ANALYSIS OF BRAIN WAVE RECORDS FROM GEMINI FLIGHT GT-7 BY COMPUTATIONS TO BE USED IN A THIRTY DAY PRIMATE FLIGHT

W. R. ADEY, R. T. KADO and D.O. WALTER

Space Biology Laboratory
Brain Research Institute
University of California
Los Angeles, California

1. Introduction

It is generally agreed that physiological monitoring of pilot or astronaut status, based on such parameters as the electrocardiogram and respiration, leaves much to be desired in assessment of broad changes of consciousness from wakefulness to deep sleep, and that such data are even less revealing of transient shifts in alertness and focused attention associated with drowsiness and fatigue. Nor is accuracy of evaluation likely to be improved by information about eye movements, or verbal response to specific questioning. There remains a paramount need for a reliable monitoring system capable of functioning with a passive subject, and even more importantly, on a non-interference basis (Adey, Kado and Walter, 1966).

These important requirements in applied physiology have their counterpart in significant questions about basic brain mechanisms, and their modification by exposure of the mammalian organism to ever-increasing periods of weightlessness. It would seem reasonable to seek evidence for altered cycling in the patterns of brain wave activity. Some of these changes might involve the brief alerted patterns occurring in the few seconds required for a discriminative judgment. Others might relate to periodicities in sleep-wakefulness cycles, of vital importance if judgment and performance levels are to be sustained at high levels in long flights.

Most importantly, it is an uncompromising requirement that we collect sufficient data over an appropriately long period to allow us to distinguish, on the one hand, changes representing an immediate reaction to the sudden imposition of weightlessness, to which adaptation may occur in varying degree; and on the other, the gradual appearance of undesirable changes after an initial period with a satisfactory physiological status.

In pursuit of these goals, adequate simulation studies in animals and man are essential for evaluation of flight related changes. Moreover, since full evaluation of central nervous function requires use of electrodes implanted directly into deep brain structures, a strong case can be made for the continued acquisition of central nervous and cardiovascular data in heavily instrumented subhuman primates (Adey, 1966). Such animal flights can be construed as a direct investment in manned flight programs, contributing vitally needed information without the potential hazards to man in the use of such deep instrumentation, and with continuity and uniformity of data acquisition not easy to duplicate in manned flight.

This paper will discuss current preparations for a 30 day biosatellite flight during 1967, and the data analysis and display techniques developed for this flight and for analysis of the electroencephalogram (EEG) of a group of astronaut candidates. It will then consider EEG data from the initial days of the Gemini GT-7 flight.

2. Preparations for a 30 day biosatellite flight, using a pig-tail macaque monkey (*Macaca nemestrina*).

Detailed data on the mounting of this experiment has been presented elsewhere (Adey, 1966). Designated Biosatellite D in the Biosatellite Program of the Office of Space Science and Applications of the National Aeronautics and Space Administration, it is planned to orbit a 15 pound (6-8 Kg) male pig-tail macaque for 30 days. This experiment encompasses a gamut from direct assessment of vestibular functions in perception, to higher nervous functions in sleep and wakefulness, and in perception, recent memory and visual discriminative performance. These central nervous studies have been combined with peripheral measures, including electrooculograms, electromyograms and galvanic skin responses. We have closely coordinated these neural investigations with proposed cardiovascular monitoring by our co-investigator, Dr. J. P. Meehan of the Department of Physiology, University of Southern California, and with catheterization procedures and urinary analyses by Dr. A. T. K. Cockett, of the Harbor General Hospital. In-flight urine analysis will be undertaken by Dr. N. Pace, of the Department of Physiology, University of California, Berkeley, and by Dr. J. Rho, Jet Propulsion Laboratories. Calcium balance studies will be performed by Dr. P. Mack, Texas Women's University. (Fig. 1).

a. Central nervous monitoring and implantation procedures.

Implantation procedures have been described elsewhere (Adey, 1964), including details of histological controls on damage arising in brain movement relative to the electrodes (Adey, Kado, Winters and DeLucchi, 1963). Bipolar electrodes formed of pairs of 29 gauge stainless steel tubing, insulated except at the tips, and separated by 2.0 mm have been stereotaxically inserted into selected deep brain structures (Fig. 2). Surface records are obtained from stainless steel screws in the calvarium, and additional screws are used to secure the mass of acrylic covering the skull and enclosing connecting plugs.

It is planned to record ten channels of EEG data. These leads have been selected, on the basis of our extensive studies in monkeys, chimpanzees and man (Reite, Rhodes, Brown and Adey, 1965; Rhodes, Brown, Walter and Adey, 1965; Adey, Rhodes and Kado, 1963; Walter and Adey, 1965), as reflecting most sensitively changing states of consciousness, including broad shifts in the range from emotional arousal and alerted behavior, through drowsiness and fatigue, to actual sleep. They also specify appropriately the various stages of sleep, including dream states. These leads are taken from the amygdaloid and hippocampal regions of the temporal lobe, from the midbrain reticular formation, and from surface leads overlying frontal, central, parietal and occipital cortex.

b. Electrooculographic and electromyographic recording.

Assessment of orienting responses places particular significance on monitoring head, eye and trunk movements. Satisfactory long-term recording from electrodes implanted in soft tissues requires that they be resistant to shearing stresses imposed by movement in tissue planes. When implanted in muscles, they should not devitalize these structures to the point of inducing scar formation and loss of electromyographic activity.

A satisfactory solution to the shearing problem appears to have been found in the use of stranded stainless steel wire, composed of 7 strands of 44 gauge wire, and insulated with silicon rubber. Loss of tone in cervical musculature has been found a consistent accompaniment of dream sleep states in animals and man (Jacobson et al.,1965), so that it will be important to assess any changes which may occur in tonic activity in cervical musculature in both waking and sleeping states during prolonged weightlessness.

Electrooculographic leads are inserted through small holes drilled in the upper and outer margins of the bony orbit. EOG data will be valuable in monitoring eye movements during orienting responses and alerted behavior, as well as in the large and rapid movements of dream sleep.

c. Monitors of autonomic responses; galvanic skin response, impedance pneumogram, and electrocardiogram.

Classic sensing techniques for galvanic skin responses (GSR) are not usually required to provide data for more than a few hours, so that special techniques were developed to record reliably for periods in excess of 30 days. A 2 cycles per second square wave, with an amplitude of a few millivolts, and applied to electrodes 1 cm square on the sole of the monkey's foot has been found a reliable method for periods in excess of 30 days, with undiminished responses to alerting stimuli, and in various sleep states, even after prolonged application.

The impedance pneumogram (ZPG) is attached to sensors in left and right midaxillary lines, and uses a carrier frequency of 70 Kcs per second with an amplitude of 20 mV. Electrocardiographic (EKG) records are secured from the same electrodes used for the impedance pneumogram.

d. Monitoring of cardiovascular functions.

These investigations are under the direction of Dr. J. P. Meehan, of the Department of Physiology, University of Southern California. Dr. Meehan's experience in the instrumentation of two chimpanzee space flights (by Ham and Enos) has provided an incomparable background in the design and performance of such experiments. Pressures will be recorded directly in femoral and carotid arteries, in the right atrium and left ventricle, by catheters connected to a total of six strain gauge transducers.

Much baseline data has been collected by Dr. Meehan in proving feasibility for a 30 day flight. Small impulse pumps, operating from a capacitor discharge power source, inject approximately 0.003 ml of heparin solution into each catheter once each minute.

e. Urine and feces collection; in-flight urine analysis.

As has been emphasized in relation to extended manned space flight, successful waste management ranks as a critical requirement. Moreover, urine and feces analysis provide vital information on whole body composition, against which changes in such functions as spatial orientation, discriminative performance and biological rhythmicity must be equated if a realistic appraisal of performance capability is to be made.

Extensive investigations by our colleague, Dr. A. T. K. Cockett, of the Harbor General Hospital, Los Angeles, have resulted in a technique of perineal urethrostomy which allows ready catheterization of the bladder, and an essential watertight system of urine collection while retaining a functional sphincter.

Dr. Pace, of the Department of Physiology, University of California, Berkeley, and Dr. J. Rho, of Jet Propulsion Laboratory, Pasadena, have investigated the feasibility of measuring concentration of calcium, creatine, creatinine and pH in urine sampled en route to storage in the adapter section of the vehicle. The readings will be telemetered every 6 hours.

Feces collection in the weightless state presents special problems. Our laboratory has evolved a technique, which, in terrestrial testing, appears to ensure reliable transfer to a collector-can behind the couch. An accurately moulded soft rubber pad is backed by a rigid plate, which is screwed to the ischial tuberosities. A flexible hose connects this plate with the collector, and is flushed with a disinfectant spray and air, injected perianally.

On recovery of the spacecraft, the calcium content of the feces will be analyzed by Dr. P. Mack, of the Texas Women's University, as part of her study of depletion of skeletal calcium in weightlessness, by wedge densitometry of the skeleton pre- and post-flight. Dr. Mack has already made extensive baseline studies of the monkey skeleton by this method.

f. Behavioral tasks, including visual orientation; food reinforcement and feeding techniques.

We have included two tasks in this experiment. They will be scheduled successively both early and late in the 12-hour "day" imposed in the flight schedule. The first involves a delayed matching-to-sample test, and the second is an eye-hand coordination task.

In the first task, a symbol appears for 5 seconds in the center of a rectangular matrix, and is then extinguished (Fig. 3). After a delay of 20 seconds, the whole matrix is illuminated for 10 seconds. The original symbol now appears embedded in the total matrix in a different location from that in which it was originally displayed. When it is touched by the animal, a food pellet reward is offered. Our experience indicates that this is an exacting task in recent memory and perception for the pig-tail macaque, and attainment of a high performance level takes approximately two months of daily training.

The second task tests coordination of eye and hand in a manner directly related to spatial orientation. Two co-rotating discs surround the periphery of the matrix board described above. A small window in the front disc allows access to the rear disc, on which is mounted a small red button switch. The discs rotate at different rates, so that the position of coincidence of window and button in successive encounters are constantly shifting in space. Our early experience indicated a surprising facility on the part of the monkey in performing this task, as well as a considerable motivation to succeed. Speeds of rotation were constantly increased to keep pace with increasing proficiency. It appears that the monkey can perform at over 80 per cent correct with a window-disc rotation speed of 85 r.p.m., and a coincidence time for window and button of the order of a fifth of a second. To accomplish its goal, the animal has its head moving through a circular pattern approximately the speed of rotation of the disc. This phenomenon alone suggests that vestibular disturbances associated with the rapid head movement in weightlessness may profoundly disrupt the performance, if frequent reports by astronauts and cosmonauts of disability in similar rapid movements provide a basis for comparison.

Feeding is by pellets dispensed from a feeder modified from a chimpanzee feeder, originally developed at Holloman Air Force Base for the Air Force Office of Scientific Research. This device carries 225 pellets on each of 8 tapes, to which the pellets are adherent.

Drinking water is provided from the General Electric Company hydrogen-oxygen fuel cell, which powers the spacecraft. After filtration, the water is delivered to a nipple adjacent to the animal's mouth. Water rationing is at the rate of 30 ml per hour during the 12-hour "day", and at one-third that rate during the "night", giving 540 ml per 24 hours. If telemetered data indicates dehydration, a ground command maintains "night" watering at the "day" rate, allowing 720 ml per 24 hours.

3. Analysis techniques for EEG flight data.

Inherent complexities of EEG records have emphasized the need for analysis methods capable of substantially compressing primary records to provide an overview of long and complex epochs of data, while retaining fine resolution of subtle shifts within the epoch (Adey, 1965a and b). Quite obviously, the utility of even the most elegant display rests upon the reliability with which the observed pattern can be equated with norms and baselines previously established for a population of comparable individuals, and/or with the subject's own mean in resting or simulated flight conditions. Morover, it would be highly desirable to employ automated pattern recognition techniques, where these can be validated in their application to the outputs of the primary analyses. Our laboratory has studied each of these three requirements (Adey, 1965a and b; Walter, 1963; Walter and Adey, 1965a and b; Walter, Rhodes and Adey, 1965; Adey, Kado and Walter, 1966).

a. Spectral techniques in massive analysis of EEG data.

It is our capacity to precisely specify the bandpass characteristics of the digital filter, particularly in the low frequency range between 0.5 and 10 cycles per second, that has established its superiority over analog methods. Since its phase shift is zero, it has become possible to measure for the first time the phase relations between EEG wave trains at each frequency across the spectrum, as well as shared amplitudes between them at each frequency. From pioneering studies by our colleague D. O. Walter (Adey and Walter, 1963; Walter and Adey, 1963; Walter, 1963), we have come to the routine calculation of the coherence function, as a measure of statistical variability in linear interrelationships between brain regions.

In our hands, the value of coherence calculations as a basis for sharp delineation of shifting EEG patterns in specified states of sleep and wakefulness has been paramount. The magnitude of the coherence function may be expressed:

$$\mathrm{coh}(f) = \mathrm{MAGS}(f)/\mathrm{ASX}(f)\mathrm{ASY}(f)$$

where MAGS(f) is the mean cross-spectral magnitude at frequency f, and ASX(f) is the autospectrum of X and ASY(f) is the autospectrum of Y, at the respective frequencies. The coherence function is expressed between 0 and 1, and is a measure of the linear predictability of activity in any area, on the basis of knowing the activity in any other area, or series of areas.

Continuous contour plots of spectral density and coherence have proved most useful tools in compression of long epochs of data into a single plot, while retaining all essential information relating to transitions occurring, for example, during visual discriminations and auditory vigilance tasks.

In Figs.6 and 7 are plotted autospectra from simultaneous scalp leads during these performances, which covered a test period of approximately one hour. Differences in densities at 1 to 2 cycles per second in left and right centroparietal and left parietooccipital leads were associated with substantially greater difficulty of the task in the second performance. An even greater difference will be noted in all leads between records during visual discrimination and during an auditory vigilance task with eyes closed. These parameters form part of a scheme of automated pattern recognition described below. Similar plots of autospectral densities and coherences during alerted behavior are shown in Fig. 8.

b. Applications of spectral methods in EEG baseline analysis; the normative library.

It has long been a matter of concern that definition of EEG patterns has rested, not only on the subjective opinion of the investigator, but also on wide individual variations in apparently normal subjects. We have, therefore, sought to establish by computer analysis the presence of common EEG factors in a significant population of astronaut candidates, both in relation to task performances and in assessment of sleep states.

