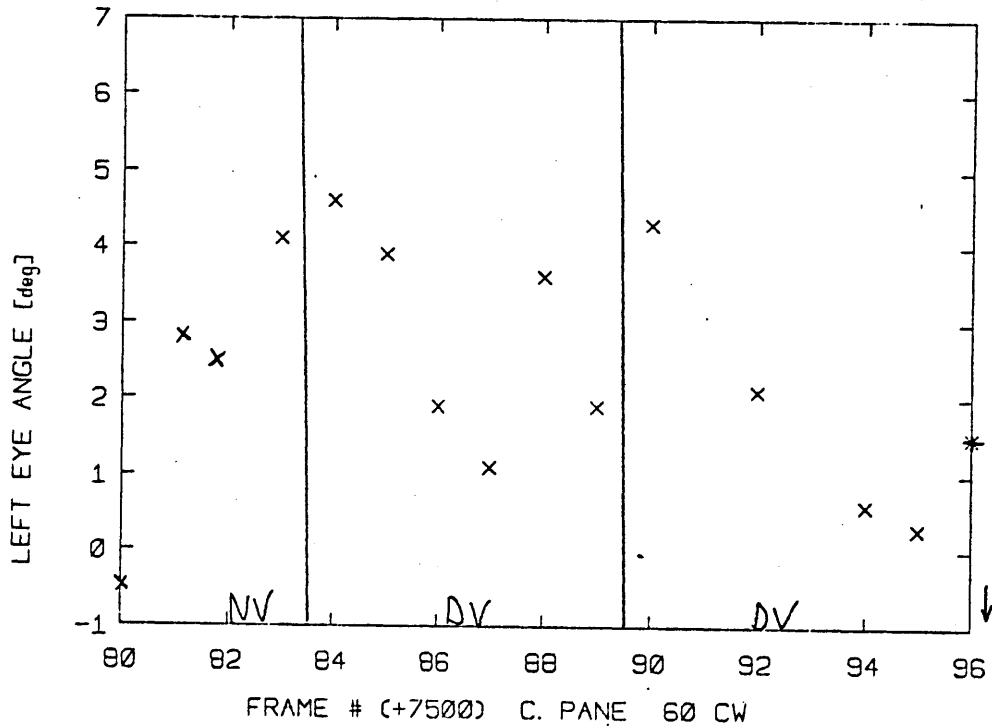
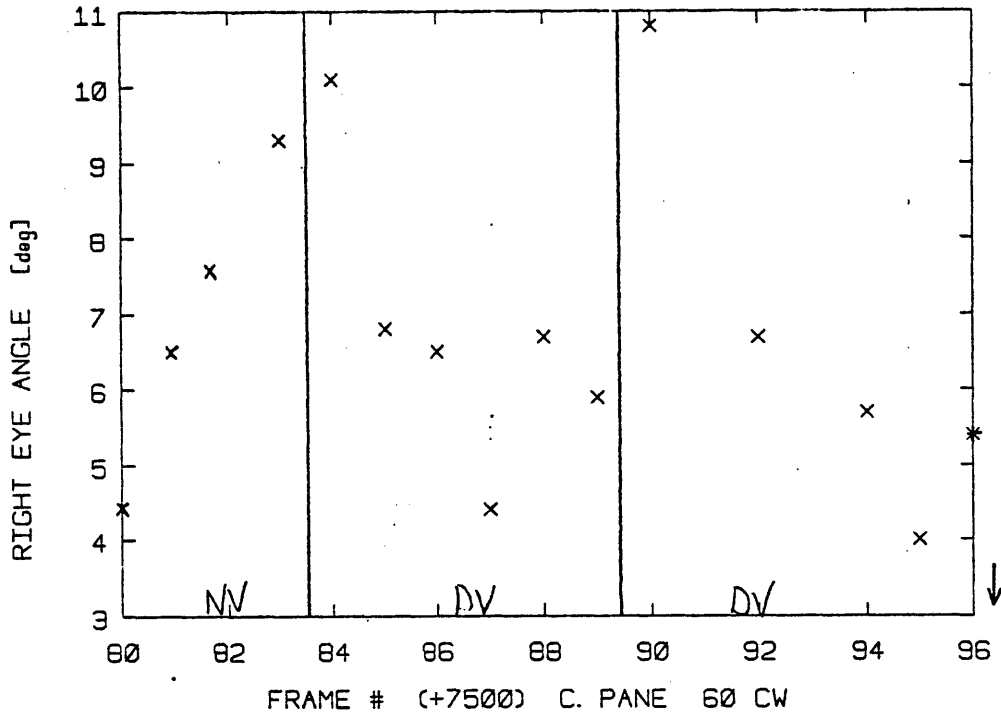


