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# A TRIDENT SCHOLAR PROJECT REPORT

NO. 84

# "AN INVESTIGATION OF POSSIBLE CORRELATIONS BETWEEN INDIVIDUAL PILOT PERFORMANCE AND NEUROLOGICAL FUNCTIONS"

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UNITED STATES NAVAL ACADEMY
ANNAPOLIS, MARYLAND
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# AN INVESTIGATION OF POSSIBLE CORRELATIONS BETWEEN INDIVIDUAL PILOT PERFORMANCE AND NEUROLOGICAL FUNCTIONS

A Trident Scholar Project Report

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# ABSTRACT

The purpose of this study was to determine whether a meaningful correlation exists between some quantifiable element of a pilot's neurological activity and his performance at the controls of an aircraft with particular emphasis on degraded performance as a result of "mental fatigue." The study represents the simultaneous development of two initially independent areas of investigation and their eventual integration for the purpose of correlation analysis.

Because the evaluation of pilot performance has traditionally been subjective in nature, a new and unique system for quantifying pilot performance was developed using the Singer GAT-1B Link Flight Simulator. A system was also developed for monitoring and recording pilot neurological functions in a cockpit environment.

Significant changes in pilot performance and neurological functions were observed as a result of sleep deprivation, holding all other factors as constant as possible. An apparent trend was observed relating changes in pilot performance to changes in a pilot's pre-flight neurological state described in terms of cross correlation and coherence function analysis of evoked potential tests. Ground work was laid for further investigation into the possibility of predicting pilot performance based on a comparison of the pilot's current neurological state to a previously recorded baseline and developing neurologically based criteria for pilot duty cycles.

# PREFACE

This study is the result of two semesters of work undertaken as part of the United States Naval Academy's Trident Scholar Research program during the academic year 1976-1977.

The guidance and assistance provided by the project's three faculty advisors, Dr. Bruce Johnson, Dr. Karel Montor, and LCDR John A. Burt is sincerely appreciated. It is recognized that without their thoughtful and patient cooperation the project would not have been nearly so successful and revealing from either the educational or the research standpoint.

Special thanks go to LT Robert Stafford, VA-174 instructor, and to the Naval Academy's Technical Support Division personnel for their timely and invaluable assistance.

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# CHAPTER I

## INTRODUCTION

The purpose of this study was to determine whether a meaningful correlation exists between some quantifiable element of a pilot's neurological activity and his performance at the controls of an aircraft. The results of this study were intended to form the basis for future research into such areas as the neurological screening of aviator/astronaut candidates and neurologically-based criteria for pilot duty cycles.

## SIGNIFICANCE OF RESEARCH

National Transportation Safety Board accident reports indicate that pilot fatigue may have been a contributing factor in a significant number of aircraft accidents. In spite of numerous references to the term "pilot fatigue," however, there currently exists no quantifiable means of defining the term pilot (mental) fatigue. As a result of these limitations, the United States Armed Forces and the Federal Aviation Administration have somewhat arbitrarily established maximum pilot-duty cycle criteria for various types of pilot operations. The standards apply uniformly to all pilots engaged in the particular form of pilot operations being governed, without regard for physiological and neurological differences among individual pilots. It is not, therefore, a valid assumption that all pilots are capable of performing their flight duties safely merely because they have met the minimum rest requirements set forth by the applicable regulations.

The study described herein represents an attempt to correlate some element of a pilot's neurological activity to his flight performance. If such a correlation could be found, the first step toward quantifying the phrase "mental fatigue" in terms of changes in an individual's neurological activity will have been accomplished.

## ASSUMPTIONS

The researcher has made certain basic assumptions related to the nature of the problem in conducting this study. It is assumed that:

1) Pilot performance is in some way related to an individual's neurological functions.

2) Mental and physical fatigue are two separate phenomena, implying that mental fatigue may be induced without the onset of significant levels of physical fatigue.

3) Not all pilots develop mental fatigue at the same rate.

4) Pilot subjects in a testing environment will attempt to fly the aircraft in the same manner, applying individual technique to maintain personally set standards, whether rested or fatigued.

5) Given a task commensurate with his flying skills, an aviator's ability to follow a specific flight path in an instrument flight environment is a function of his thought processes. It is further assumed that a change in the manner in which an aviator tracks along the same flight path resulting in more frequent and extreme excursions from the desired path represents a degradation in individual pilot performance.

6) Given an aircraft appropriate to his level of mechanical flying

skill and experience, an aviator's ability to fly a specific flight path is directly related to the mental difficulty of the problem. It is further assumed that problems causing similar excursions from the desired flight path by two different, rested pilots are of similar mental difficulty for the individual pilots, regardless of their levels of experience.

7) Pilots being tested should be located along the relatively horizontal portion of the learning curve for the problem involved, in order to eliminate bias to flight performance measurements.

8) Most significant neurological activity occurs between the frequencies of one and 180 $H_z$ (cycles per second).

## LIMITATIONS

The results of this study can only be applied to the specific group studied. However, the sample group is composed of a reasonable cross-section of the aviation community at large, including male and female aviators at widely varied levels of pilot experience and age. Further research involving a much larger sample must be conducted in order to warrant applying the results to the population of aviators at large.

# CHAPTER II. RELATED RESEARCH

## PROCESSING NEUROLOGICAL SIGNALS

Although the concept of frequency analysis of EEG (electroencephalogram) data has been around for quite some time, serious efforts to apply such techniques have evolved only within the past decade. As early as 1932 Dr. G. Dietsch, a physicist, was performing analysis of normal and pathological EEGs.[1] By 1938 Drs. Grass and Gibbs had developed a method of EEG spectral analysis using analog filters.[2] However, it was not until the advent of the low-cost digital computers and the application of the Fourier Transform algorithm that a practical system was made available to investigators for EEG analysis.[3] Technological advances in the field of digital time-series analysis have provided the basis for the development of a new generation of spectral analyzers capable of evaluating a multitude of functions in a real time environment.[4] These functions include the Forward and Inverse Fourier Transform, the Transfer Function, the Auto and Cross Spectrum, the Auto and Cross Correlation, and the Coherence Function.

It is significant that prior to the development of the Fast Fourier Transform algorithm by Cooley and Tukey in 1965, EEG analysis had primarily been conducted in the time domain since low frequency analog filters are difficult to use. The development of the FFT algorithm literally added another dimension to EEG signal processing by providing for signal analysis in the frequency domain. These new capabilities in digital time-series analysis also opened a new and controversial field of research dealing with the optimization of EEG analysis techniques.

The variety of functions available to the research in evaluating neurological phenomena creates a problem in determining which functions provide meaningful information and what the significance of that information actually is.

Although many investigators continue to examine EEG signals in the time domain, a considerable amount of interest has recently been focused upon frequency domain analysis.

Dr. Enoch Callaway, of the Langley Porter Neuropsychiatric Institute, continues to measure evoked potential (EP) latency with a zero-crossing technique while researchers at the Naval Academy prefer cross correlation techniques.[5,6] Dr. Callaway chooses to evaluate differences between EPs from homogeneous sites on opposite sides of the scalp through asymmetry calculations, while other laboratories extract similar information from cross spectrum analyses.[10]

Yet another area of controversy in the field of neurological signal processing is the question of what length of sample should be taken and what portions of the signal yield meaningful information.

Dr. Duilio Giannitrapani of Duke University has devoted a significant amount of research to the problem of optimizing spectral analysis of EEG information. Because of equipment constraints, he has chosen to analyze one 8-second artifact-free record from each of 16 scalp locations tested in a spectral determination from one to 33 $H_z$.[7] In contrast, researchers at the United States Naval Academy have examined from 32 to 256-second averages from one to 180 $H_z$, and even as high as 400 $H_z$ with the Spectral Dynamics SD-330 and SD-360 spectral analyzers. Still other researchers, such as Dr. Callaway, prefer to deal with average evoked potentials (EP) from a specific number of light flashes.[8,9,10,11]

Going beyond the question of optimizing the EEG analysis techniques, some researchers have even made clinical applications of newly developed processing techniques. Among these was Dr. Jean Gotman of the Montreal Neurological Institute.[12] These researchers have taken positive steps toward classifying brain wave characteristics so that abnormalities in these characteristics become readily apparent using their processing techniques.