In detailed studies to be reported elsewhere (Walter, Rhodes, Kado and Adey, 1966), a series of 200 astronaut candidates were tested in a series of perceptual and learning tasks, by means of a programming device, developed in our laboratory by Raymond T. Kado, and using a magnetic tape ccmmand system to ensure accurate timing in task presentation from one subject to the next. Subject testing and EEG recording on magnetic tape were performed by Dr. P. Kellaway and Dr. R. Maulsby, at the Methodist Hospital, Houston.

To synthesize the data, an averaging procedure was adopted on the spectral outputs, covering 50 of the 200 subjects in the various test situations, and in selected sleep epochs. These averages were made for each scalp region, and are presented as a series of bar graphs (Fig. 4), covering the spectrum from 0 to 25 cycles per second. First, an average was prepared of spectral densities at each scalp recording site for all test epochs (Fig.4, top left), including sitting with eyes closed at rest, eyes closed during 1 per second flash stimuli, during an auditory vigilance task, during visual discriminations at 3 second intervals, and a similar series of more difficult discriminations at 1 second intervals.

The contours of these "lumped" spectra were then used as the mean for comparison with the spectra for the individual situations. The subsequent graphs in Fig. 4 thus show the variations about the mean established by the average over 12 situations in the top left figure. Spectral densities above the mean at any frequency have bars above the baseline, and vice versa. It will be seen that such a display clearly separates spectral density distributions for the 50 subjects in the five situations shown. In particular, the distributions for more difficult visual discriminations (Fig. 4, lower right) exemplify trends that already characterize discriminations made in three seconds (Fig. 4, lower middle). Pattern recognition techniques described below clarify differences between records in these two tasks. It is also possible to compare an individual with the mean for the group, or with his own mean, using a two-color display technique.

Similar averages were made for 30 subjects in various stages of sleep and drowsiness (Fig. 5). Here, the mean was established by an average over 7 stages of presleep, sleep and postsleep, and thus became the baseline for measurement of variance for individual sleep states. It will be noted that states of drowsiness, and light, medium and deep sleep can be readily distinguished from each other, but that separation of deep "slow wave" sleep from subarousal with "K-complexes" is less clear.

c. Application of simple pattern recognition techniques to spectral parameters for definition of states of attention.

Discriminant analysis was applied to these spectral outputs in four subjects (Walter, Rhodes and Adey, 1965) covering five situations: eyes closed at rest, eyes open at rest, an auditory vigilance task, and the two visual discriminative tasks described above. A computer program attempted to assign each segment to the situation from which it came, using measurements derived from four EEG channels.

This discriminant analysis program initially considers all the measurements for all the segments, and selects that parameter which best discriminates segments recorded in different situations. It then reexamines all measurements and chooses the parameter which will add most to the discriminating power of the first measurement. It calculates five linear functions of those two measurements whose values differ as much as possible among the situations. The program continues this iteration of selecting and calculating linear functions, until insufficient improvement is made by adding another parameter.

The separate analysis of each subject's records in the same way yielded a higher proportion of correct classifications than the group analysis. With his own best four measurements, between 62 and 69 per cent of a single subject's samples were correctly classified, as contrasted with 51 per cent for the subjects simultaneously. An even greater disparity appeared after 15 measurements were selected. Individually, 95, 93, 96 and 90 per cent were correct, while for the subjects together, only 65 per cent were correctly classified. It would thus appear that each subject may have a spatially and numerically characterized individual EEG "signature", as to which measurements are most effective in distinguishing different situations.

4. Applications of these spectral analysis techniques to baseline data and flight data from Gemini GT-7.

Obviously, critical evaluation of data gathered in actual flight requires careful consideration of baseline records gathered in terrestrial environments, and particularly in circumstances which simulate, as far as possible, the capsule environment. Before proceeding to the flight data, analyses will be presented of EEG data recorded from Astronaut Borman in the laboratory of Dr. P. M. Kellaway by Dr. R. Maulsby at Houston Methodist Hospital, in accordance with the normative library procedure described above; and from recordings made in a Gemini capsule, using electrode placements and tape recording equipment identical to those in the Gemini GT-7 flight during an altitude chamber simulation at Macdonnell Aircraft Company in St. Louis, Missouri.

a. Analyses of EEG baseline data from Astronaut Borman in laboratory tests and under simulated space flight conditions.

(i) Analysis of data from physiological laboratory records.

Two aspects of EEG data collected from Astronaut Frank Borman during testing in the "normative library" procedures will be presented here; analyses of a series of epochs during which the subject sat with eyes closed between a variety of perceptual and learning tasks, in a resting state or subjected to slowly repetitive visual, auditory and somatic stimuli, in contrast to a second series of recordings taken during performance of these tasks.

The records with eyes closed, with and without simple physiological stimuli, clearly indicate the normality of the subject's EEG (Fig. 6). A contour plotting display of spectral densities depicts increasing powers at any frequency with progressively darker shading towards black. In this display, the EEG spectrum from 0 to 30 cycles per second is plotted on the ordinates and analyses of successive epochs of EEG record (each 10 or 20 seconds long) on the abscissae. In these analyses, since several such epochs were usually analyzed from a single behavioral situation, groups of identical numbers appear on the X-axis. Analyses are presented from simultaneous records from six EEG channels, in left and right central, parietal and occipital scalp regions.

Dark bands, indicative of high spectral powers in the range from 300 to 1000 microvolts squared per second per cycle, occurred at frequencies from 9 to 11 cycles per second through most of the eyes-closed analyses. By contrast, powers in the range from 2 to 7 cycles per second were low (30 uV^2/sec/cycle or less). At frequencies below 2 cycles per second, all six channels showed higher powers than in the range from 2 to 7 cycles per second, but typically, were lower than the simultaneous intensities at 9 to 11 cycles per second.

During the performance of visual discriminative tasks (Fig. 7) epochs 60-119), activity at 9 to 11 cycles per second (alpha waves) declined sharply in all areas, in conformity with the classic "alpha blocking" phenomenon. At the same time, powers at frequencies from 0 to 2 cycles per second (delta waves) were augmented considerably over the eyes-closed situations in left and right centroparietal and left parieto-occipital leads. In view of the findings in flight records, it may be pointed out that powers at frequencies from 5 to 7 cycles per second (theta waves) were low in all these resting and visual discrimination records.

Performance of an auditory vigilance task (recognition of a 3-tone pattern presented every 5 seconds) with eyes closed caused a recrudescence of high powers at alpha frequencies in all six leads (Fig.7, epoch 56).

(ii) Analysis of EEG data from altitude chamber test in simulated Gemini flight.

These data were collected under the supervision of Dr. P. Kellaway and Dr. R. Maulsby, and in view of the identity of amplifiers and tape recording systems with actual flight items, provided a valuable comparison with flight data. Electrode placements for the two channels in this test and in space flight spanned a wide zone of scalp from vertex to occipital region, with one pair located in the midline and the other spanning the left parietooccipital area (Kellaway and Maulsby, 1966).

In this test, samples of record were analyzed over a 10 minute period (Fig. 8), characterized by typical alerted patterns, and occasional movement artifacts (epochs 28 to 30 in channel 4, and epoch 29 in channel 5). It will be noted that, in comparison with laboratory task performances (Fig. 7), these contour plots show relatively low powers at all frequencies above 5 cycles per second, and lack any clear peak in the alpha range around 10 cycles per second. For these reasons, and in order to provide a broad general classification of spectra, simple averages of spectral density were prepared for each channel, covering the whole test epoch (Fig. 8, lower graphs). The solid line shows a linear plot of spectral densities, and the dashed line a logarithmic plot, over the spectrum from 3 to 30 cycles per second. In both channels, a broad and ill-defined alpha peak at 9 to 13 cycles per second is overshadowed by higher powers in the range from 4 to 7 cycles per second (theta waves). As discussed below, this decrease in alpha and augmented theta activity is clearly intermediate in the altitude chamber test between laboratory tests (Fig. 8) and space flight records (Fig. 16).

b. Analysis of data from the Gemini GT-7 flight.

For the first 30 hours, two channels of data were recorded, and one thereafter. As will be indicated, even one channel has provided highly significant data on sleep and wakefulness. Epochs with gross movement artifacts have been deleted from these computed analyses, and in general, the records are remarkably clean. A low frequency cut-off of 3 cycles per second was arbitrarily designated in the computation to minimize contamination of the analysis by movement artifacts.

The prelaunch period and a substantial part of the first orbit have been analyzed on the basis of two consecutive 10 second samples approximately every minute, to afford a fine grained analysis (Fig. 9). In this figure, the EEG spectrum is plotted on the abscissa, and time on the ordinate. The prelaunch period was characterized by increased amounts of theta rhythms than occurred in the baseline records, and may be interpreted as relating to strongly focused attention and orienting responses in an undoubtedly novel situation. At one minute before lift-off, there was an increment in this activity and in the higher frequencies in the alpha and beta bands. The power density of the EEG was augmented by a factor of 10 over many frequencies immediately before and following launch, indicating a strong "arousal reaction" in the classic neurophysiological sense. Thereafter, there was a slow decline in these augmented densities, with recurrent epochs of higher powers in the higher frequency bands above 10 cycles per second in the first half hour of flight. Coherence between the two channels (right hand figure in each row) was high at theta frequencies up to the time of lift-off, but fell to low values across the entire spectrum for the next 30 minutes. Thereafter, it resumed high values from 3 to 9 cycles per second. Taken in conjunction with simultaneously diminishing powers in both leads at the higher frequencies, the findings indicate a progressive decline in levels of physiological arousal.

With the prime interest in this experiment centered on drowsiness and sleep, analyses of subsequent data are displayed in a fashion emphasizing these phases. During the waking state, two consecutive 15 second samples were analyzed every 10 minutes, whereas in the drowsy and sleep states, two consecutive 10 second samples were taken every 2 minutes. The graphic display thus emphasizes even brief drowsy episodes.

From the third to the seventh hour of flight (Fig. 10) the subject was awake, with gradually diminishing power in the frequencies from 3 to 10 cycles per second, although remaining somewhat above ground-based analyses in the theta range (3 to 7 cycles per second) even at the seventh hour. This decline suggests a diminution in orienting reactions to the new environment, and in the seventh hour (Fig. 5E), drowsy episodes with eyes closed and concomitant brief trains of high amplitude alpha waves occurred. The EEG and computed analyses clearly revealed these episodes lasting only from 3 to 15 seconds, in the absence of concomitant changes in respiration or heartrate.

From the seventh to the eleventh hour (Fig. 11), these episodes were more numerous, and trended to continuous epochs lasting many minutes. These epochs were characterized by high coherence between the two channels (right-hand figures in each row) over a broad band from 5 to 11 cycles per second. Return to wakefulness in the twelfth hour was accompanied by a decline in coherence and much lower powers in the alpha range. From the fifteenth to the twenty-first hour, there were long episodes of drowsiness and light sleep, with a brief episode of slow-wave sleep in the sixteenth hour (Fig. 12). Coherence between the two channels again rose sharply with the onset of drowsiness and actual sleep, corresponding to the increasing synchrony observed in the EEG paper records (Kellaway and Maulsby, 1966).

The records clearly indicate that no further significant sleep occurred on this first "night" in space, and in the ensuing period from the twenty-first to the twenty-ninth hour, only occasional drowsy episodes occurred. These are clearly emphasized by the contour display technique, although not included here.

Beginning in the thirty-fourth hour, and shortly after a meal, the astronaut passed rapidly through a drowsy phase with eyes closed (Fig. 13, top right), into deep sleep, with high amplitude slow waves (Fig. 13, lower row of maps). It will be noted that from this point only one channel remained. Even here, however, computer analysis shows elegantly the transitions in states over many hours. Moreover, the EEG clearly reveals changes in pattern during shifting states of sleep and wakefulness not easily detectable with EKG or respiration.

The cyclic nature of the sleep is clearly shown in Figs. 13 and 14, with a periodicity of 90 to 100 minutes between brief periods of wakefulness that mark the start of a new cycle, with progressive descent to the deepest, or slow wave, phase, followed by a more rapid return toward wakefulness. This sleep epoch lasted from the thirty-fifth to the forty-first hour, and shows no abnormalities, although there is no clear evidence of paradoxical or REM (rapid eye movement) sleep, associated with the dream phase, and forming approximately 20 per cent of a normal night's sleep. It may be that the electrode locations were too posterior to record EOG potentials, although blink artifacts were clearly present.

Records from the forty-first to the forty-eight hour show a progression to full wakefulness through approximately one hour of drowsiness (Fig. 15). The awake records show persisting high theta densities noted in early phases of the flight. Increasing artifacts in this one remaining channel from electrode displacement appeared beyond the forty-third hour, and interrupted much of the remaining data until recording ceased in the fifty-fifth hour. The contour plots in this period indicate a continued wakeful state, with substantial theta activity.

In clarification of the differences between flight and ground-based records, averaged spectra have been prepared from the normative library records during visual task performances in the laboratory, from scalp areas similar to those used in flight. These averages have been plotted together with similar averages in awake states during the first seven hours of flight (Fig. 16). Taken in comparison with the altitude chamber test performed with flight equipment, it is apparent that there was a progression from a substantial persistent alpha peak and low theta activity in laboratory visual tasks; through an intermediate type of contour with a broad, low alpha peak and increasing theta activity in the altitude chamber test; to flight records characteristically showing little or no alpha peak, and substantially more theta activity than in the altitude chamber. These findings support the view that the augmented theta activity in this subject is indeed a physiological response to the weightless environment, and may arise in augmented orienting responses to this most unusual experience.

In these circumstances, it would be interesting to seek its presence in other subjects, and its persistence over longer periods of flight, since it may represent an adapting phenomenon to the strange, and, indeed, hazardous environment of space. It is for this reason that lengthy recordings initiated, for example, after the fifth day of prolonged flights would be particularly useful in revealing the extent of adaptation to the space environment. Such information would also be relevant to the evolution of sleep patterns in prolonged flight. From the bioinstrumentation point of view, an improved electrode design, that might be incorporated into a cap, and was effective through a non-adhesive contact, and free from contact potential, would permit simple wearing or removal by the subject. This would allow initiation of recording at any desired phase of the flight, and eliminate problems of preflight adhesive fixation.