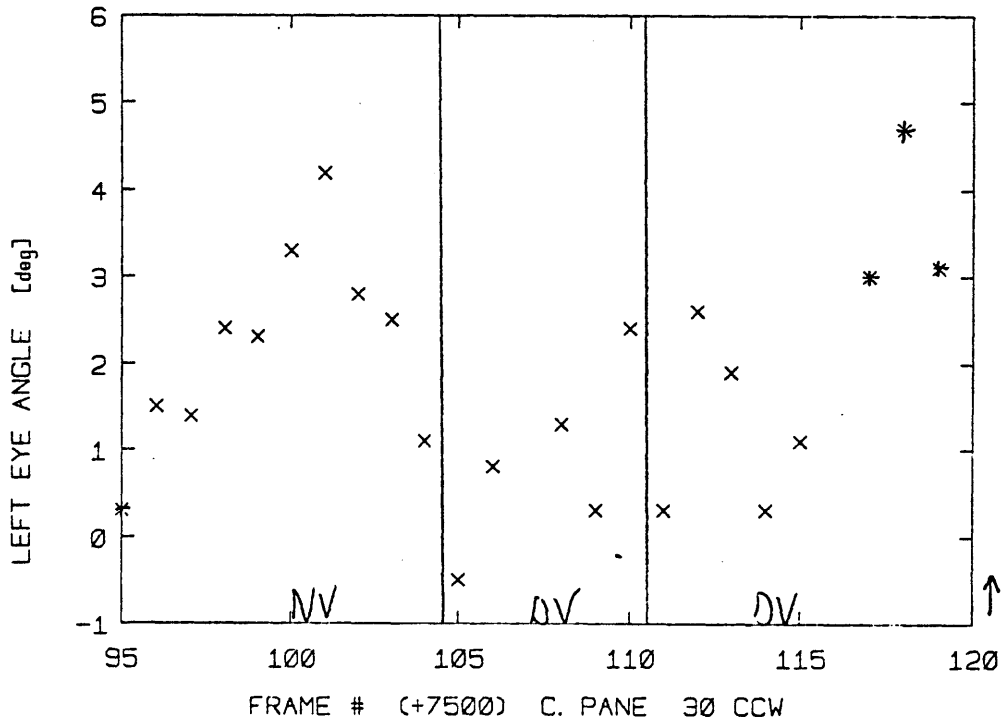
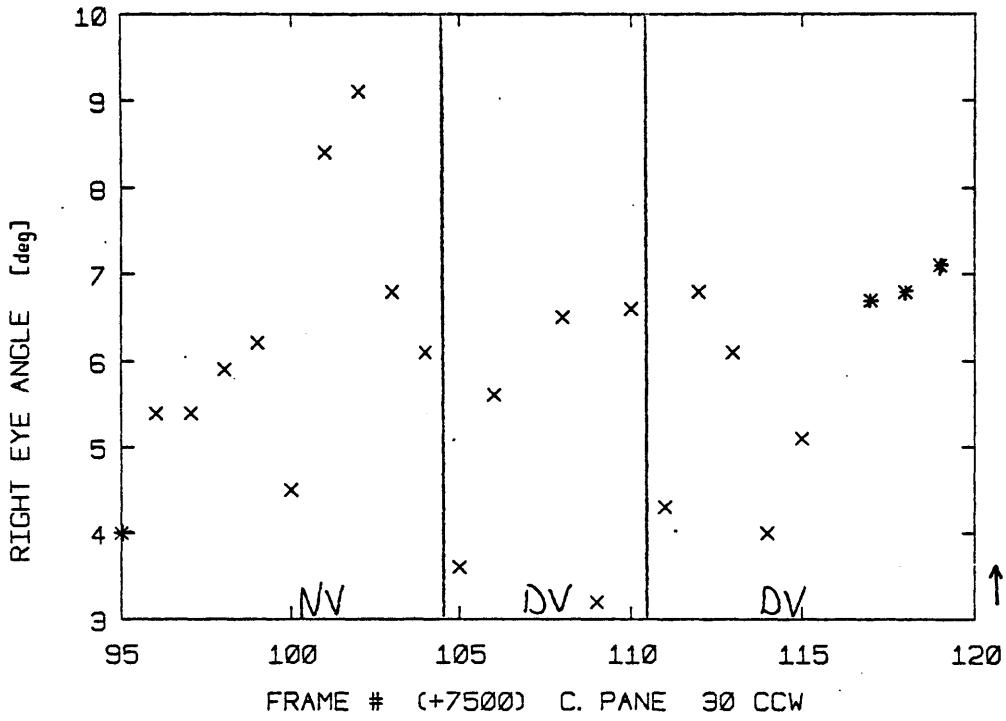