## RELATING BRAIN WAVES TO HUMAN BEHAVIOR

In 1966 Dr. R. J. Ellington stated that "no study has been done conclusively showing the relationship between any feature of the normal adult EEG recorded under standard conditions and any personality trait or variable .... Since alpha and beta activity appear to be quite primitive functions of neural tissue, it is difficult to believe that any measure will be found to correlate with any of the dimensions of so complex and logenetically recent an entity as the human personality."[1]

In 1969 Primbram stated, "Changes in EEG frequency relate more to the balance between cellular synchrony and desynchrony than to the specific information content of a signal. If recorded with adequate resolution, they may indicate where the action is, but not what the action is all about."[2] Yet even though it is unlikely that current EEG measurement techniques will ever provide the capability of interpreting the meaning of individual thought processes, researchers have demonstrated the ability to extract data from EEG signals as to the manner in which the brain conducts its information processing. In fact, it is this approach of examining the brain's information processing characteristics which most investigators have chosen to adopt in their study of relating brain waves to human behavior.

In 1936, Davis reported that a high alpha index was characteristically associated wtih a passive, dependent, negative attitude toward other persons, while a low alpha index generally indicated a consistent, well-directed, freely indulged drive to activity.[3] In 1942, Rubin and Bowerman verified these findings with tests on peptic ulcer patients.[4] In 1949, Saul, using a psychoanalytic approach in searching for correlates of personality with EEG patterns, found trends opposing those found by Davis, Rubin and Bowerman.[4]

In 1956, Kennard reported significant differences in frequency pattern distributions between groups having different personality characteristics.[4] Lack of agreement with respect to the significance of these findings prompted Ellington to comment on the lack of validity in these findings as previously mentioned.

In 1975, Midshipman W. A. Woods found several areas of significantly different visually evoked potentials between groups of Naval Academy midshipmen showing psychological/motivational test differences.[5] In spite of those individual findings, however, it has yet to be proven that a definite relationship exists between personality test measures and neurological frequency spectra.

With respect to intelligence, several correlations have been made between EEG information and intelligence test measurements. In 1968, Bennet reported a correlation coefficient of .593 in relating an individual's dominant brain wave frequency ("mode frequency") to the Wechsler adult intelligence scale measurement, with I.Q. increasing with mode frequency.[6] Ertl found in 1969 correlations from 0.30 to 0.50 between I.Q. test scores and parameters at visual evoked potentials in a sample of 300 children between the ages of 86 to 185 months.[7]

In terms of individual performance, Midshipman Charles Hill determined in 1975 a correlation of .560 between individual "throughput latency" (TPL) and grade point average (GPA) in a group of 77 midshipmen at the U. S. Naval Academy.[8] In 1976, Dr. Enoch Callaway noted significant differences in the parameters of evoked potential between successful and unsuccessful subjects in a Navy remedial reading program and again observed similar results in a 1977 study of aptitude among Navy recruits.[9,10] In 1961, the Navy observed significant differences between individual EEG's of pilots with a history of accidents/incidents and a control group of 1375 aviation candidates.[11]

Dinard and Defoyolle achieved a correlation of .79 between I.Q. and average evoked potential (AEP) by compiling the AEP measure to a task which itself was a good measure of I.Q. of some 100 subjects.[10]

In general, there has been a vast amount of research done in looking for correlations between individual EEG's and personality potential, and performance. Unfortunately, there has been very little significant research into the question of what happens to an individual's neurological activity as his physical and mental states change affecting his performance of various tasks. One such study by Midshipman C. A. Hill studied differences in individual EEG's before and after being fatigued by the Harvard Step Test. Hill found a decrease in the level of high frequency (beyond 60 $H_Z$) neurological activity in most individuals after physical exertion.[8] The investigator has yet to find, however, evidence of research into the area of individual differences in neurological activity while rested and mentally fatigued by long periods of mental exertion.

## PILOT PERFORMANCE EVALUATION

The evaluation of pilot performance has historically been a largely subjective matter. Pilots have traditionally been graded by flight instructors who base their evaluations of their student's performance upon their own perceptions of the task being executed. These perceptions are influenced by any number of factors affecting the instructor's physical and mental state. What might be perceived as acceptable one day could just as well be unsatisfactory the next.

In licensing and examining civilian pilots, the Federal Aviation Administration continues to evaluate pilot performance using the subjective opinions of designated examiners.[1] Commercial airline flight crews continue to be evaluated by FAA personnel riding on the aircraft's flight deck.[2] Specific tolerance limits have been established regarding deviations from the desired flight path; however, since many activities occur during a check ride it is possible that out-of-tolerance deviations may go unnoticed by both the pilot and the examiner. The in-flight evaluation of military air crews is currently being conducted in this same manner.[3]

With the advent of modern flight simulators capable of realistically reproducing any situation encountered in actual flying conditions, efforts have been made to provide instructors and examiners with some form of record of each flight for post-flight evaluation and debriefing. Many simulators produce hard copy records showing plan and profile views of the aircraft's flight path in the time domain.[4] Some even record the number of excursions and the furthest excursion from pre-established tolerances.[4] However, the evaluation of this data has remained a subjective matter. Using the present system, the instructor or examiner must still make judgments based on his own experience in grading air crew performance.[5]

# CHAPTER III. METHODS AND PROCEDURES

The objective of this study was to determine whether a meaningful correlation exists between an individual pilot's performance at the controls of an aircraft and some quantifiable element of his neurological activity. The project, which in itself was composed of two major individual projects: flight performance evaluation and neurological signal analysis, required the coordination of effort in seven specific areas:

1) The development of a system to provide a quantifiable measure of flight performance;

2) The design of a system capable of in-flight (simulated or actual) neurological data collection;

3) The development of a neurological signal processing system utilizing the Spectral Dynamics SD 360 Real Time Analyzer;

4) The identification of the subjects to be tested;

5) The development of an experimental test plan;

6) The implementation of the test procedures and data collection; and

7) The analysis of the data collected applying several advanced times series analysis algorithms.

This chapter describes the activities and decisions involved in the completion of each element of the project.

## FLIGHT PERFORMANCE ANALYSIS

Until recently, the problem of grading pilot performance has been a purely subjective matter. Flight instructors and examiners have traditionally graded pilots based upon their own perceptions of an individual's flight performance. Many factors ranging from racial or sexual prejudice to personal preference in pilot technique have biased and continue to bias this type of grading system. A well known expression in the aviation community states that "... a student must learn to fly differently with each instructor he flys with...." To achieve the primary goal of this study, however, a more objective system had to be developed for quantifying pilot performance.

In quantifying pilot performance, the basic goal of flying must be considered. Each time a pilot intentionally provides an input to the controls of an aircraft it is with one purpose in mind - to direct the aircraft along a desired flight path. Applying this information, it may logically be inferred that pilot performance is a measure of how well a pilot directs his aircraft along the desired flight path. The flight path may be selected by the pilot or his instructor, or it may be directed by the authority controlling the air space through which the aircraft is transiting. The magnitude of the pilot's excursions from the desired flight path may also be limited by regulations or personal discipline. In general, regulatory agencies, such as the Federal Aviation Administration or the military training commands, establish tolerances which a pilot may not exceed during check flights for pilot certification, but it is impractical to attempt to apply these standards to everyday flight operations. Ground controllers have neither the information available nor the time to monitor this closely the activities of all the aircraft they control. It is, therefore, the pilots themselves who generally set the tolerances within which they will fly.