SUMMARY

Recent developments in acquisition and analysis of electroencephalographic (EEG) data are reviewed, in the frame of their use for physiological monitoring in space flight. The application of spectral analysis, with calculation of coherence functions, is described, and display techniques for compression of long epochs of analysis are reviewed. Results of baseline analyses from a population of 50 astronaut candidates and simple pattern recognition techniques suited to on-line flight monitoring are described.

Development toward a 30-day biosatellite flight with a 6.8Kg pigtail macaque monkey are evaluated. Instrumentation will include electroencephalographic, electro-oculographic, and electromyographic implantation,blood pressure transducers in heart chambers and great vessels. Urinary collection procedures will allow inflight analysis.

Computer analyses have been applied to approximately 50 hours of EEG data from the initial phases of the Gemini GT-7 flight. Two channels were available for the first 29 hours and one thereafter. Baseline data from the same astronaut in laboratory task performances, and in altitude chamber tests in a Gemini capsule, were similarly analyzed. Contour displays of spectral densities, and of coherence between the two channels have provided a fine assessment of states of sleep and wakefulness throughout the recording. Even one EEG channel provided highly significant information on alerted behavior, brief drowsy episodes and depth of sleep, in a manner not readily available from electrocardiographic or respiratory data.

EEG power densities in the theta band (4 to 7 cycles per second) were substantially higher in the waking state in flight records than in leads from similar scalp locations during laboratory visual task performances, or in altitude chamber tests. A gradation in theta-band power densities was observed from low levels in laboratory tasks, to intermediate levels in Gemini flight simulations, with highest levels as a consistent feature of the flight records. These findings are inter-

preted as possibly arising in a continuing orienting reaction in the unfamiliar space environment.

The EEG analysis revealed only one brief episode of deep sleep on the first "night" in space. On the second "night," sleep with a normal cyclic periodicity of about 90 minutes occurred for about seven hours. The occurrence of dream sleep ("paradoxical" phase of sleep) was not certain, due to the posterior location of the EEG electrodes on the head, and the absence of clear eye movement records.

The highly detailed monitoring of levels of alertness in man and of brief shifts in states of consciousness, often lasting only a few seconds; available from only one or two scalp EEG channels, suggest the importance of further development of the technique to allow repeated assessment of central nervous status in prolonged manned flights. Recordings initiated after the fifth day would be useful in revealing the extent of adaptation in such phenomena as the high initial theta activity seen here, and possible modifications in sleep-wakefulness cycles.

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Legends to Figures

Fig. 1. Oblique view of biosatellite mockup, showing disposition of animal on restraining couch, with behavioral programmer before him. (From Adey, 1966).

Fig. 2. Xray of head of Macaca nemestrina monkey, showing implanted electrodes of stainless steel tubing (29 gauge) stereotaxically implanted in deep brain structures. Screws in calvarium provide attachment for surface cortical EEG leads, as well as mechanical fixation. (From Adey, 1966).

Fig. 3 Arrangement of psychomotor test panel, showing windows for matrix of symbols used in delayed matching-to-sample task. Discs for eye-hand coordination test surround the matrix display. (From Adey, 1966).

Fig. 4. Spectral analyses from 50 astronaut candidates, pooled into averages for each scalp location (see text). Top left figure is average for all subjects over 12 situations. Bars cover spectrum from 1 to 25 cycles per second. The average over 12 situations was used as the mean for measurements of variance at each frequency in the five situations shown for the population of 50 candidates. (From Adey, Kado and Walter, 1966).

Fig. 5. Spectral analyses for sleep records from 30 astronaut candidates, prepared as in Fig. 4. Averages over 7 stages of presleep, sleep and postsleep (A) were used as the mean for assessment of variance for records with eyes closed, awake, (B), drowsy states (C), light sleep (D). Calibrations for stage average are in microvolts

squared per second per cycle, and for the individual states in standard deviations. (From Adey, Kado and Walter, 1966).

Fig. 6. Analysis of baseline records in laboratory from Astronaut F. Borman during resting state and during simple physiological stimuli. Contour plots show high density in alpha band (8-13 cycles per second) with eyes closed.

Fig. 7. Contour plots of baseline records in laboratory visual and auditory task performances by Astronaut F. Borman. Plots are from six EEG channels recorded simultaneously during performance of visual discrimination tasks in 3 seconds (epochs 60 through 79), followed by more difficult visual discriminations each performed in 1 second (epochs 100-119), and leading to an auditory vigilance task presented at 5 second intervals (epoch 56). This condensed presentation covers an elapsed time of many minutes.

Fig. 8. Analysis of records from altitude chamber Gemini flight simulation, showing autospectral densities in two EEG channels, and coherence between them. Electrode placements, amplifiers and recording equipment were identical with actual flight systems. Averaged spectral densities for each channel (lower traces) show enhanced theta activity (in range 3 to 7 cycles per second) by comparison with laboratory records (Fig. 16). These averages were prepared from more than 40 epochs, each 20 seconds in duration. Solid line in lower traces, linear plot; dashed line, logarithmic plot.

Fig. 9. Contour maps of EEG data from F. Borman in Gemini Flight GT-7, showing enhancement of autospectral densities in theta range in two EEG channels (CPEEG 4 and CPEEG 5) prelaunch, and great exaltation of many EEG frequencies immediately before and during lift-off. By comparison with later awake and sleeping records, coherences (CPEEG 4/CPEEG 5) were low at this time. Spectral densities above 10 cycles per second gradually declined in first 30 minutes of flight, but very little alpha activity appeared before 70 minutes. Numerals on abscissae indicate minutes of record in that analysis frame. Calibrations in autospectral contours are in microvolts squared per second per cycle. Shaded contours are: 100-300 uV^2/sec/cycle, horizontal shading; 300-1000, vertical shading; over 1000, solid black. In the coherence plots, values above 0.7 (statistically significant level) are in black.

Fig. 10. Contour maps similar to those in Fig. 9 for two EEG channels with spectral density (CPEEG 4 and CPEEG 5) and coherence (CPEEG 4/ CPEEG 5) plots from the third to seventh hour. There is a drifting from alertness to occasional drowsy episodes in this period. Calibrations as in Fig. 9. (From Adey, Kado and Walter, 1966).

Fig. 11. Contour maps as in Fig. 9 for period from seventh to eleventh hour.

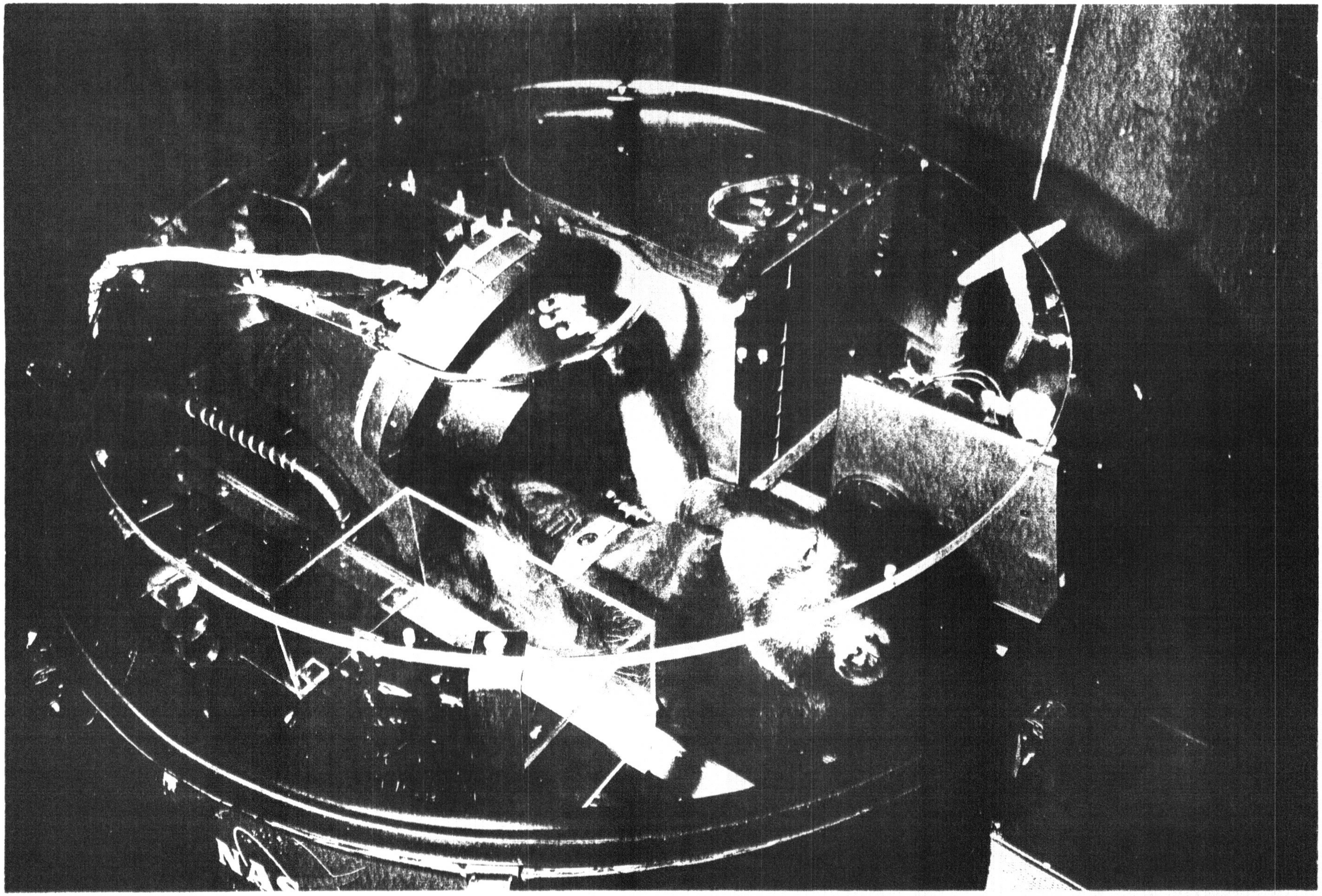
Fig. 12. Contour maps as in Fig. 9 for period from fifteenth to twenty-first hour, showing a mixture of awake, drowsy and light to medium sleep states. Significant coherences extend to higher frequencies at this stage than in the awake records. Calibrations as in Fig. 9. (From Adey, Kado and Walter, 1966).

Fig. 13. With only one functional EEG channel remaining, a detailed and highly revealing analysis of the onset of sleep on the second "night" in space was still possible. After a brief drowsy episode (top right graph), there was a rapid descent into deep sleep, with big slow waves (bottom row of figures). This sleep exhibited normal cycle lengths of 90 minutes, with brief wakeful periods (Bottom row, middle figure) between successive cycles.

Fig. 14. Continuing sleep cycles on second "night" in space, with much deep, slow-wave sleep, ending with gradual arousal in forty-first hour (lower right).

Fig. 15. Return to wakefulness on third "day" in space through periods of drowsiness (top row, left two figures). Some lead noise began to appear intermittently in these records.