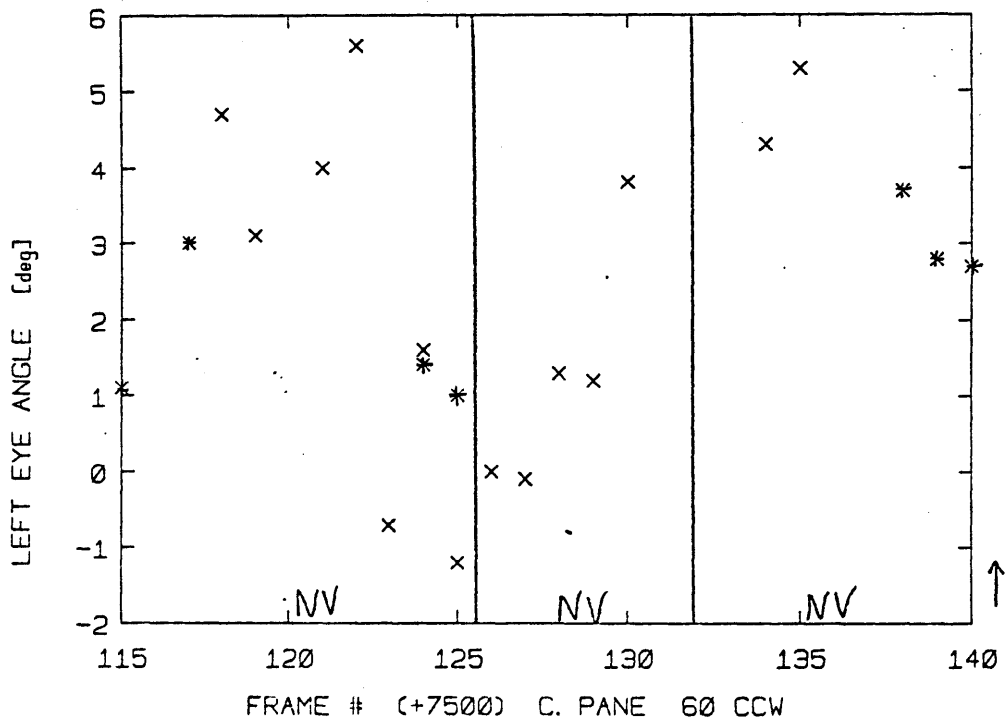
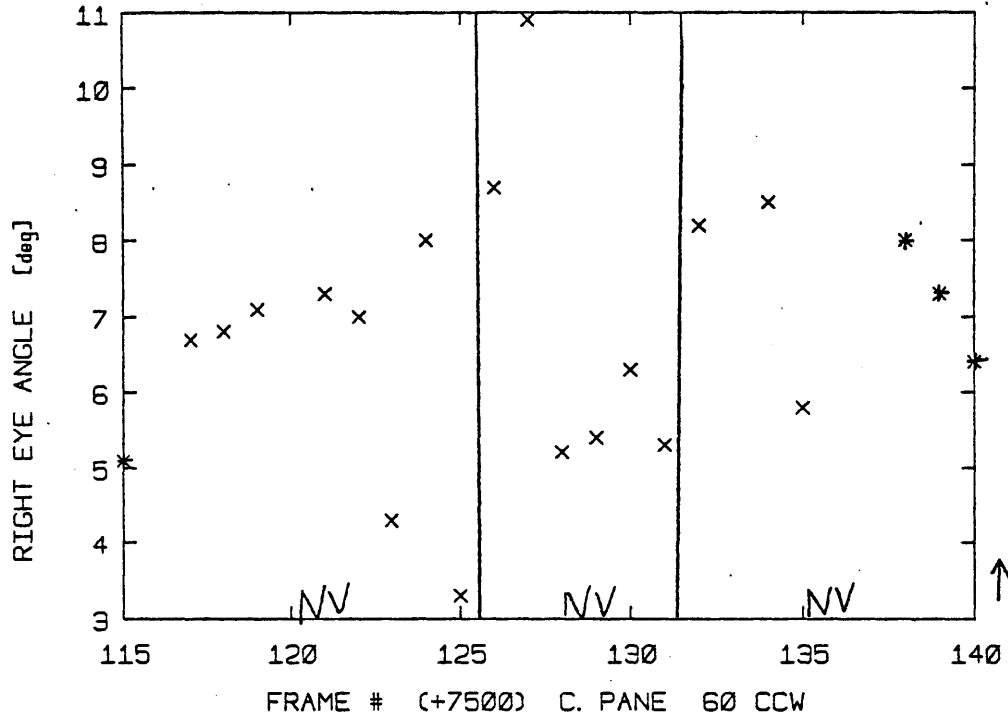


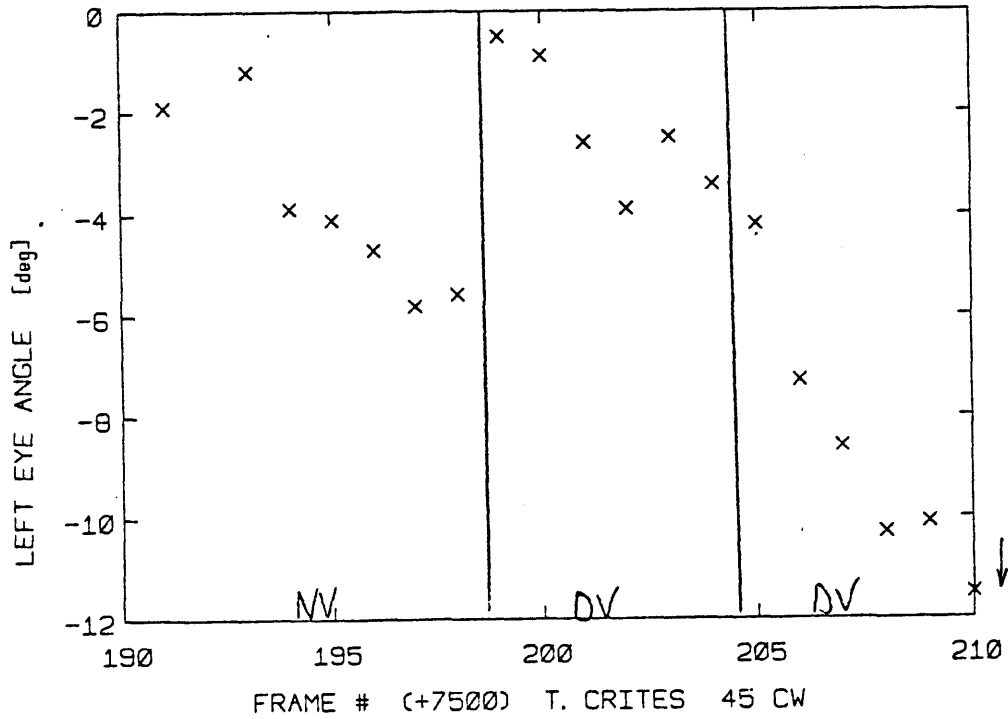