Another point to consider with respect to flight path tolerances is the fact that the position of the aircraft determined from the aircraft's instruments rarely agrees exactly with the aircraft position indicated by ground equipment. For this reason, ground personnel separate aircraft operating under their control by more than adequate distances to provide for safe flight operations. The significance of this point is not, however, the effect of these differences upon ground personnel observations, but that to provide an objective system for measuring pilot performance, deviations from the desired flight path must be measured with respect to the pilot's frame of reference - the aircraft's instrument indications. The same is true with respect to flights conducted in simulators as there are often differences between instrument and recording equipment indications. This principle provides the basis for a quantifiable pilot performance grading system developed for this study. The grading system utilizes an amplitude distribution function of the deviations from the desired flight path.

The pilot performance monitoring system developed for this project consisted of four elements:

1) The Singer GAT-1B Flight Simulator's circuit boards;

2) A Gould Brush 200, 4 channel strip chart recorder;

3) A Honeywell Saicor SAI-43A Correlation and Probability Analyzer,

and

4) A Hewlett-Packard 7044A X-Y Recorder.

These elements were combined to produce hard copy records of the percentage of time that an aviator remained within any given set of tolerances about the desired flight path.

Flight path information was observed relative to the pilot's frame of reference by taking electrical outputs from the simulator's instrument drive circuit boards. These electrical signals were then input to the Gould Zero Suppression potentiometers where an "on-flight path" indication on the pilot's instruments was set to zero voltage. Any deviations from the desired flight path thus appeared as either positive or negative voltages at the pen drive output from the Brush recorder. These positive and negative voltages from the Brush pen-drive were then input to the SAICOR SAI-43A where an amplitude distribution histogram was computed. Examples of time domain and amplitude histogram records of pilot performance are shown in Figures 1 and 2.

The amplitude distribution histogram represents the integral of the amplitude density histogram from negative infinity to the point where the function is evaluated with the experimental apparatus set up as described. The amplitude density histogram represents the relative amount of time that the pilot flies at any given deviation from the desired flight path. A typical example is shown in Figure 2. The distribution function, as shown in Figure 3, may therefore be normalized and used to indicate the percentage of the total time that a pilot spends outside any specified limits about the desired flight path.

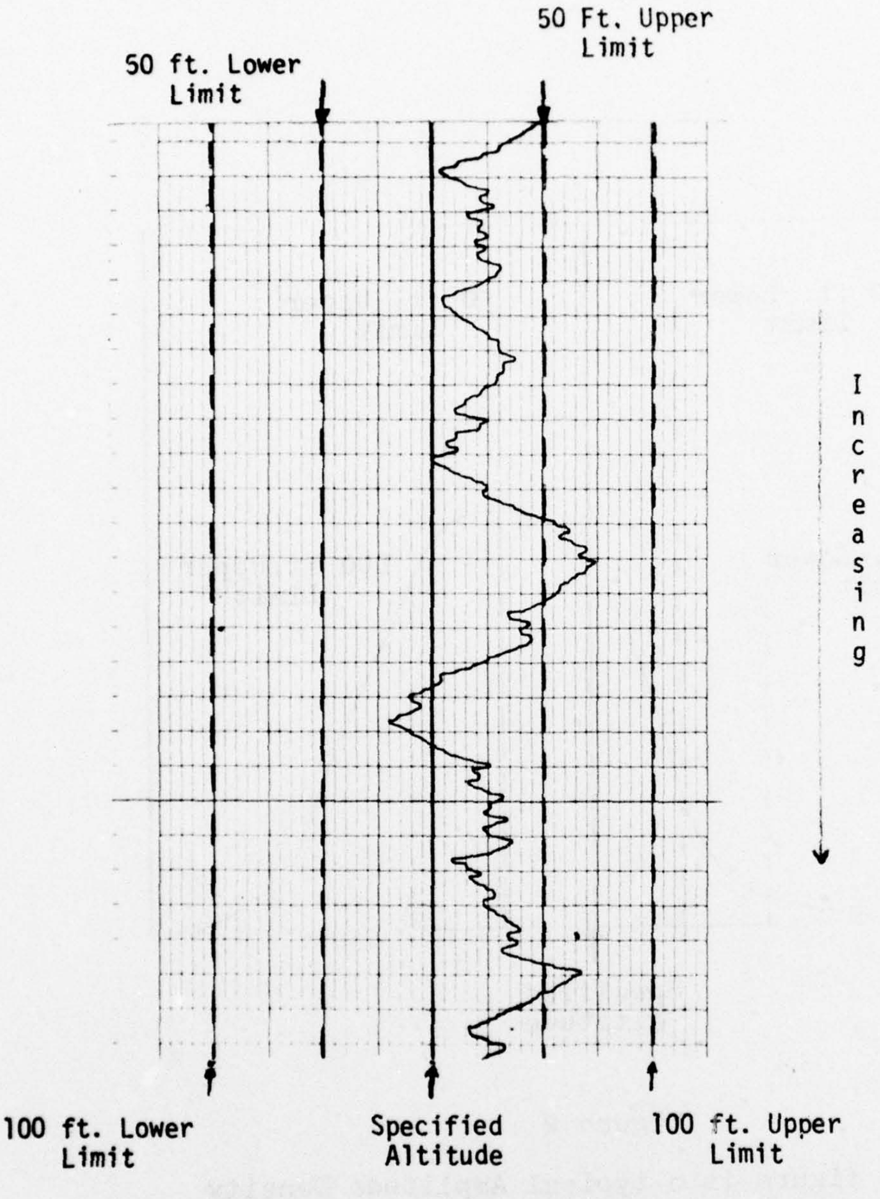


Figure 1

This figure represents the time domain record of indicated altitude as the pilot attempts to maintain a specified altitude shown as the centerline of the graph.

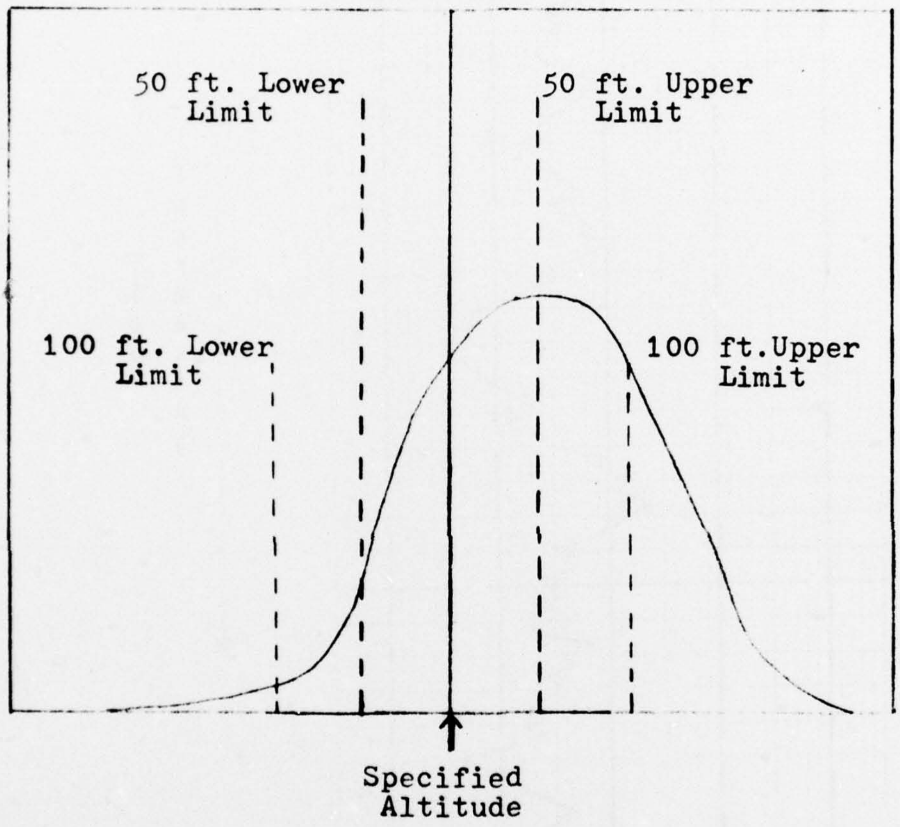


Figure 2

This figure is a typical Amplitude Density Histogram record of a pilot's attempts to maintain a specified altitude over a prolonged period.