Fig. 16. Comparison of autospectral densities in similarly located leads on scalp of Astronaut F. Borman in laboratory visual tasks (left) and in awake flight records (right), exemplifying diminished alpha peak (8 to 13 cycles per second) and augmented theta density (3 to 7 cycles per second) in flight records. These averaged spectral densities were prepared from approximately 40 epochs, each of 20 seconds, for both laboratory and flight records. Solid line indicates linear density plot; dashed line is logarithmic plot.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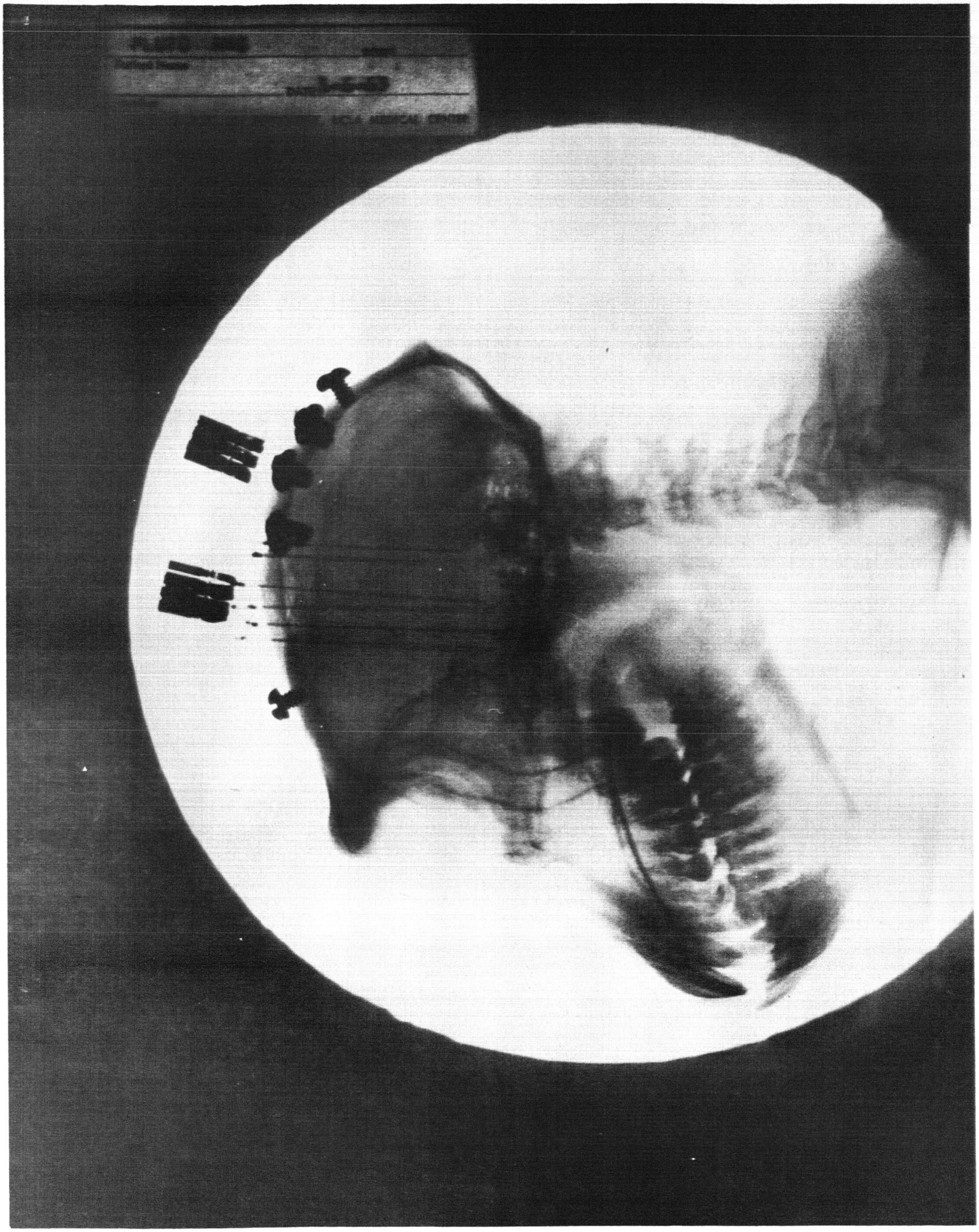
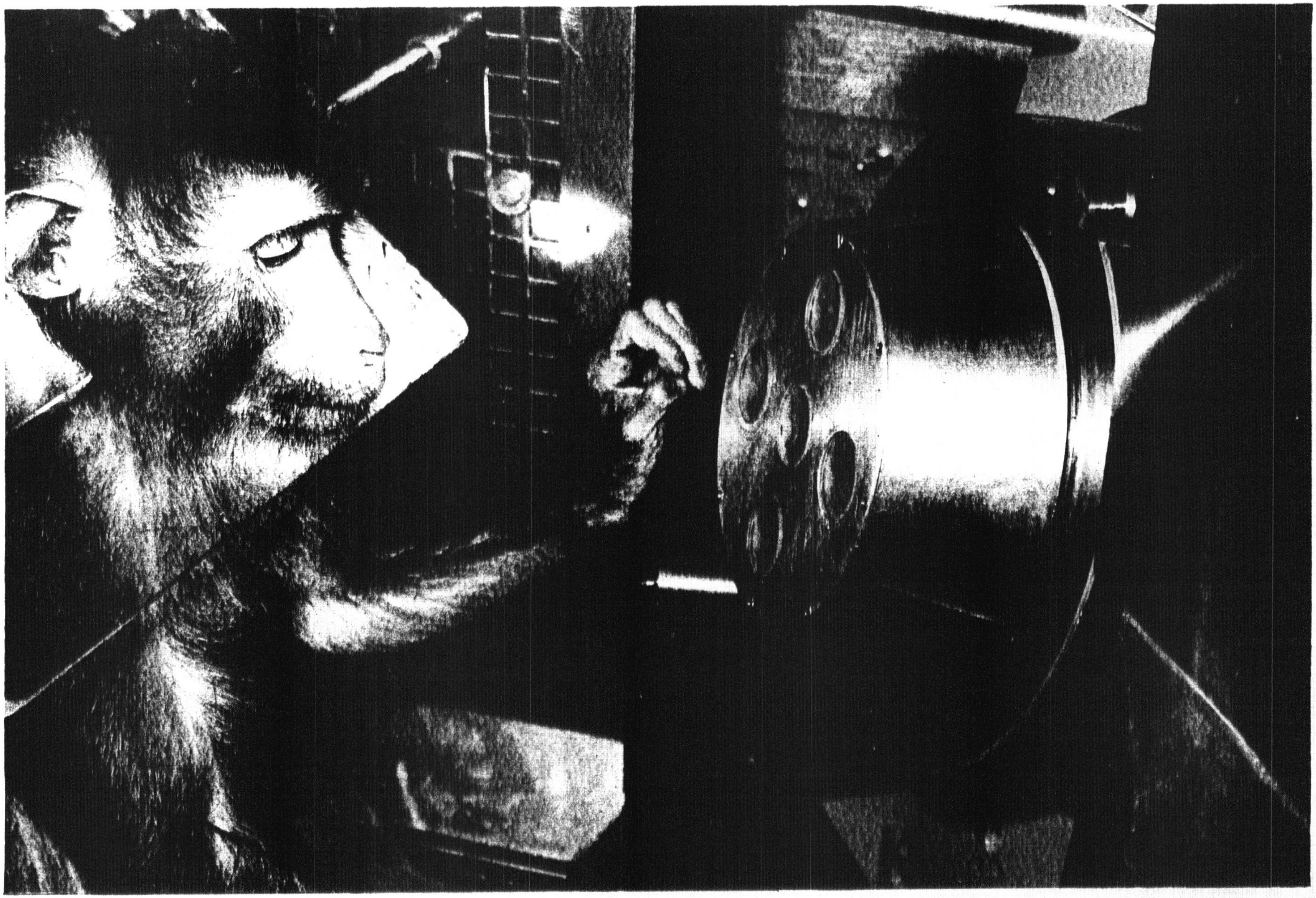
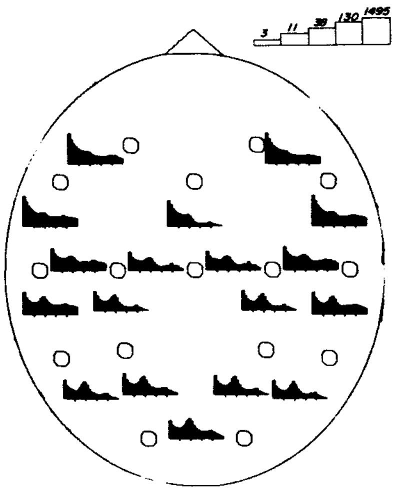

PLUTO
Patient Name
DATE 3-6-63
UCLA MEDICAL CENTER

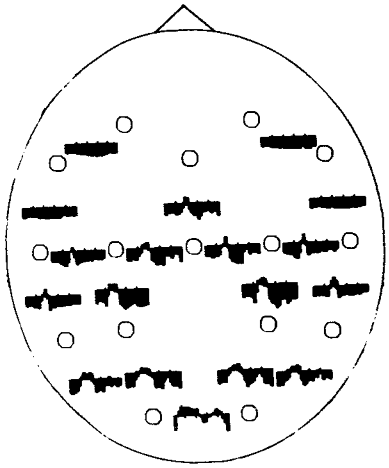


RESPONSES OF ELECTROENCEPHALOGRAM TO DIFFERING SITUATIONS

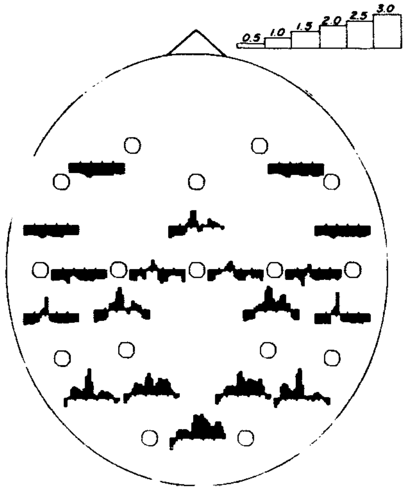
TOPO-SPECTROGRAPHIC VARIATIONS OF AVERAGES OVER FIFTY ASTRONAUT CANDIDATES



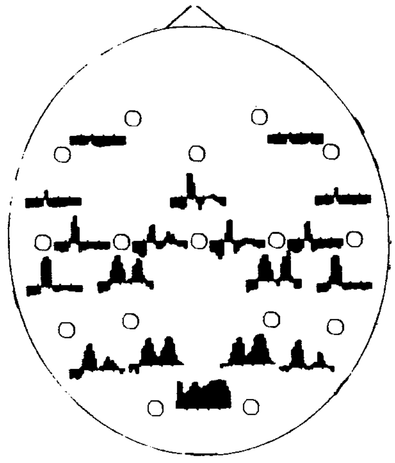
AVERAGE OVER
TWELVE SITUATIONS



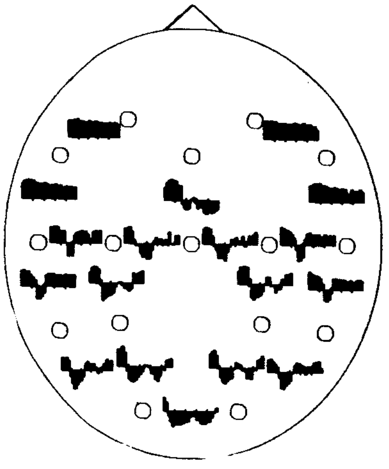
EYES CLOSED
INTERSTIMULUS RESTS



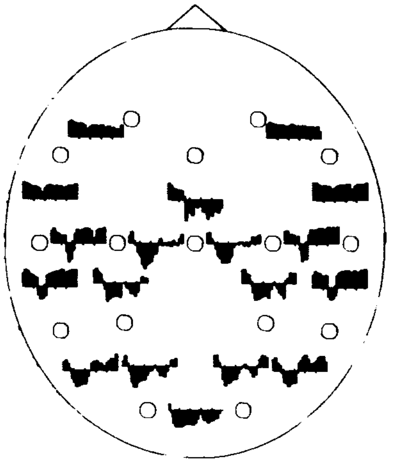
EYES CLOSED
FLASHES, ONE PER SEC.