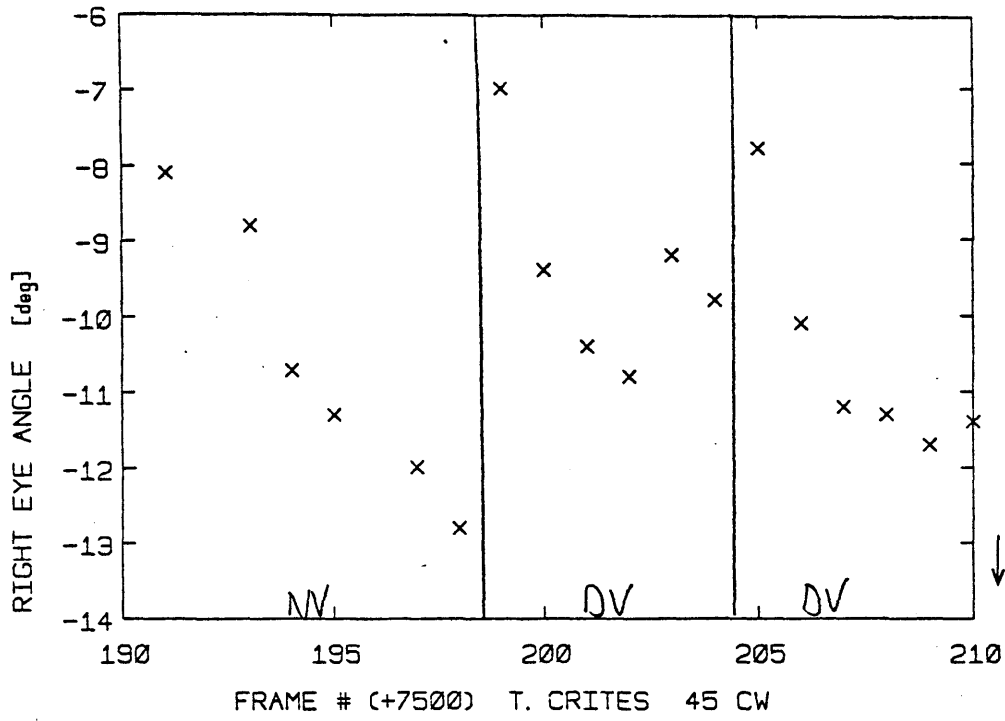


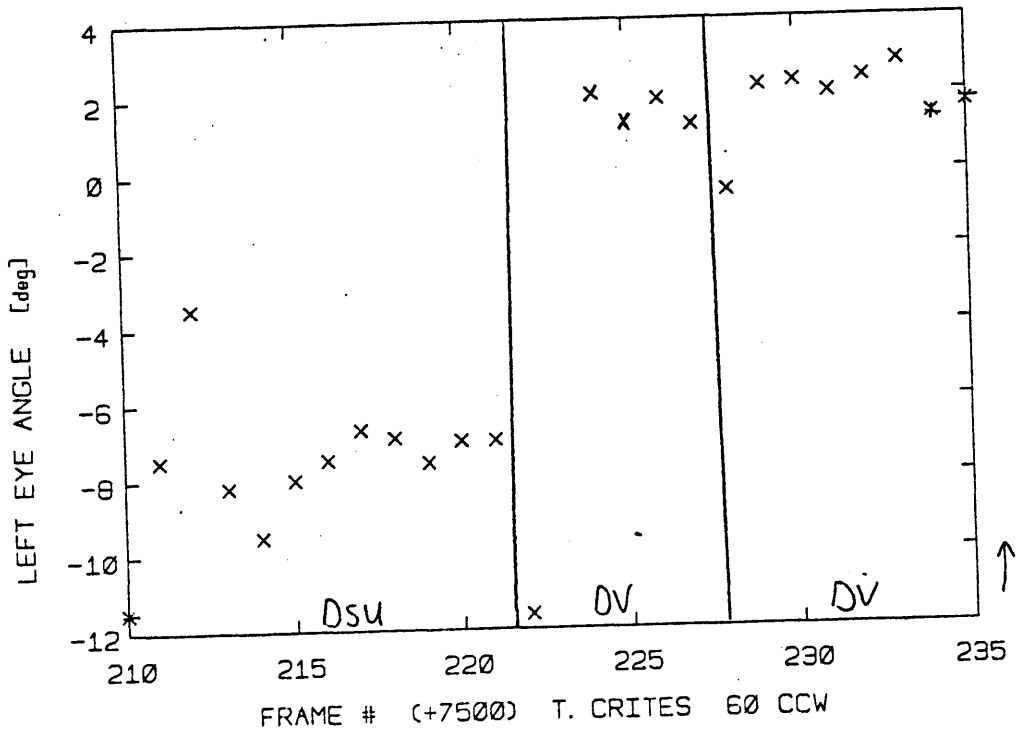