Considering the application of the equipment and techniques described, several inferences can be made concerning the interpretation of recorded pilot performance data:

1) By following the desired flight path without deviations, the resulting distribution histogram would produce a vertical line at the point representing the "no voltage" or "on course" signal (i.e. the pilot flies the aircraft 100 percent of the time exactly on course);

2) By never flying along the desired flight path, the distribution histogram would be a horizontal line passing through either zero or 100 percent indicating that the pilot remains biased to one side of a given parameter and never crosses to the other extreme;

3) The point on the X-axis where the value of the histogram becomes greater than zero and the point where the value becomes 100 percent represent the points of furthest excursion from the desired flight path;

4) The slope of a straight line fit to the points of the distribution histogram curve represents the magnitude and duration of the excursions from the desired path that the pilot is willing to accept under the given set of circumstances ...a vertical line indicating no excursions from a specific flight path; and

5) the abscissa value at the 50 percent point indicates the mean path about which the pilot flies the aircraft; thus any difference between this value and the desired path value represents individual pilot bias with respect to the given parameter. A graphic presentation of the above is displayed in Figure 3.

By tapping the appropriate points on the Link Flight Simulator's circuit boards the researcher was able to extract and calibrate signals

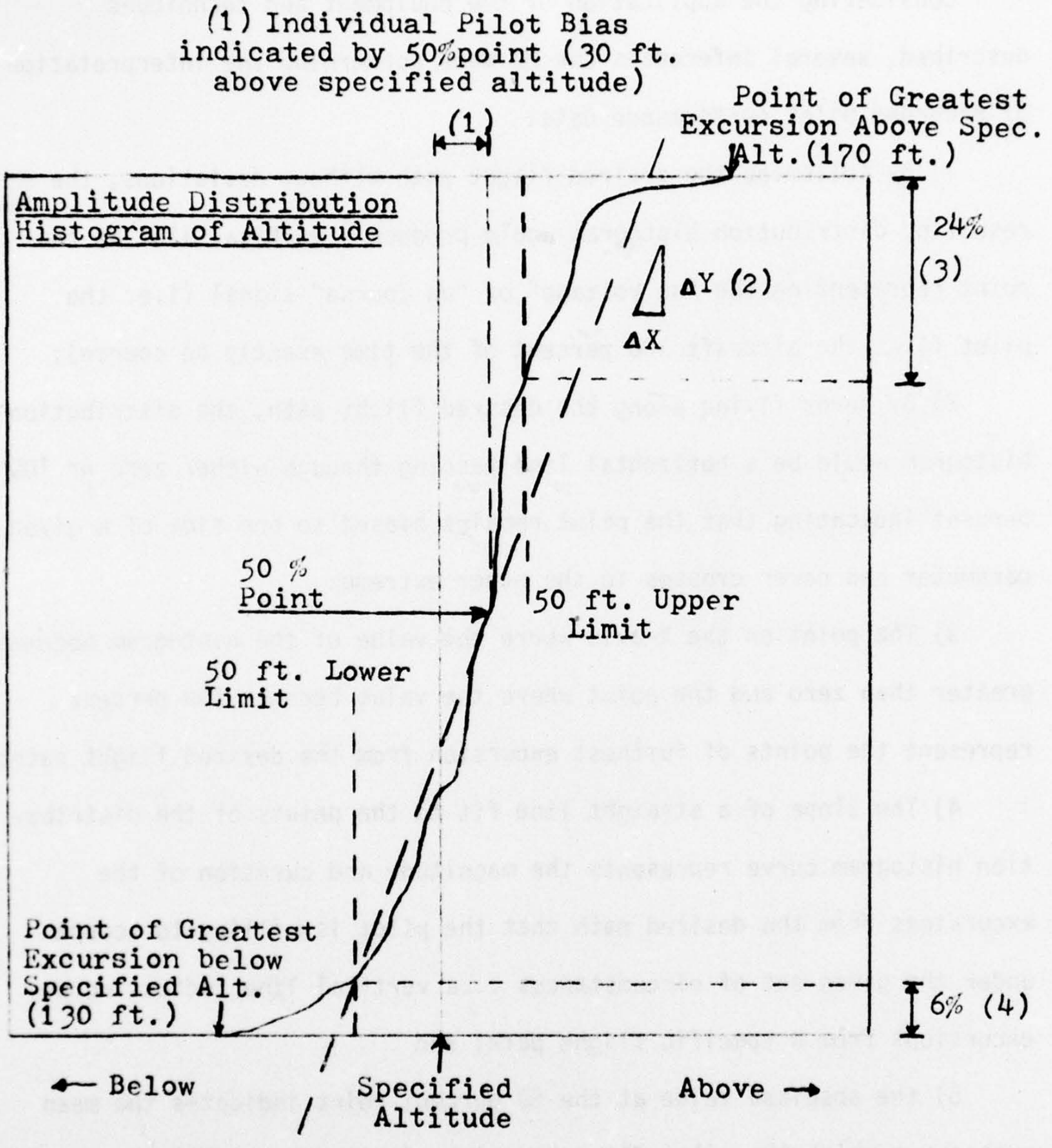


Figure 3.

(2) $m=\Delta Y/\Delta X$=the slope of an approximate least squares fit to the curve

(3) the pilot flew 24% of the graded period at least 50 ft. above the specified altitude

(4) the pilot flew 6% of the graded period at least 50 ft. below the specified altitude

to correlate specific instrument indications to the desired flight path line on the distribution histogram. As the pilot extracts flight path information, through proper use of his instruments, calibrated signals representing air speed, altitude, rate of climb, heading, turn rate, course deviation and glide slope deviation were more than adequate to describe all flight path parameters in the normal operating regime. Realizing that no more than three of these instruments produce meaningful information at any given time, the outputs from these instruments were initially divided into three groups: 1) air speed; 2) altitude, rate of climb, and glide slope deviation; and 3) heading, turn rate, and course deviation.

Upon closer examination of the flight parameters and pilot techniques encountered during most normal operations, it was recognized that: 1) air speed and 2) altitude, rate of climb, and glide slope deviations are related. Although further examination of this relationship shows potential for the development of a quantifiable definition of pilot "smoothness" and "precision," time and equipment constraints prevented this investigation from being further pursued during this study. It was, therefore, decided to eliminate air speed information from the pilot performance grading system. Based upon the assumption that a pilot's attitudes toward the significance of instrument indications remain unchanged from one flight to the next, it was further decided that a single instrument indication could be used as a measure of flight performance provided: a) the subject was unaware of which instrument indication was being monitored, and b) the same type maneuver was executed under the same conditions each time a comparison was made.

Although information from six independent indications was available, it was therefore decided that during constant altitude maneuvers, altitude alone could be used to provide a valid indication of pilot performance. This decision was applied to the experimental test plan as a result of the investigator's workload and time constraints during experimentation. It was recognized, however, that errors in heading, turn rate and course deviations would not be accounted for using this procedure. For this reason, a subjective grade based upon the traditional approach to pilot performance guiding was assigned by the researcher, a certified flight instructor having over 1000 hours of flying experience. The subjective grade, initially 100 percent and diminished by ten percent for any gross error which might endanger the safety of the flight during actual instrument flight conditions, was later factored into the total flight performance grade along with the quantifiable elements.