EYES CLOSED
VIGILANCE TEST
TONES & BUTTON PRESSING



EYES OPEN
VISUAL DISCRIMINATION
3 SEC. EXPOSURE



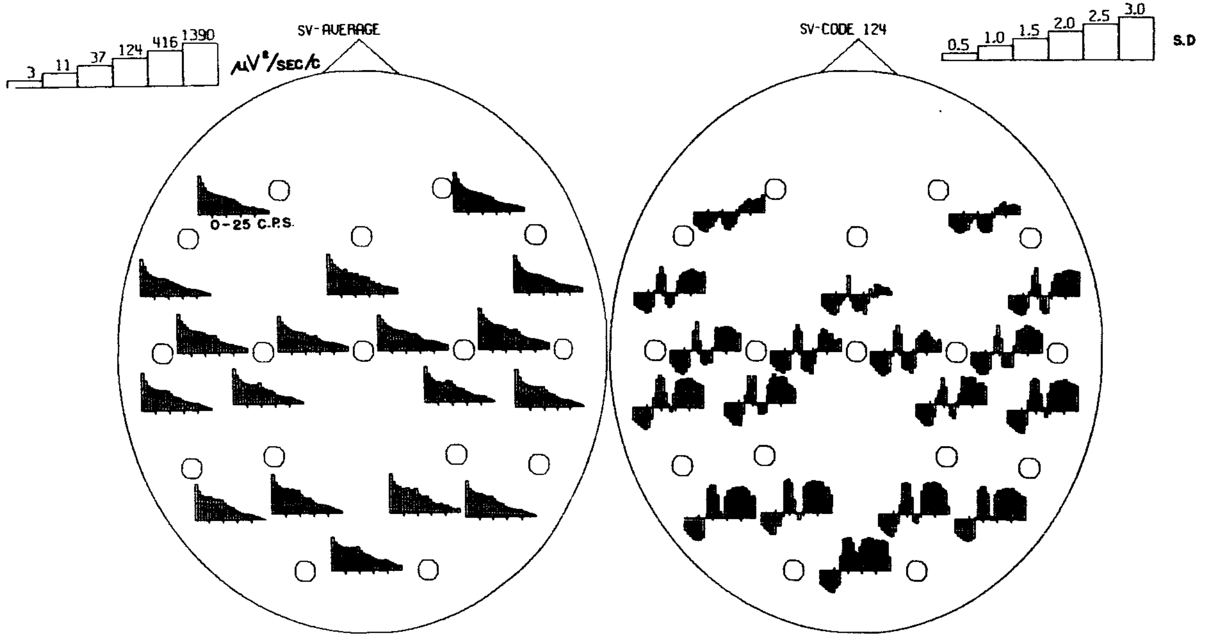
EYES OPEN
VISUAL DISCRIMINATION
1 SEC. EXPOSURE

ELECTROENCEPHALOGRAPHIC CHARACTERISTICS OF SLEEP

TOPOSPECTROGRAPHIC VARIATIONS OF AVERAGES OVER 30 ASTRONAUT CANDIDATES

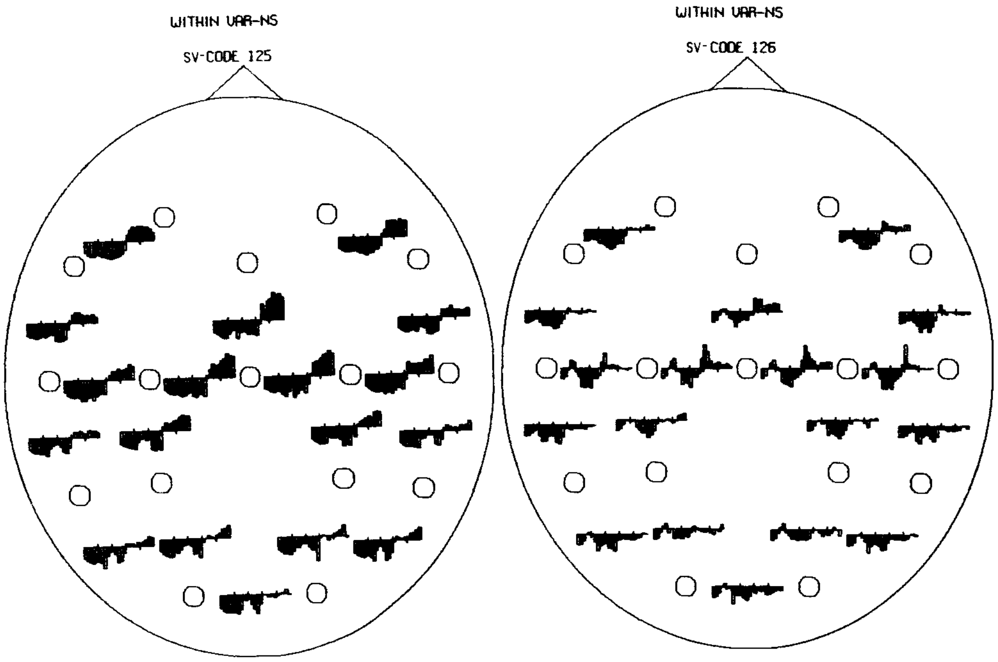
A. AVERAGES OVER 7 STAGES OF PRESLEEP, SLEEP & POSTSLEEP

B. SLEEP 0 — EYES CLOSED, AWAKE



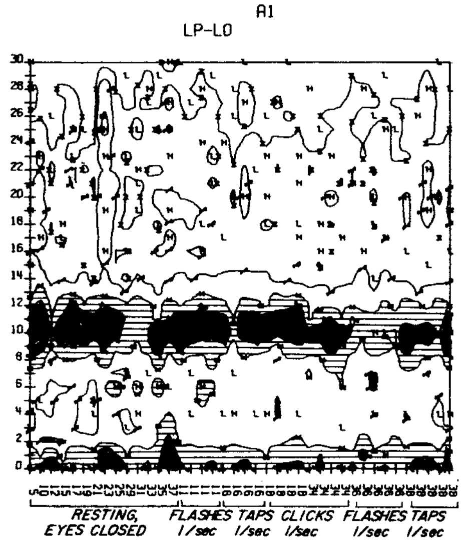
C. SLEEP I. "DRIFTING" OR DROWSY

D. SLEEP II. LIGHT SLEEP—"PARIETAL HUMPS"

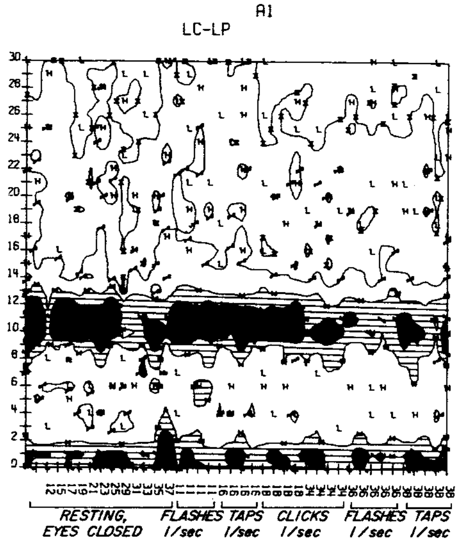


ASTRONAUT F.B. NORMATIVE STUDY
RESTING STATE, EYES CLOSED

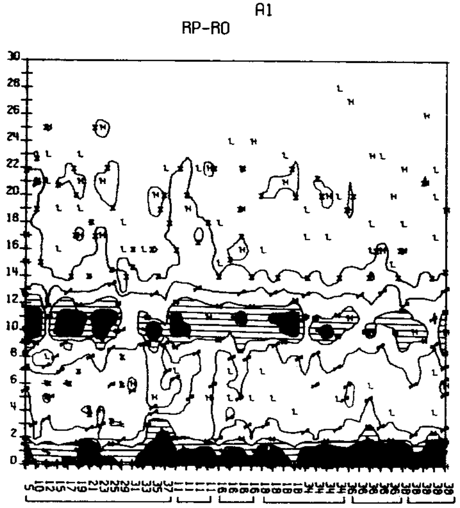
1. L. PARIETO-OCCIPITAL



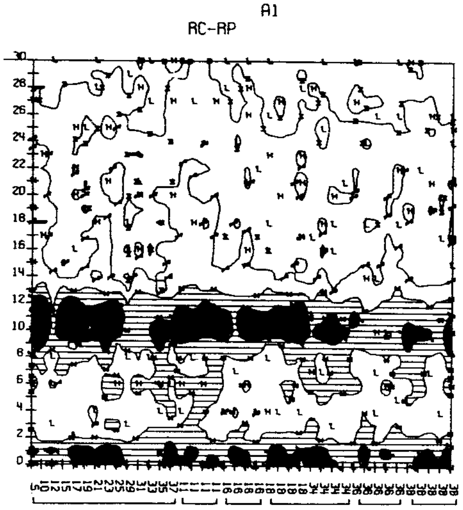
3. L. CENTRO-PARIETAL



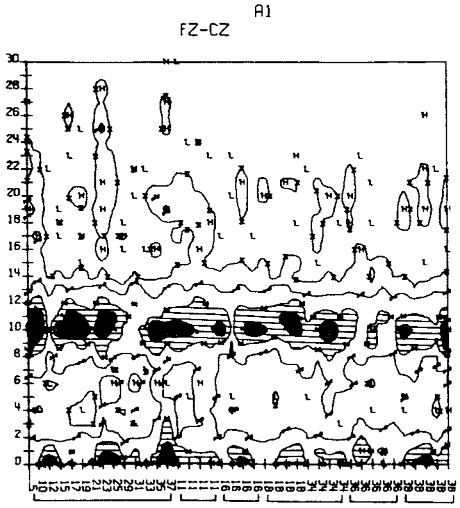
2. R. PARIETO-OCCIPITAL



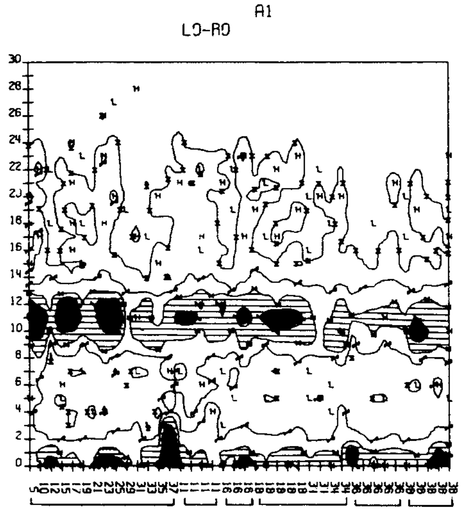
4. R. CENTRO-PARIETAL

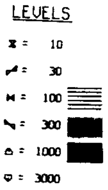


5. VERTEX



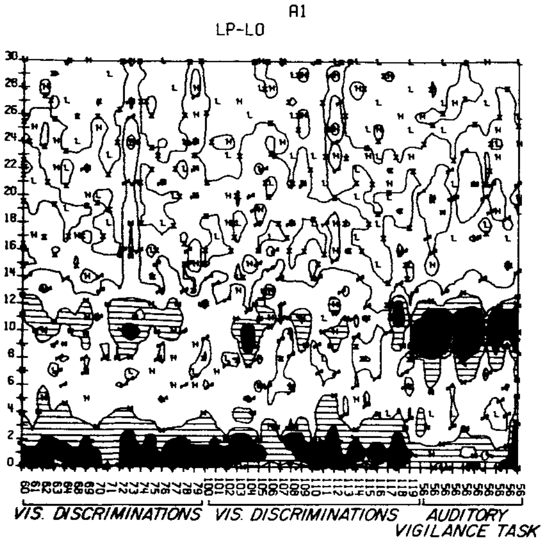
6. BI-OCCIPITAL



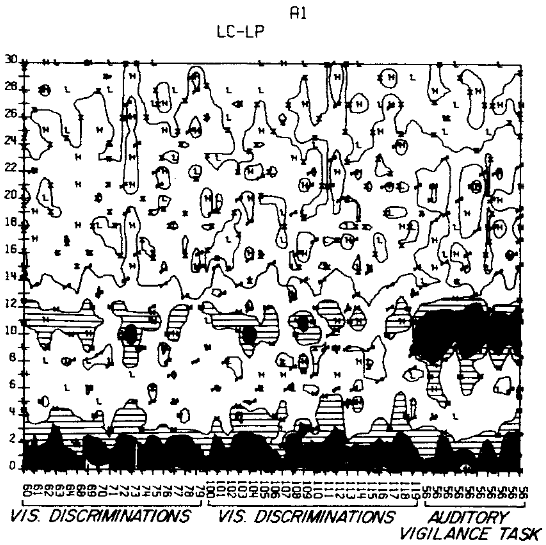


ASTRONAUT F.B. NORMATIVE STUDY
VISUAL DISCRIMINATIVE and AUDITORY VIGILANCE TASKS

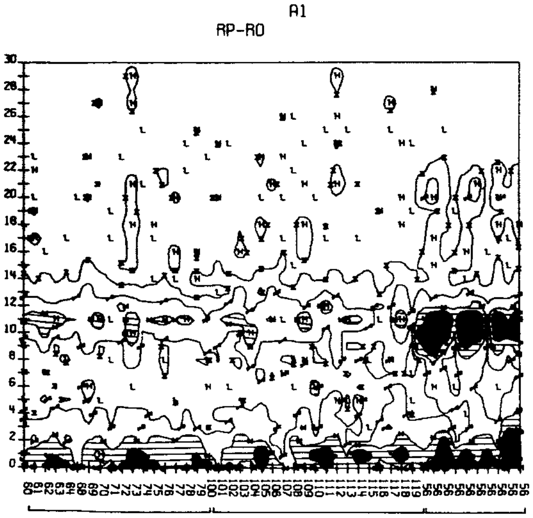
1. L. PARIETO-OCCIPITAL



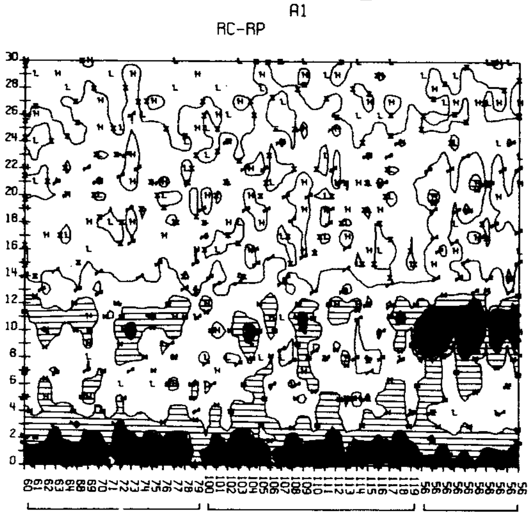
3. L. CENTRO-PARIETAL



2. R. PARIETO-OCCIPITAL



4. R. CENTRO-PARIETAL



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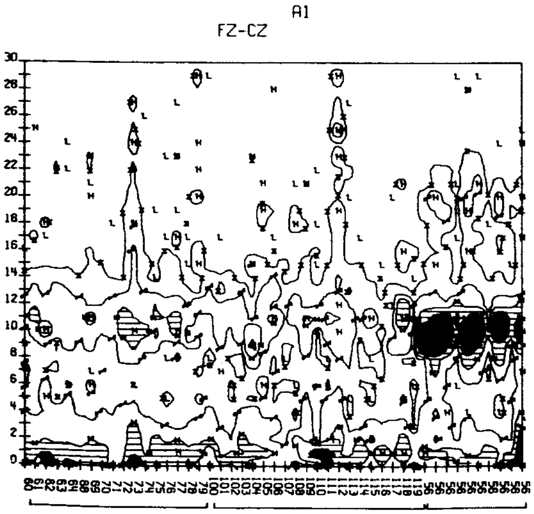
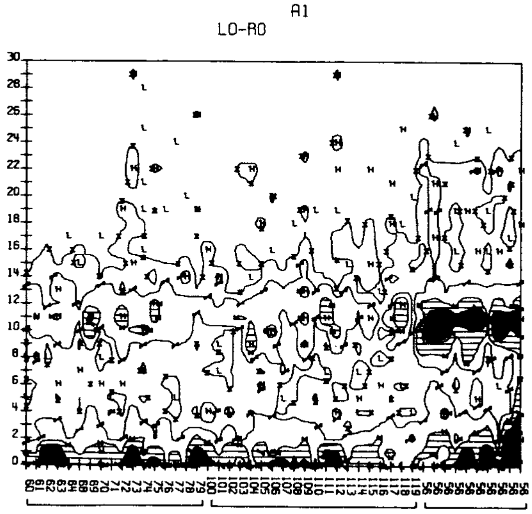


6. BI-OCCIPITAL

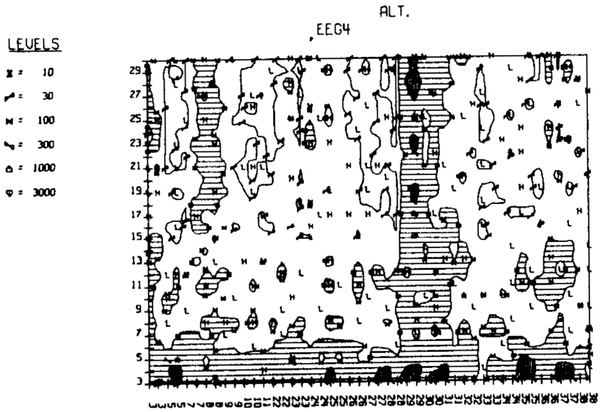


CALIBRATIONS
(μV^2/sec/cycle)
LEVELS

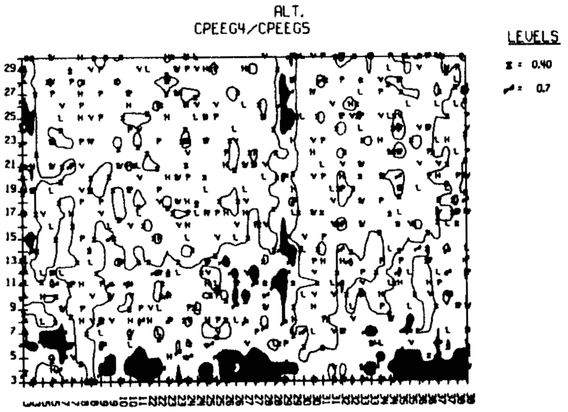
x = 10
↗ = 30
H = 100 ▤
↘ = 300 ■
⌂ = 1000 ■
φ = 3000