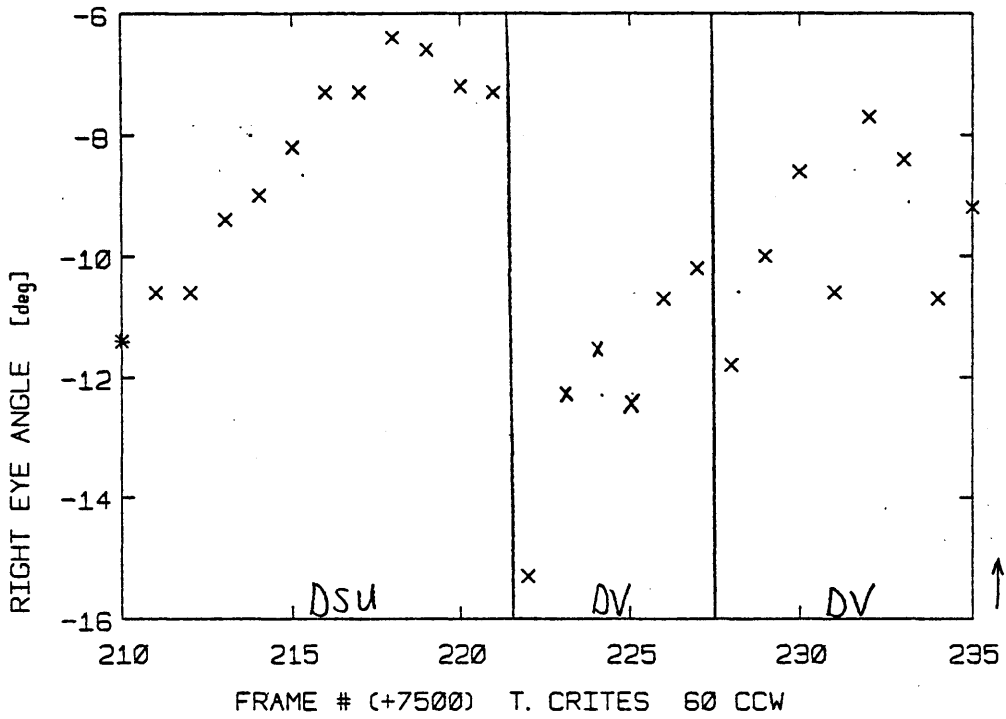


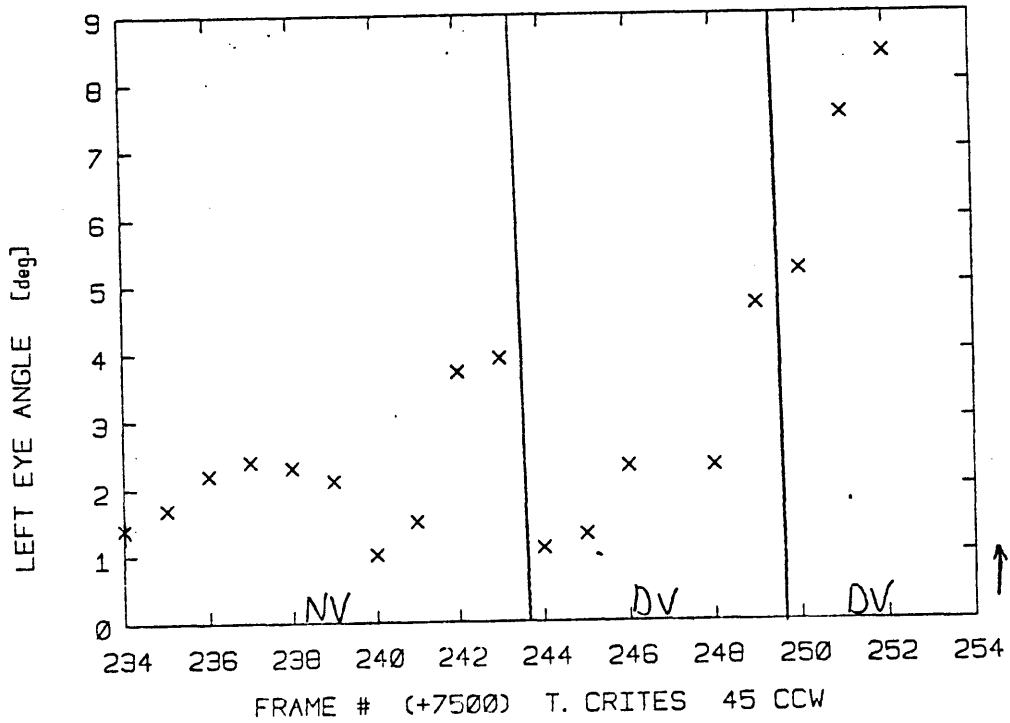