It was further determined that differences in individual pilot techniques and attitudes fostered by the non-uniformity of instructional programs throughout the aviation community rendered pilot performance grades, based only upon deviations from absolute flight path limits, inadequate. The very nature of certain types of flying creates biases in pilot attitudes related to deviations from an assigned altitude. On a bombing pass or instrument cross-country flight at minimum obstruction clearance altitude, it is safer to fly above an assigned altitude than below it. Conversely, on instrument approaches some pilots capable of excellent altitude control have developed the habit pattern of flying slightly below minimum authorized altitudes hoping to complete an approach which might otherwise be missed. Likewise, formation flying requires that gentle corrections be made for altitude deviations thus inducing greater oscillations about the desired flight path than for a single aircraft on a precision approach under poor meteorological conditions.

For these reasons, it was decided that the most objective indication of pilot performance should be determined from a criterion function based upon each quantifiable element and the subjective flight performance grade. The function was designed with normalized variables and weightings to produce a score of 100 percent with perfect flight path tracking and no gross safety errors. A summary of the weightings and normalizing techniques shown in Table 1 indicates the heavy emphasis upon objectiveness in the criterion grading function.

TABLE 1

| QUANTITY | WEIGHTING | NORMALIZING CRITERIA |
|---|---|---|
| Deviation from absolute altitude assigned ($X_1$) | $W_1 = .2$ | 1) On altitude - 100 percent<br>2) Assigned altitude ± 50 ft. - zero percent |
| Scope of Histogram (indicating duration and magnitude of deviations acceptable to pilot) ($X_2$) | $W_2 = .3$ | 1) slope angle of 90° - 100 percent<br>2) slope angle of 0° - 0 percent |
| Altitude bias indicated by difference between mean flight path and assigned altitude ($X_3$) | $W_3 = .3$ | 1) no bias - 100 percent<br>2) bias above assigned altitude 200 ft - zero percent<br>3) bias below assigned altitude 100 ft - zero percent |
| Subjective Grade based upon safety violations ($X_4$) | $W_4 = .2$ | 1) initially set to 100 percent<br>2) ten percent deduction for every unsafe action on the part of the pilot |

*Note that normalizing takes place along a linear scale between the extreme limits indicated here.

PILOT FLIGHT PERFORMANCE GRADE (FPG) = $X_1W_1 + X_2W_2 + X_3W_3 + X_4W_4$

## IN-FLIGHT NEUROLOGICAL DATA COLLECTION

Although a proven system for collecting and recording neurological signals in the form of a two-channel EEG (Electroencephalogram) was already in use at the Naval Academy prior to the inception of this project, the system required significant modification to make it acceptable for use in the cockpit environment.

It was desirable from the standpoint of both safety and practicality to power the system from an independent source. As only a few millivolts of potential are required to do significant damage to brain tissue, without the knowledge of either the subject or the investigator, it was decided that an independent D.C. power supply would reduce the risk of the pilot inadvertently becoming part of an electrical circuit grounding the power supply. The independent power supply was also desirable for the airborne study of neurological phenomena because of the unavailability of a suitable power supply for previously used systems in most light aircraft. An independent battery supply system for the Grass EEG amplifiers using rechargable Nickel-cadmium batteries was designed and built by the Grass Corporation.

Because of the inherently high levels of 60 $H_z$ and 400 $H_z$ "noise" in the GAT-1B flight simulator cockpit, a wire mesh shield had to be designed and built for the electrical leads connecting the electrodes on the pilot's scalp to the EEG amplifiers. The amplifiers themselves were likewise shielded using aluminum foil. The result of this shielding was a 25 dB reduction in 60 $H_z$ noise.

With the exception of these two modifications, the EEG recording system used for this study was essentially the same system used by Trident Scholars Hill (1975) and Olson (1974) in their research. Gold-plated electrodes attached with an electrically conductive paste to the subject's scalp at locations O1-C3 and O2-C4 (see figure 4) were connected to two Grass P-511 EEG amplifiers through shielded cables. The outputs of the EEG amplifiers were transmitted by coaxial cables from the flight simulator cockpit to the Vetter C-4 cassette recorder at the researcher's control station. Signals from the left and right hemispheres of the brain were recorded on channels two and four, respectively. With the recorder calibrated for unity gain, neurological signal analysis could be conducted on or off-line using either the SD-360 or the SAI-43A time series analyzers. Two Hewlett Packard model 1201A Dual Trace Oscilloscopes were also an integral part of the control station providing a monitor of raw brain wave and strobe information.

Visual stimulus for producing evoked responses in the brain was provided by a strobe light mounted on the nose of the flight simulator where the flashes were directed toward the pilot's eyes through the translucent covering of the forward windshield. The strobe was triggered by a Grass PS-22 photo stimulator, and the flash rate controlled by a Spectral Dynamics model SD-104 sweep generator located at the control station. Strobe flashes were monitored from an output of the PS-22 and recorded simultaneously with the subject's brain waves in channel three of the Vetter recorder.

In addition to neurologically related equipment, the control station also consisted of flight control and performance monitoring equipment.

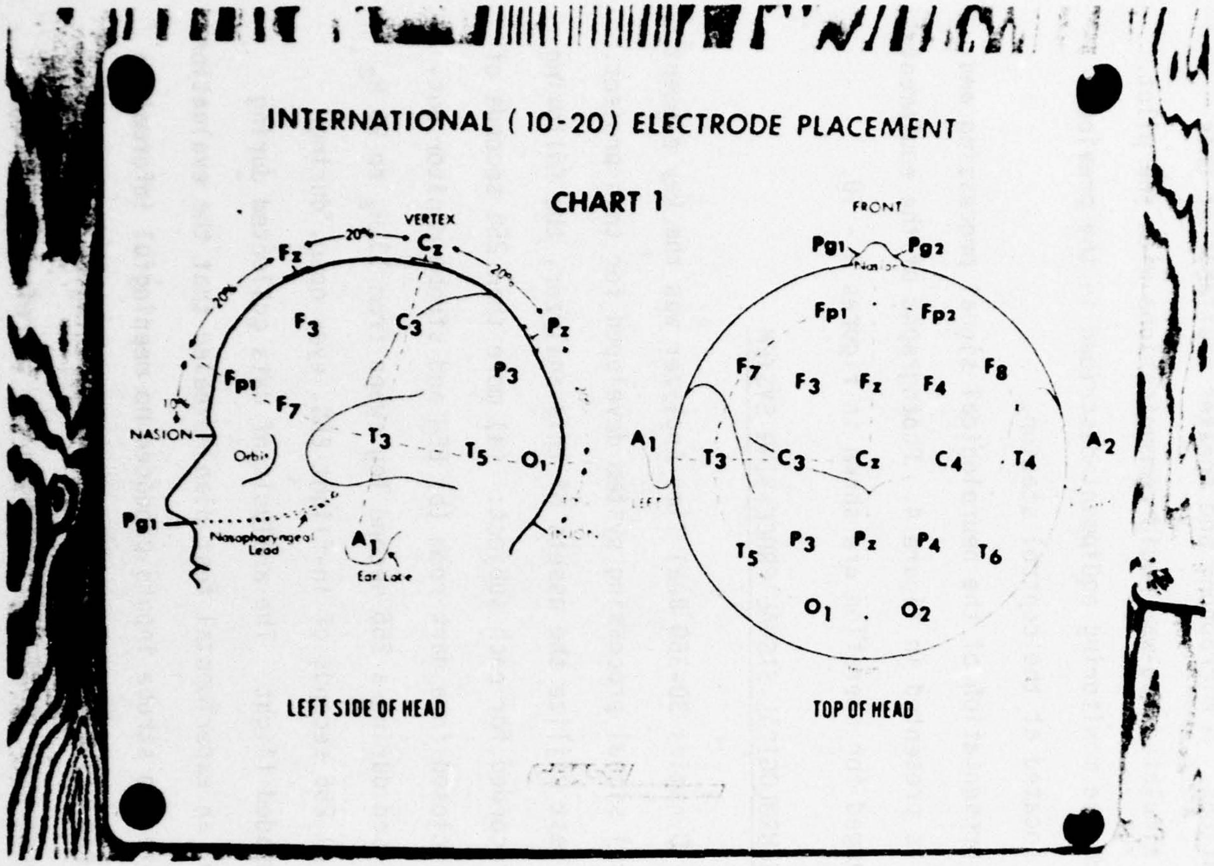


FIGURE 4A - International Electrode Placement System

An X-Y plotter provided horizontal position information similar to that displayed on an air traffic controller's radar screen while a closed-circuit television monitored cockpit activities and displayed flight instrument indications. A microphone and speaker available at this station provided simulated two-way radio communications with the pilot. The flight performance monitoring equipment described in the previous section was also located at the control station.