ASTRONAUT F. B.
ST. LOUIS ALTITUDE TEST

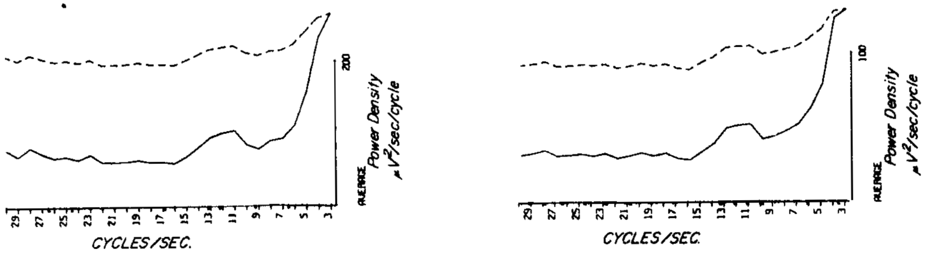
SPECTRAL CONTOURS OVER 70MIN. PERIOD SUBJECT ALERT



COHERENCE BETWEEN CHANNELS 4 and 5

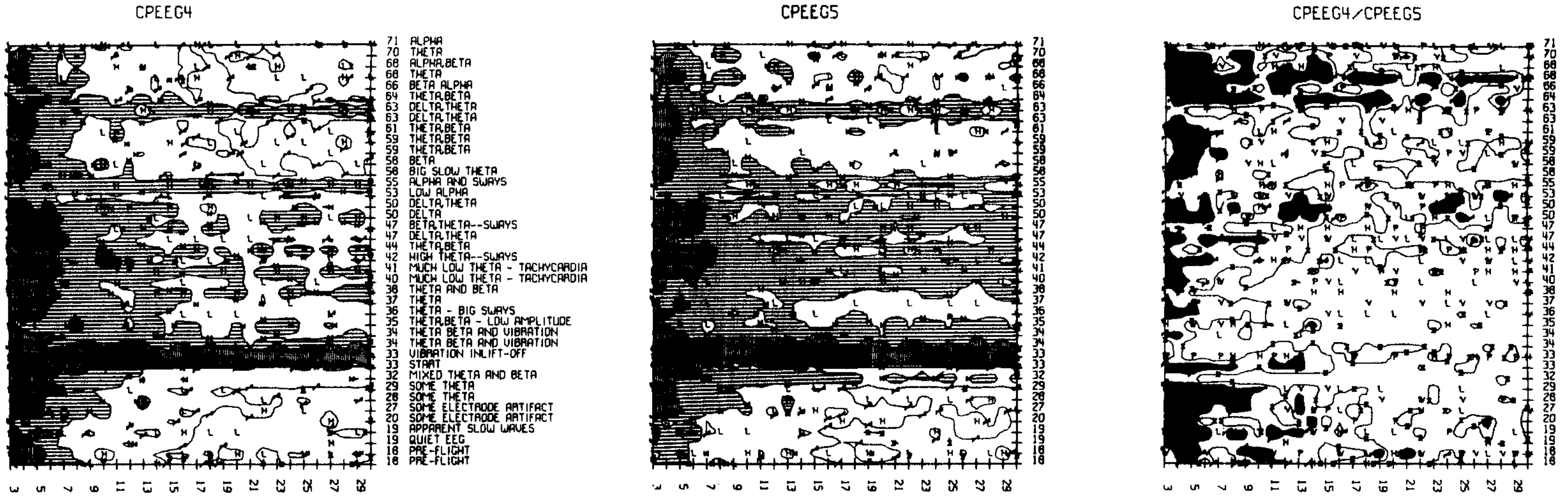


AVERAGED SPECTRAL DENSITIES FOR CHANNELS 4 and 5

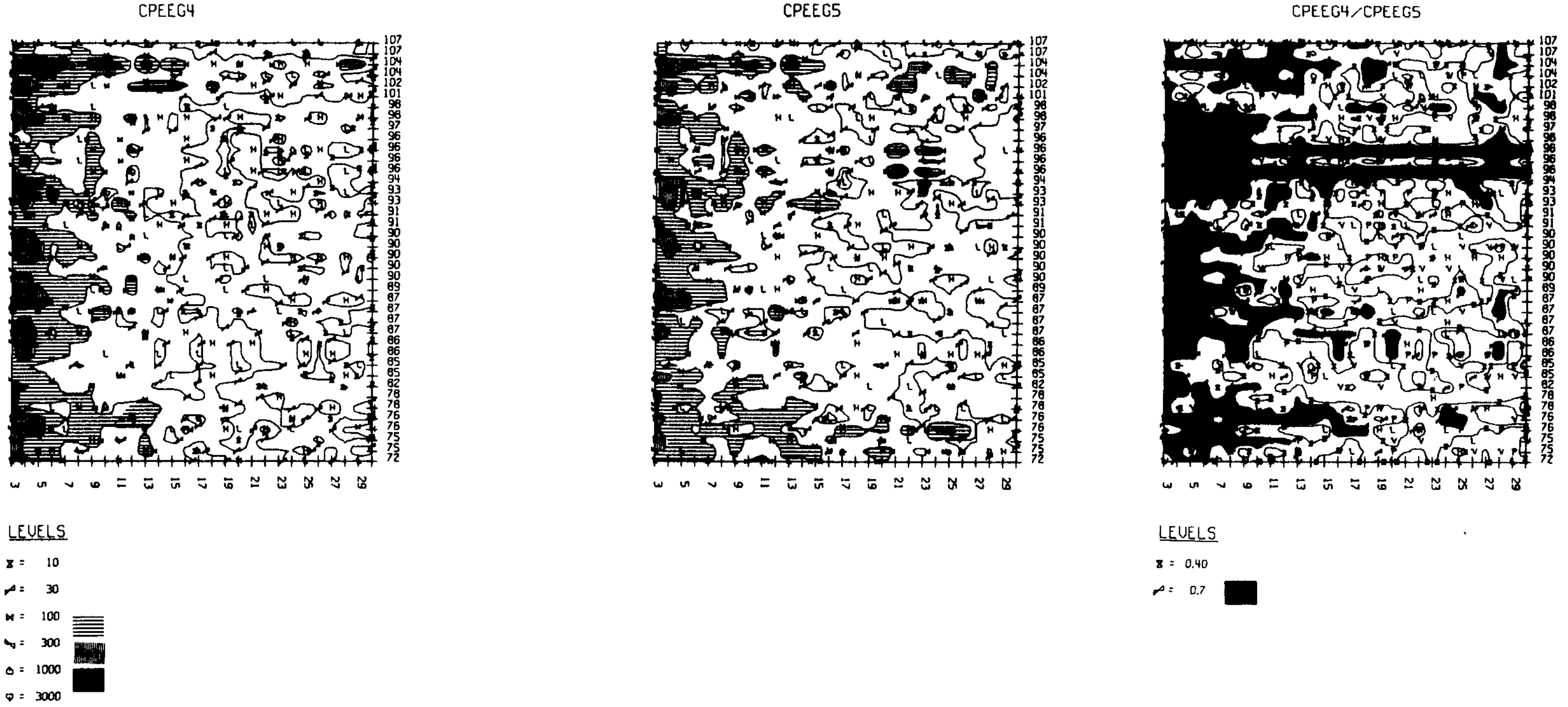


GEMINI GT-7

A. PRELAUNCH-ORBITAL INJECTION

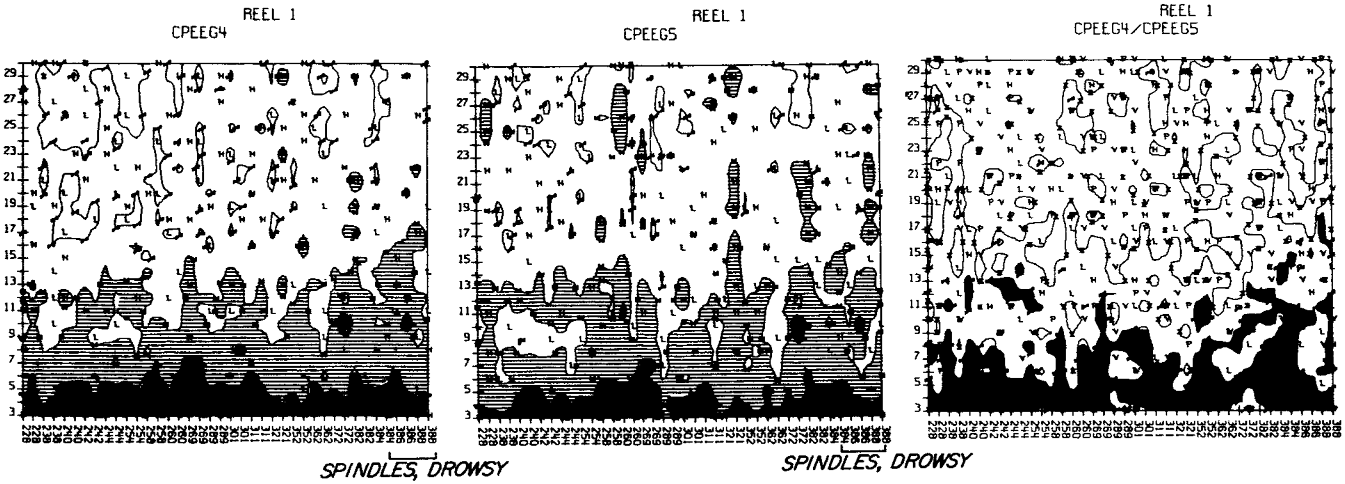


B. CONTINUATION OF FIRST ORBIT

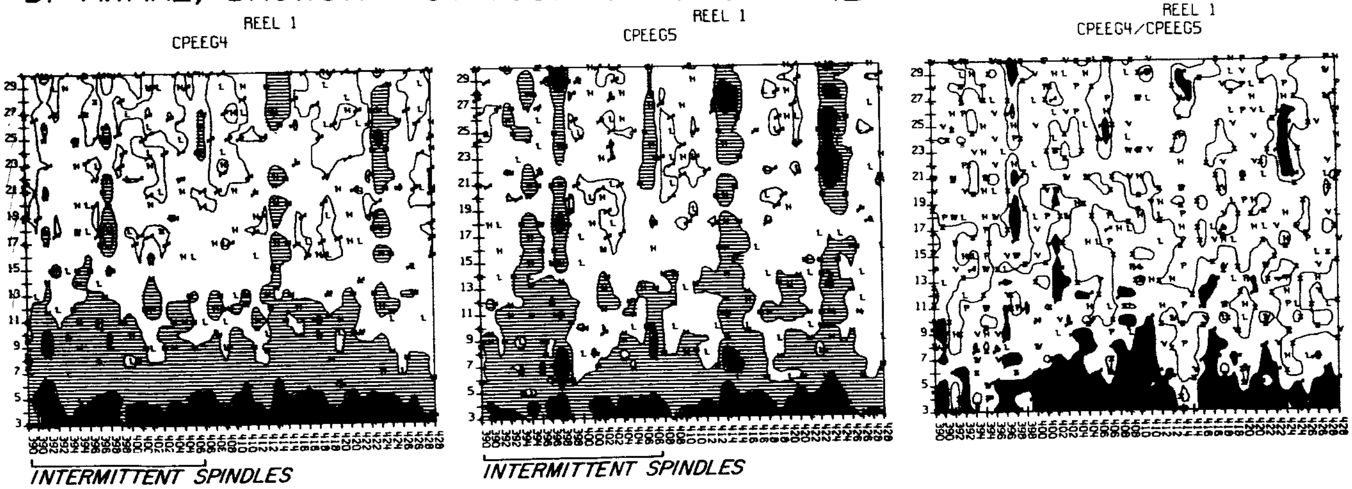


GEMINI GT-7

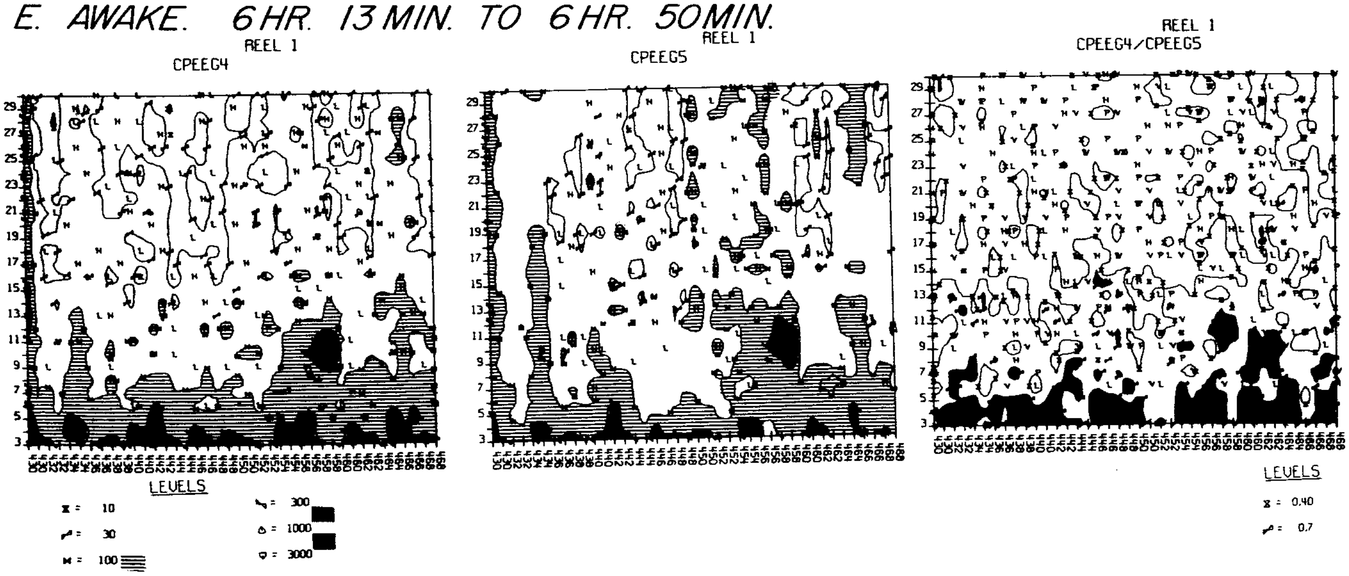
C. ALERT, BECOMING DROWSY. 3 HR. 4 MIN. TO 5 HR. 34 MIN.