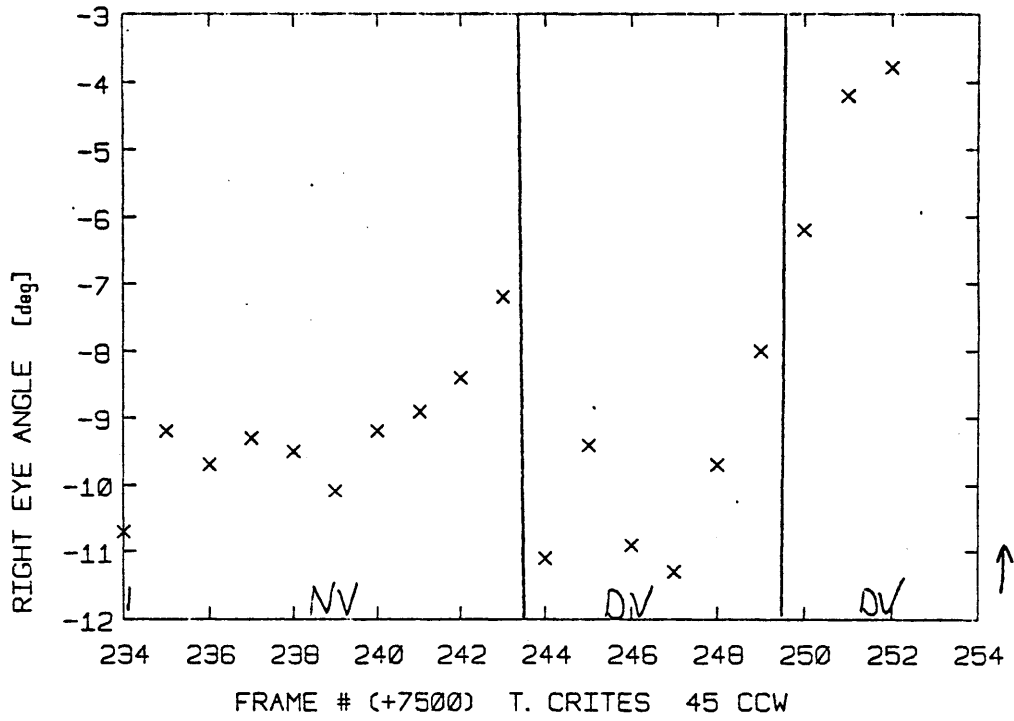


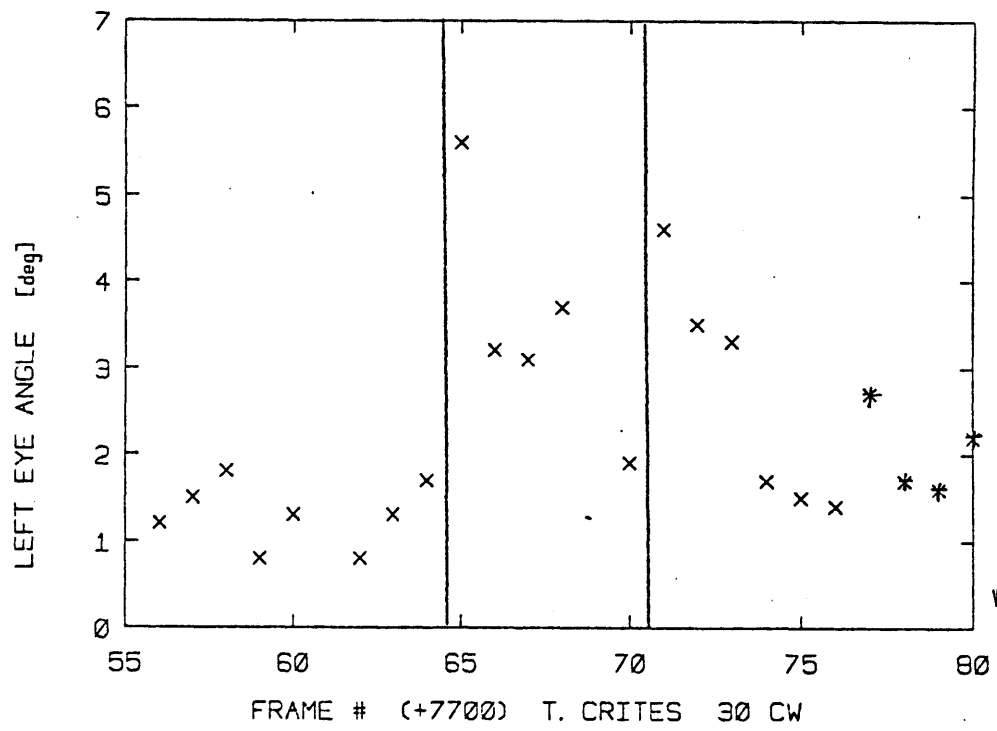