A graphical presentation of the neurological signal processing and recording system is presented in figure 4. Photographs of the equipment described as arranged for operation are shown in figures 5 - 10.

## NEUROLOGICAL SIGNAL PROCESSING SYSTEM

The Spectral Dynamics *SD-360 Real Time* Analyzer was the key element in the neurological signal processing system developed for this project. In an attempt to best utilize the assets of this analyzer, the following information was recorded for each subject: (a) more than 256 seconds of resting EEG, eyes closed in a dark room (b) EEG and strobe monitor outputs with eyes closed during a 256 second log sweep from 13 $H_Z$ to 26 $H_Z$ (1 octave), and (c) 256 seconds of in-flight EEG, eyes open, during each segment of graded flight. The analysis of data collected during the development of an experimental test plan revealed that the evaluation of functions related to strobe inputs produced no meaningful information when the subject had his eyes open and was concentrating on a task other than watching the strobe. In-flight strobing was therefore eliminated from the neurological data recorded.

## NEUROLOGICAL SIGNAL PROCESSING SYSTEM

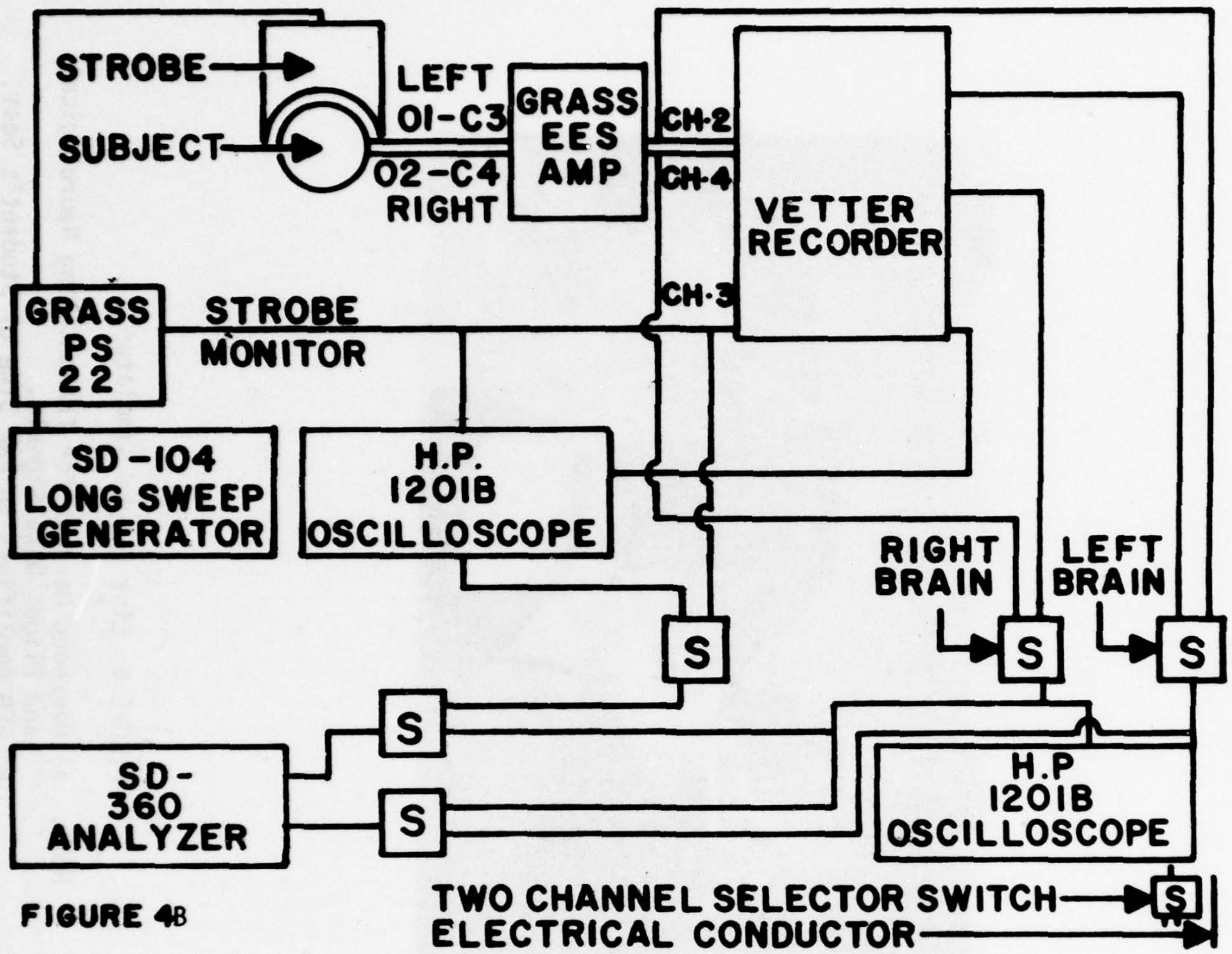


FIGURE 4B

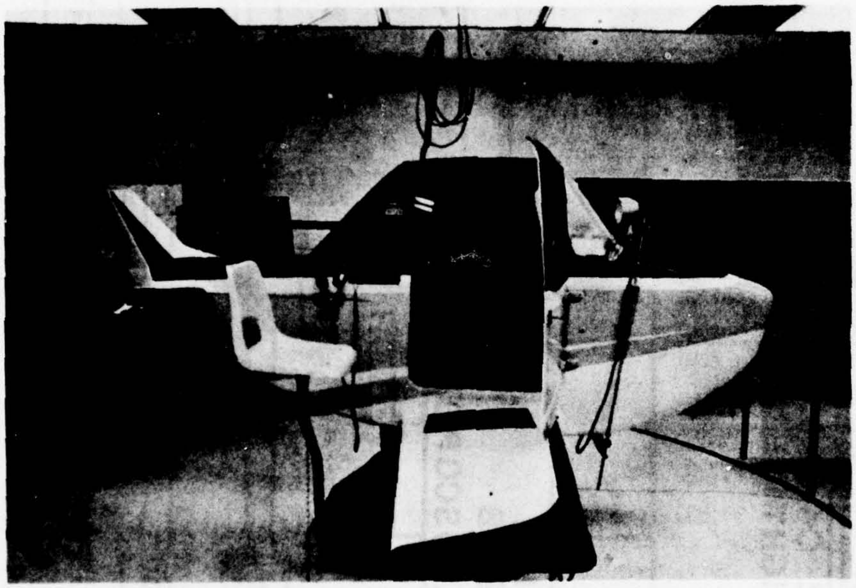


FIGURE 5 Link Flight Simulator

NOTE: a) Overhead Harness for Transmitting Neurological and Flight Data Signals,
b) EEG Amplifiers on Far Side of Student's Seat,
c) Strobe Light Mount on Nose of Aircraft.