D. AWAKE, DROWSY. 5 HR. 35 MIN. TO 6 HR. 12 MIN.

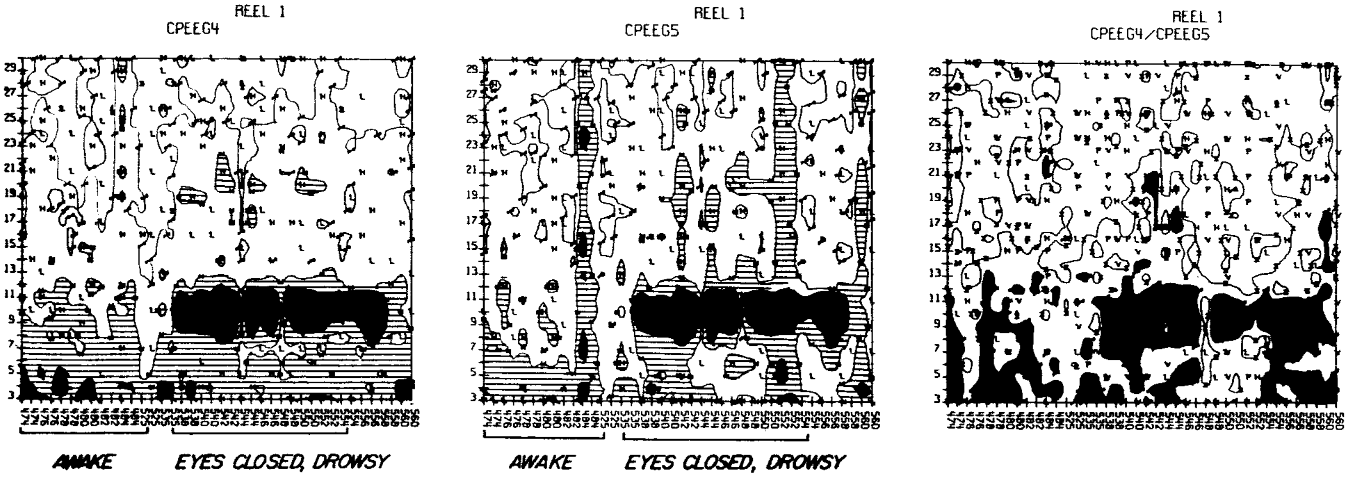


E. AWAKE. 6 HR. 13 MIN. TO 6 HR. 50 MIN.

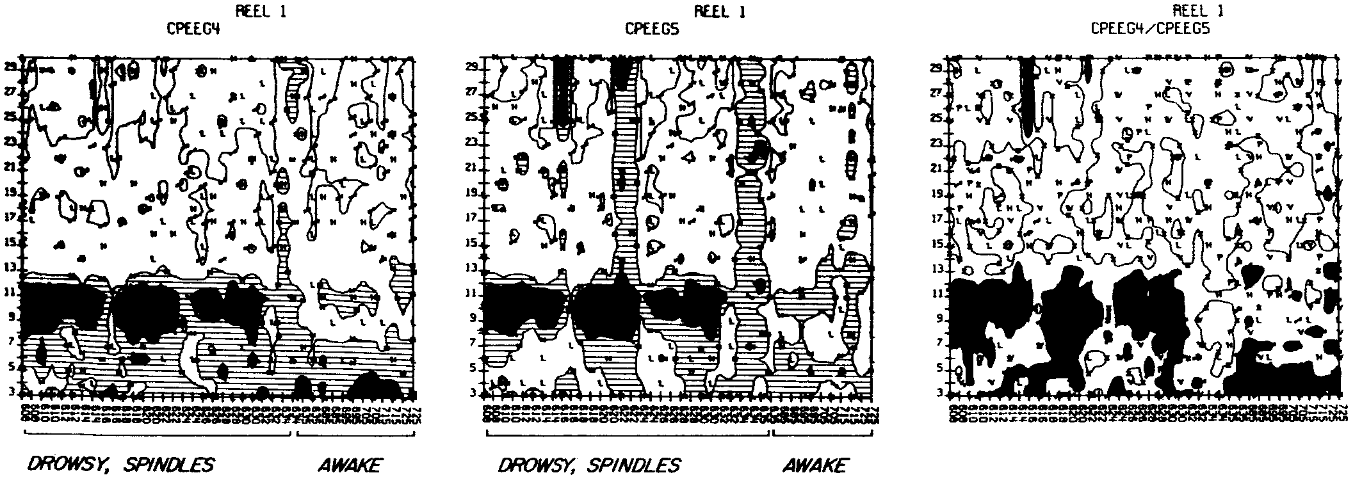


GEMINI GT-7

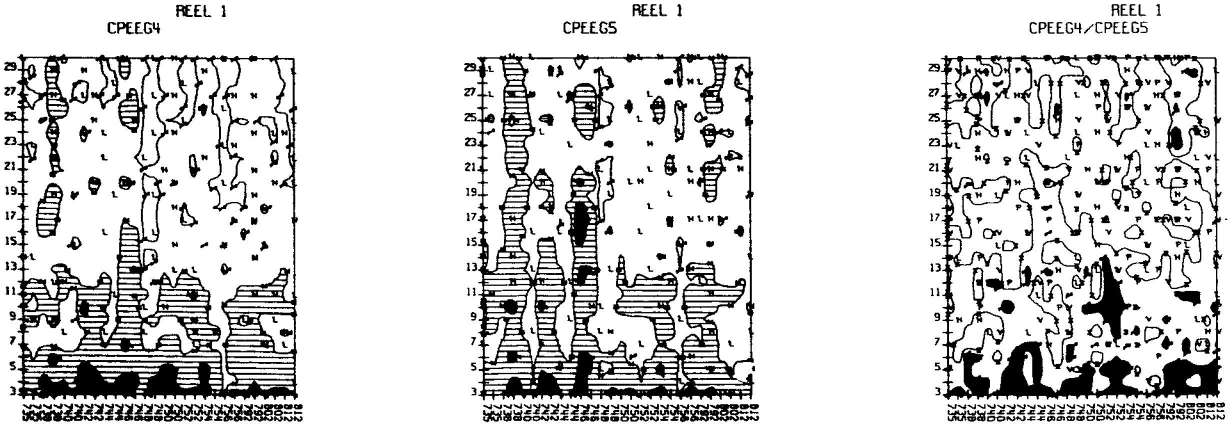
AWAKE, OCCASIONAL DROWSY EPISODES - 6HR 55MIN TO 8HR 15MIN



DROWSY, EYES CLOSED - 9HR 1MIN TO 10HR 51 MIN

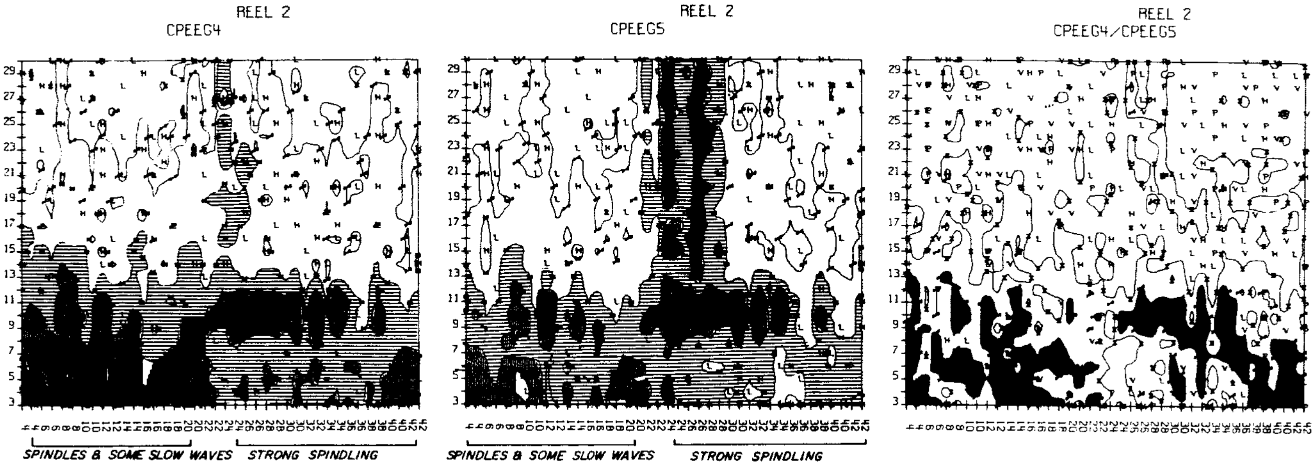


AWAKE - 11HR 0MIN TO 12HR 12MIN

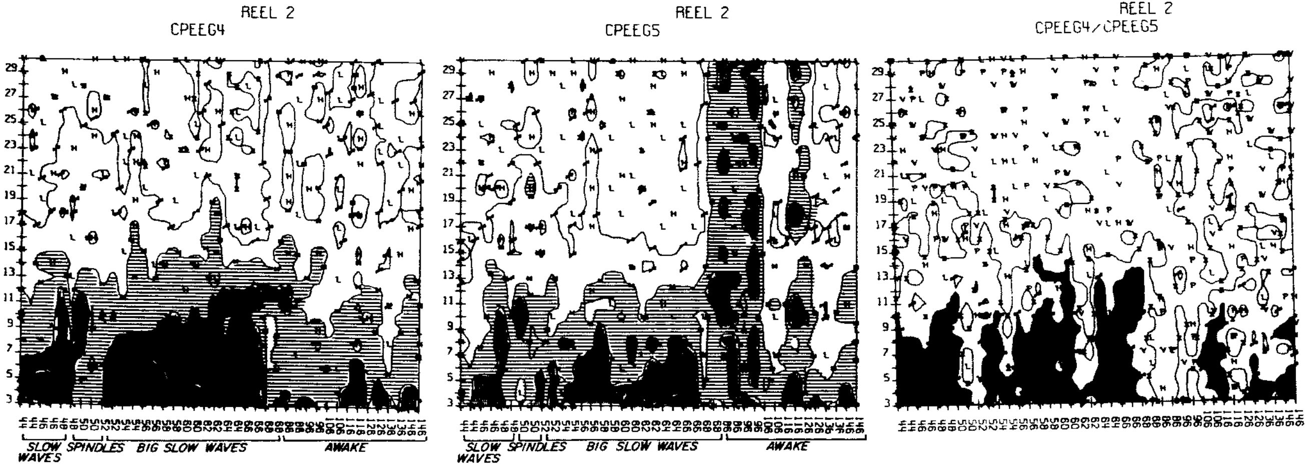


GEMINI GT-7

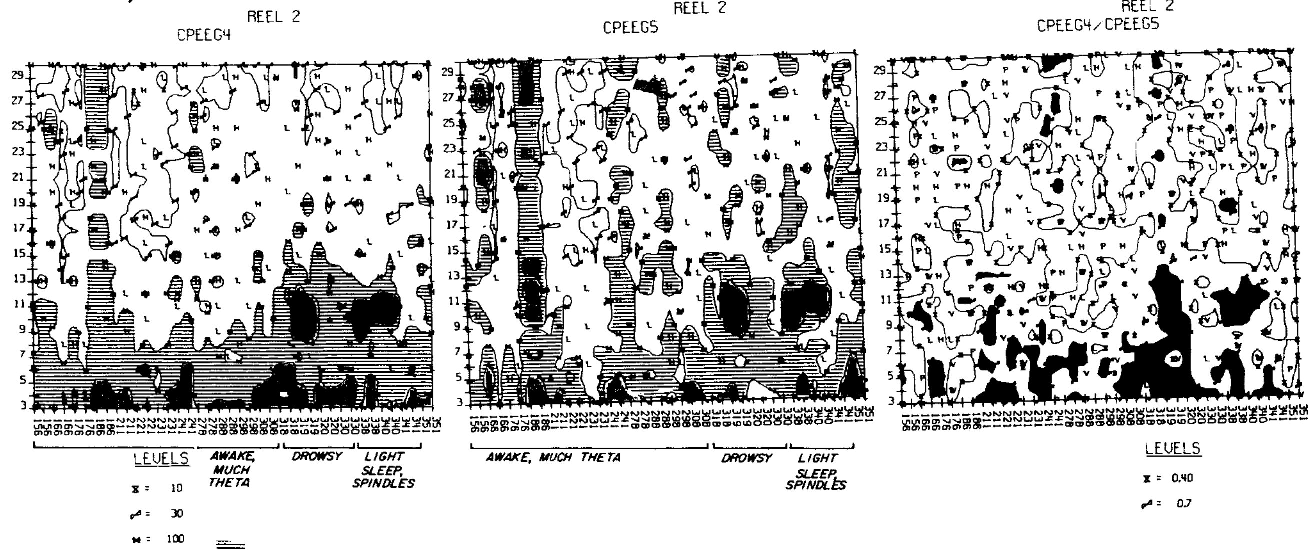
LIGHT SLEEP - 14HR. 36MIN. TO 15HR. 12MIN.



MIXED DEEP & LIGHT SLEEP, DROWSY - 15 HR. 14MIN. TO 16HR. 47MIN.

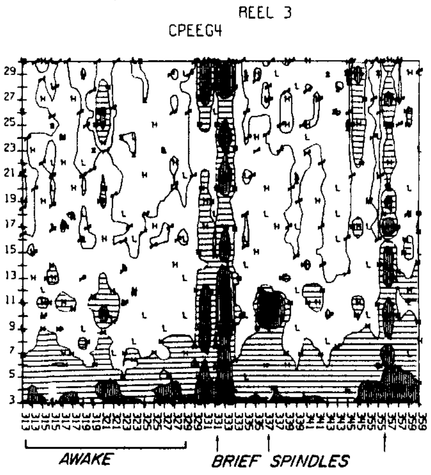


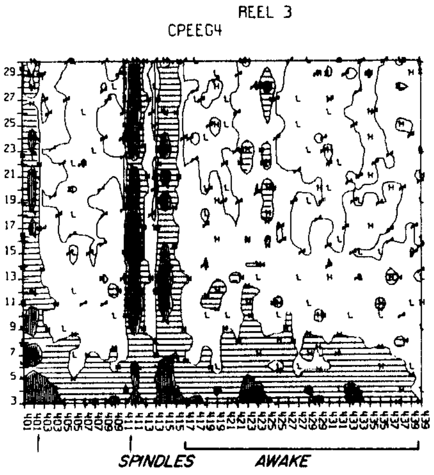
AWAKE, BECOMING DROWSY - 16HR. 56MIN. TO 20HR. 2MIN.

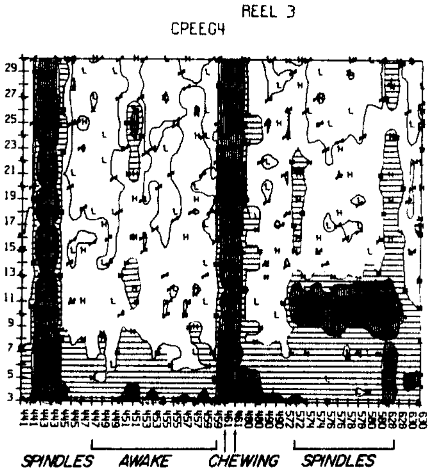


GEMINI GT-7

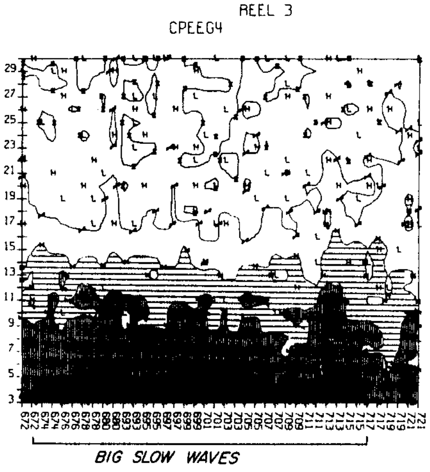
AWAKE, OCCASIONAL DROWSY EPISODES - 28HR. 56MIN. TO 33HR. 50MIN.