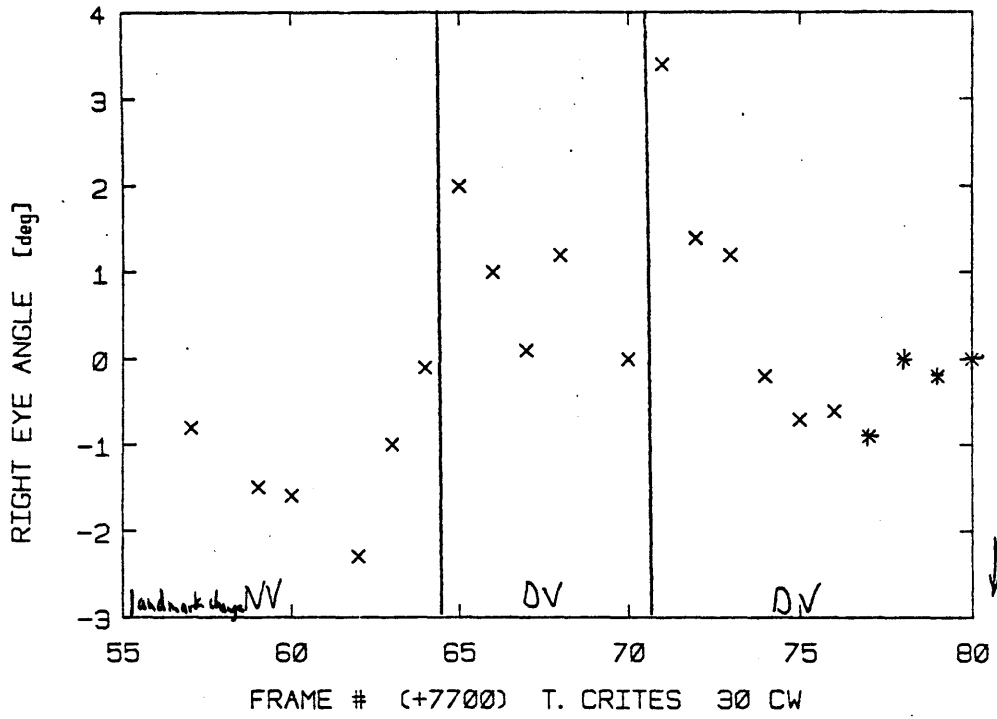




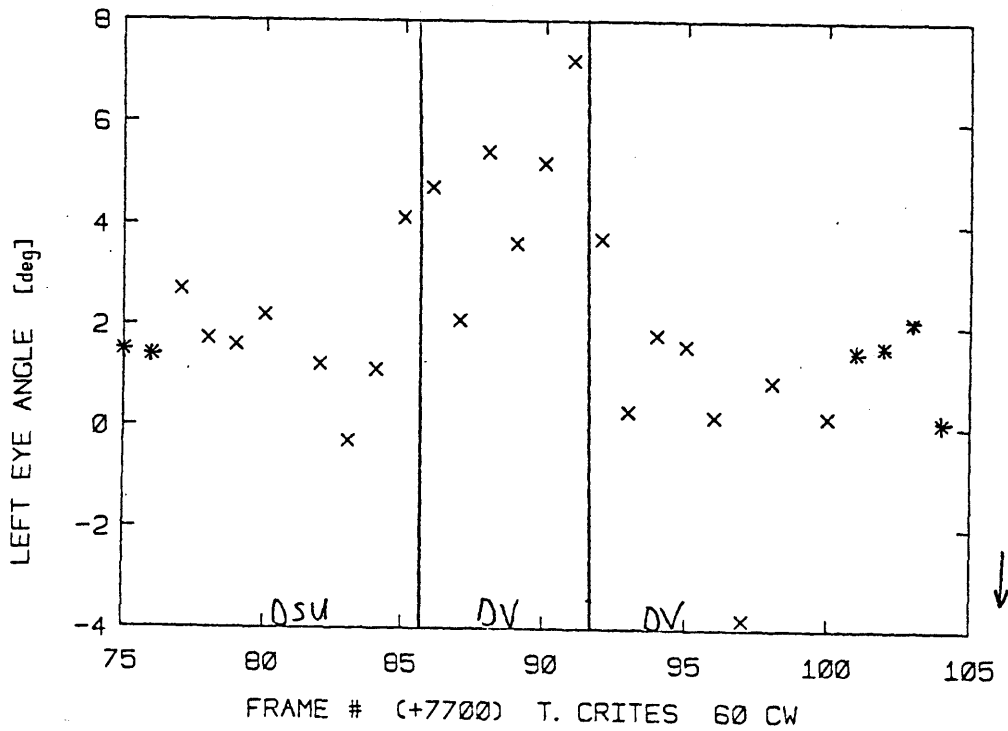