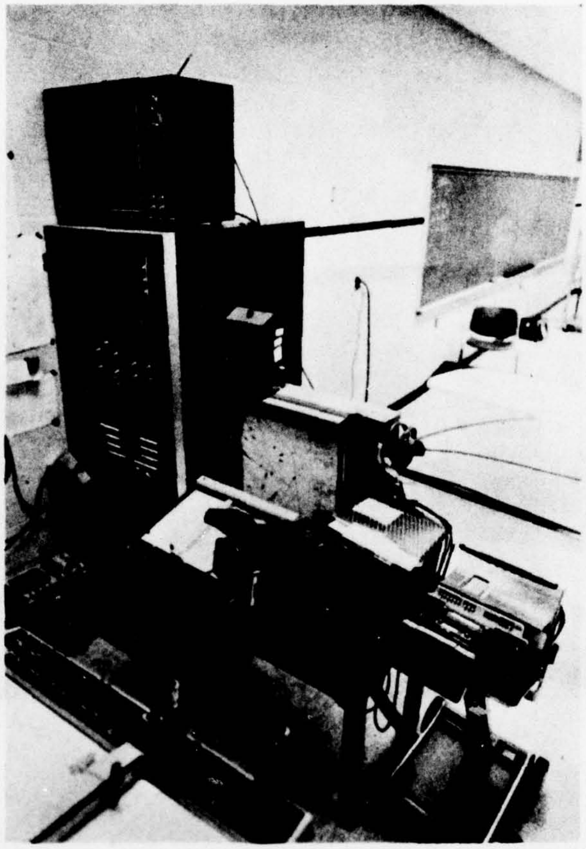


FIGURE 6 - Right Side of Control Station

(Left to right and top to bottom) Equipment consists of: a) Remote Television Monitor of Aircraft Instruments located atop of the b) SD-360 Analyzer, c) A vertically Mounted Flight Path Recorder with Associated Instructor to Pilot Communications Equipment, d) A X-Y Plotter for Producing Hard Copy Real Time Analyzer (RTA) Information, and e) Oscilloscopes and Associated Cameras for Monitoring RTA and Waterfall Displays.

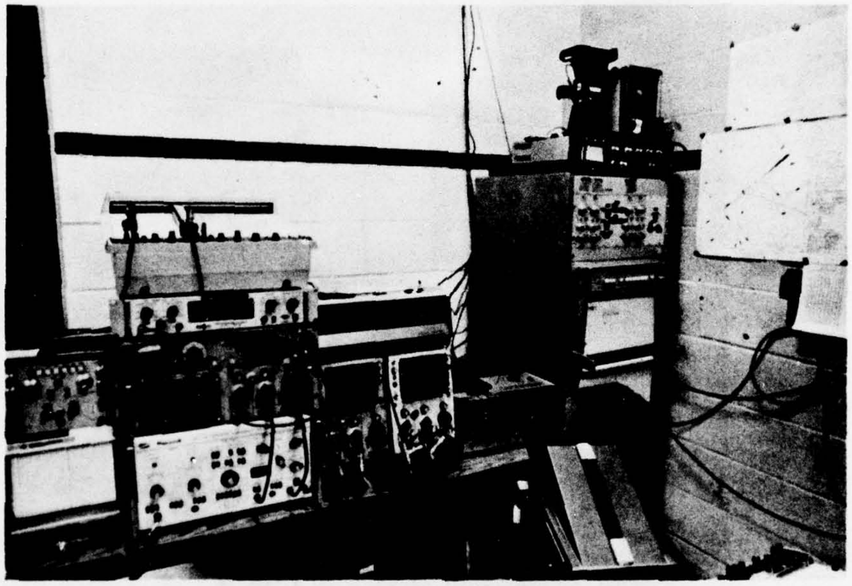


FIGURE 7 - Left Side of Control Station

(Left to right and top to bottom) Equipment consists of: a) Strip-Chart Recorder and X-Y Plotter for Hard Copy Histogram Information, b) Strobe Frequency Counter, c) Low Pass (less than 10K $H_z$) Filters, d) SAI-43 and Oscilloscope Monitor, e) Flight Data Recorder, f) Strobe and Neurological Signal Oscilloscope Monitors, g) Neurological Signal Recorder, h) Log-Sweep Generator (Strobe) and Amplifier, and i) Time Domain Flight Data Monitor (Gould Strip Chart Recorder).

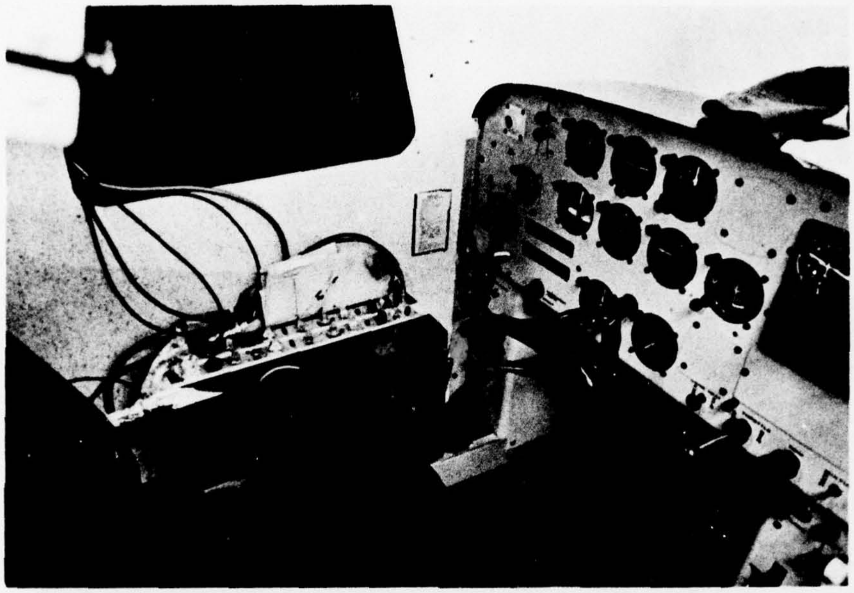


FIGURE 8 - Pilot Station Inside Simulator

(Note EEG Amplifiers to left of seat)