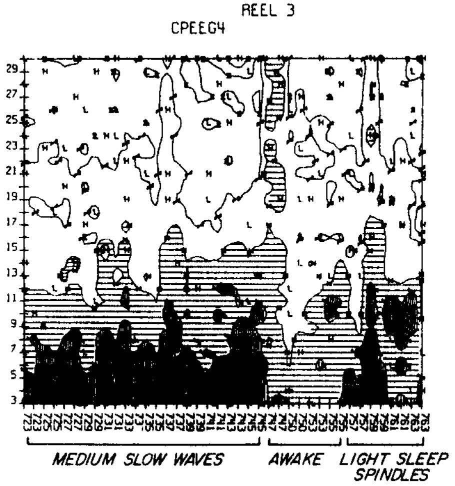


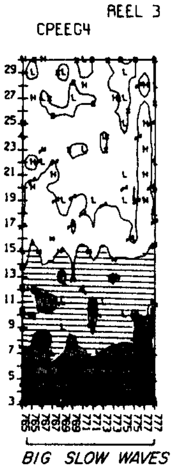




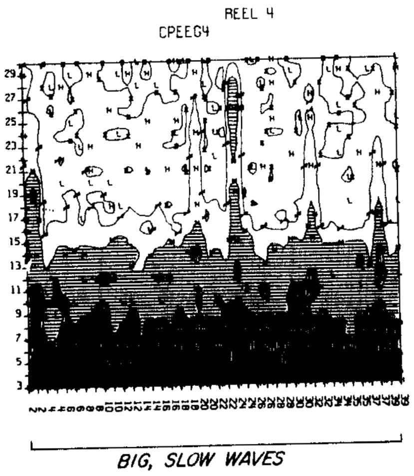
MEDIUM TO DEEP SLEEP - 34HR. 33MIN. TO 36HR. 12MIN.

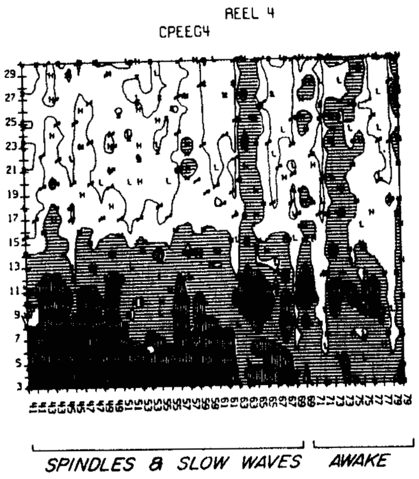


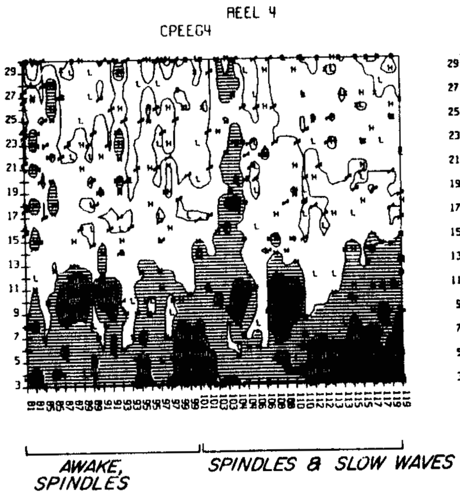


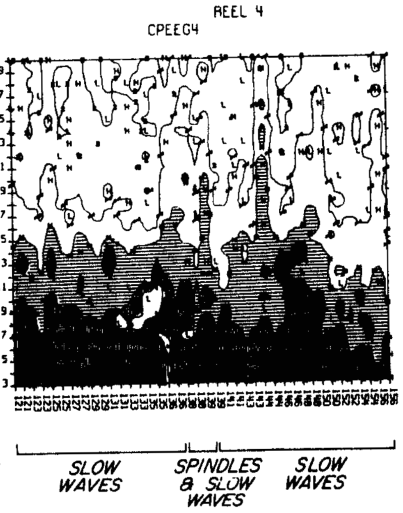


GEMINI GT-7
DEEP SLEEP - 36 HR. 7 MIN. TO 38 HR. 31 MIN.

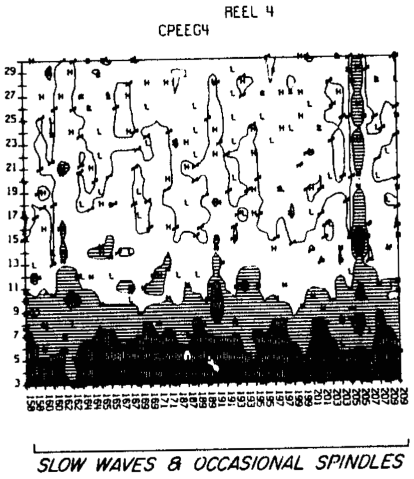


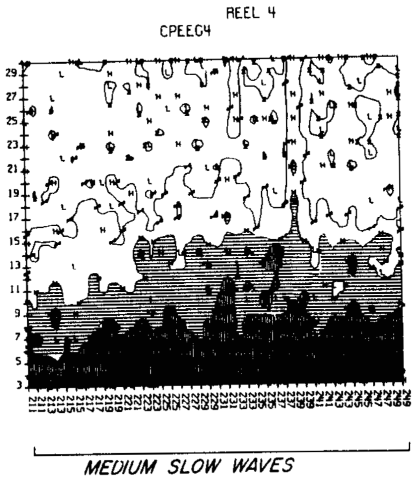


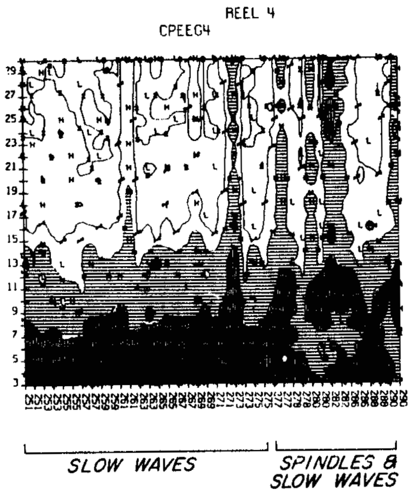




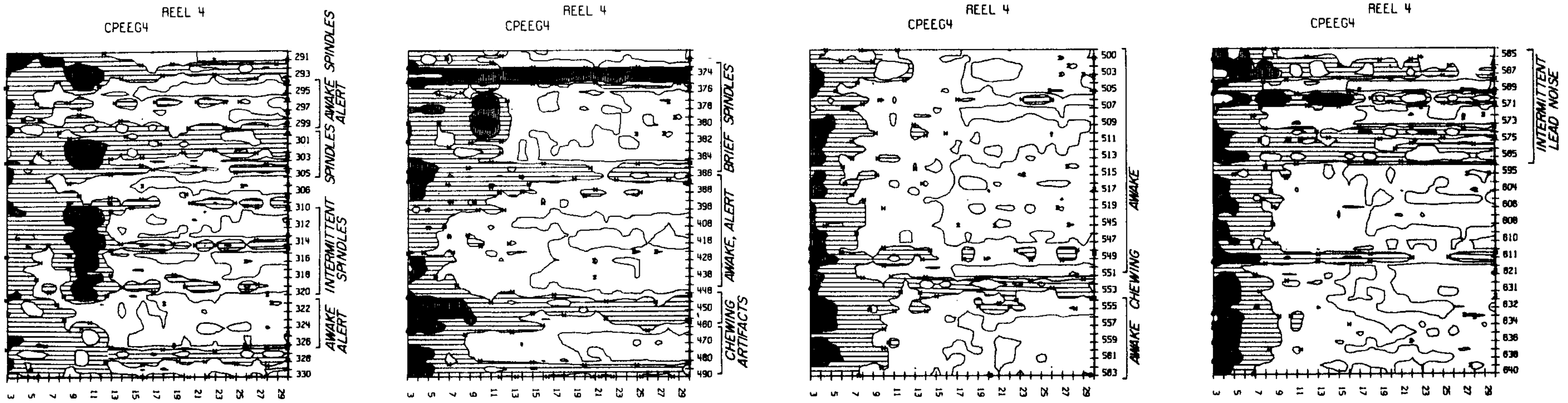
MEDIUM & DEEP SLEEP 38 HR. 33 MIN. TO 40 HR. 37 MIN.



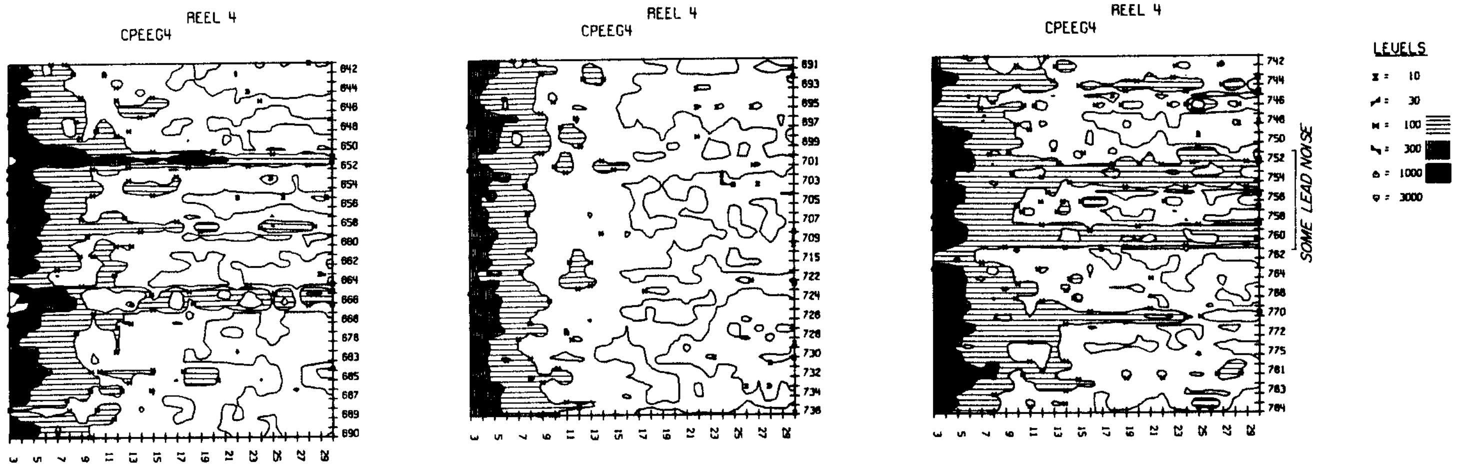




GEMINI GT-7
AWAKE, DROWSY INTERMITTENTLY - 40HRS. 39MINS. TO 45HRS. 27MINS.



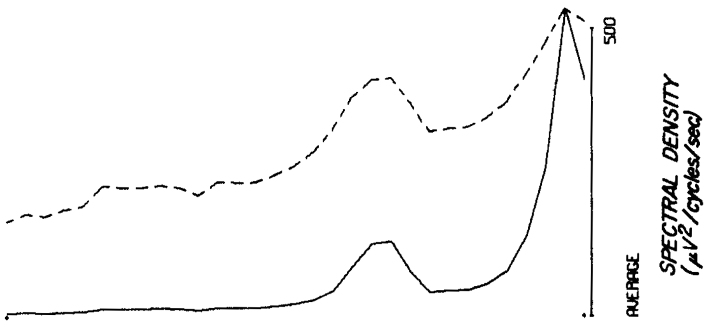
PROLONGED EPOCH OF AUGMENTED THETA (AWAKE) – 45HRS. 29MINS. TO 47HRS. 43MINS.



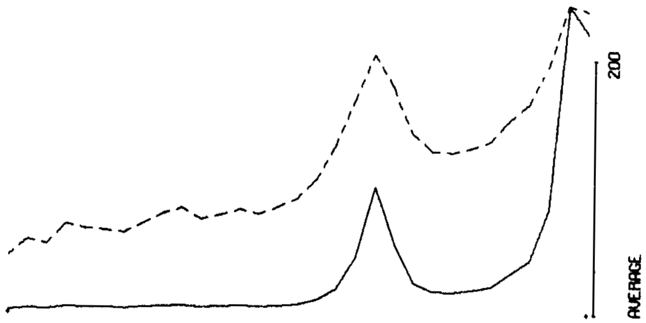
ASTRONAUT F. B.
A. NORMATIVE LIBRARY

VISUAL DISCRIMINATION PERFORMANCES
SPECTRAL AVERAGES

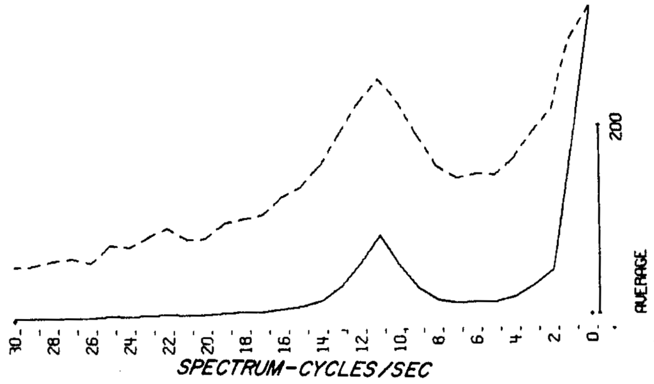
1. L. PARIETO-OCCIPITAL LEAD



2. R. PARIETO-OCCIPITAL LEAD



3. BI-OCCIPITAL LEAD



B. FLIGHT RECORDS

AWAKE STATES IN FIRST 7 HRS. OF FLIGHT
SPECTRAL AVERAGES

1. CHANNEL 1

2. CHANNEL 2

3. CHANNEL 1