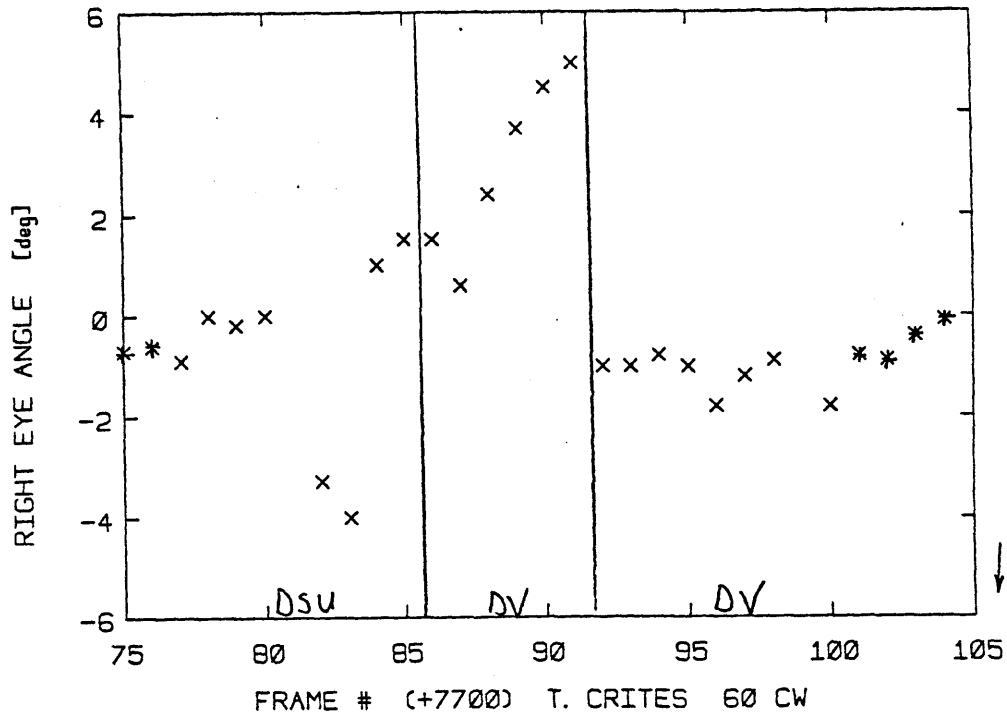








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