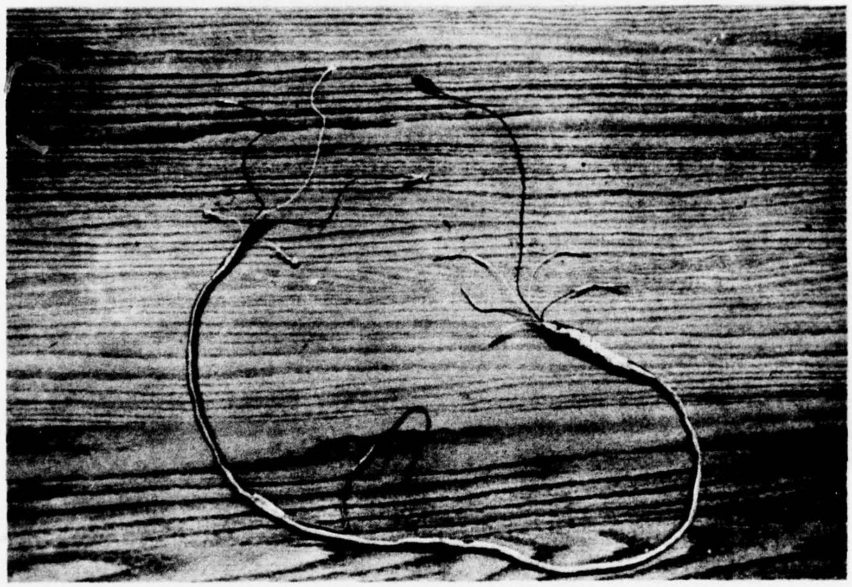


FIGURE 9 - Shielded Electrode Harness

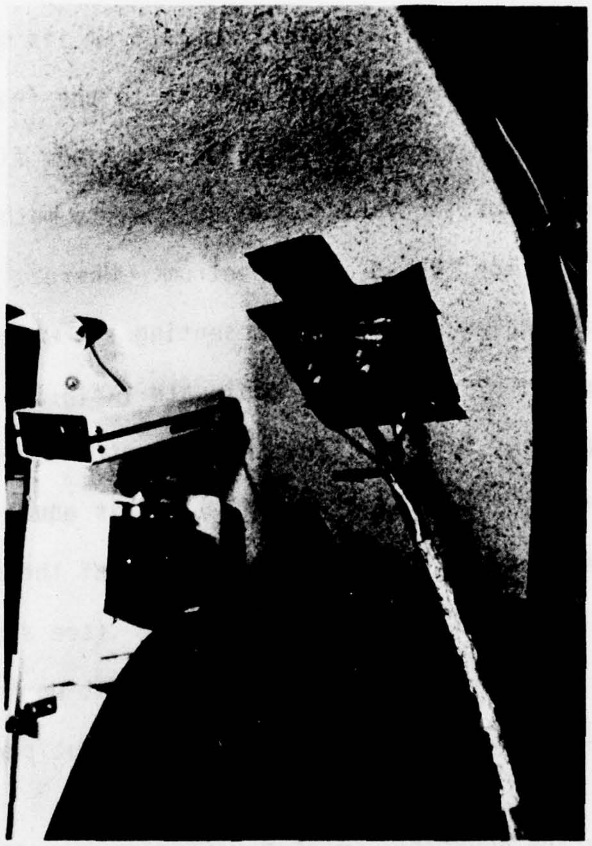


FIGURE 10 - Remote Television Monitor and Electrode Attachment Points Behind Pilot's Seat

The techniques used in analyzing the neurological signals collected during this project entailed the use of five functions available with the SD-360: (1) the auto spectrum, (2) the cross spectrum, (3) the cross correlation function, (4) the coherence function, and (5) the waterfall display of auto spectrum. The auto spectrum of a wave form ($G_{xx}$) is simply the magnitude squared of the forward Fourier transform of a wave form (see figure 11). It takes a signal composed of its many Fourier components in the time domain and transforms it to the frequency domain. (For a geometrical interpretation of auto spectrum, see figure 12.)

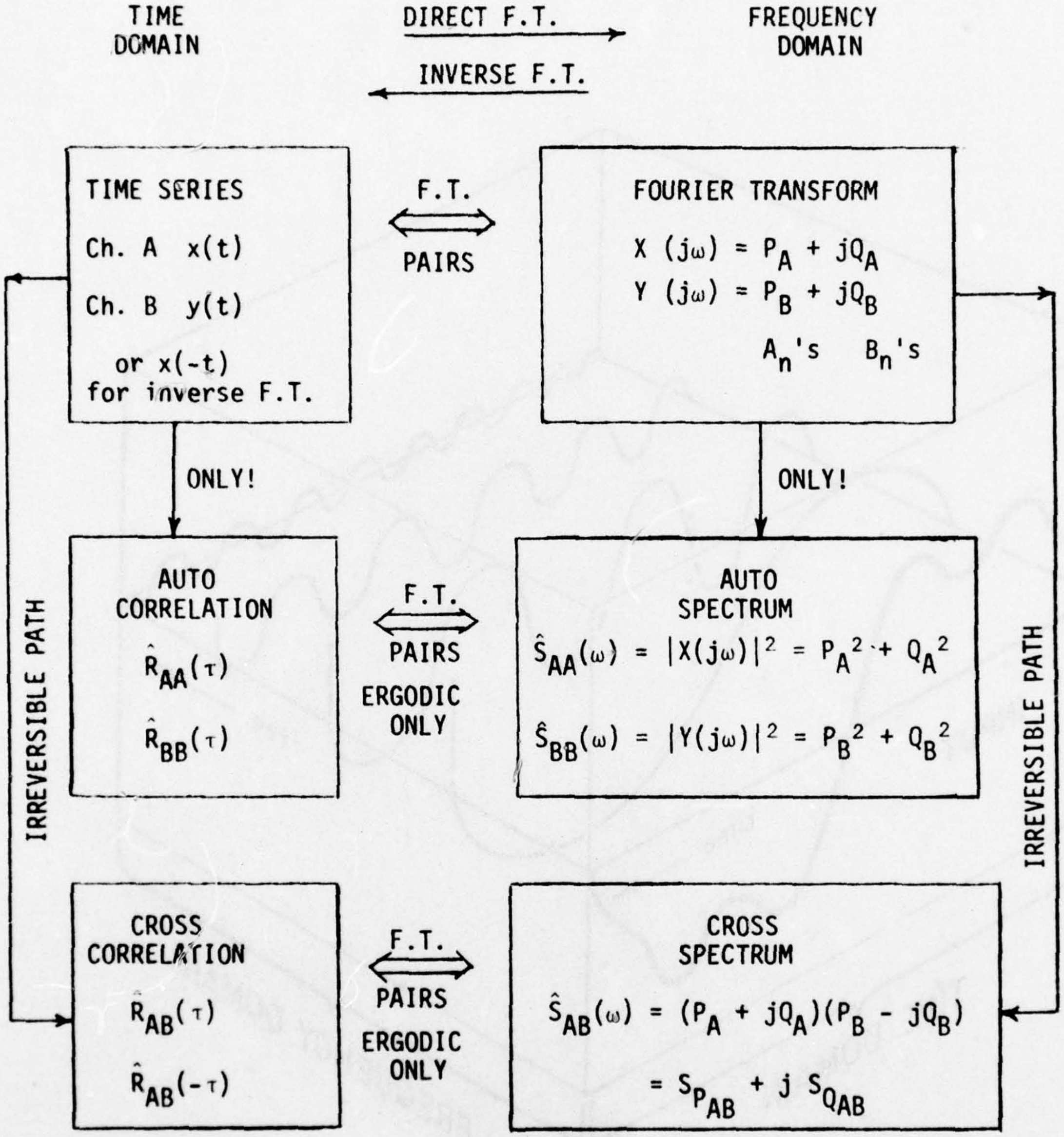
The cross spectrum of two wave forms is simply a mathematically more sophisticated version of the auto spectrum. Whereas in computing the auto spectrum a complex quantity representing the wave form ($X(j\omega) = P_A + jQ_A$) is multiplied by its complex conjugate ($X^*(j\omega) = P_A - jQ_A$) to produce the auto spectrum function, the cross spectrum involves two wave forms ($X(j\omega) = P_A + jQ_A$ and $Y(j\omega) = P_B + jQ_B$) and is equal to the product of one wave form and the complex conjugate of the second ($X(j\omega) \bullet Y^*(j\omega) = G_{AB}(\omega) = (P_A + jQ_A)(P_B - jQ_B)$). (see also figure 11).

The coherence function attempts to identify that portion of measured cross spectrum related to the measured input and output power spectra.

Represented by the equation $\gamma_{xy}{}^2 = \dfrac{|G_{yx}(j\omega)|^2}{G_{xx}(\omega)\ G_{yy}(\omega)}$, the function

can be seen by definition $\dfrac{|G_{yx}(j\omega)|^2}{G_{xx}(\omega)\ G_{yy}(\omega)} = \dfrac{|(P_A + jQ_A)(P_B - jQ_B)|}{[(P_A + jQ_A)(P_A - jQ_A)]} \times$

$\dfrac{|(P_A - jQ_A)(P_B + jQ_B)|}{[(P_B + jQ_B)(P_B - jQ_B)]}$ to equal unity for each data sample. By independ-



COHERENCE

$$\gamma^2 = \frac{\left|\overline{S_{AB}(\omega)}\right|^2}{\overline{S_{AA}}\ \overline{S_{BB}}}$$

WHERE:

Co-spectrum $S_{P_{AB}} = P_A P_B + Q_A Q_B$ (Real)

Quadrature $S_{Q_{AB}} = P_B Q_A - P_A Q_B$ (Imag.)

NOTE: For cross functions, relative phase is conserved but as in auto functions, absolute phase is lost

FIGURE 11

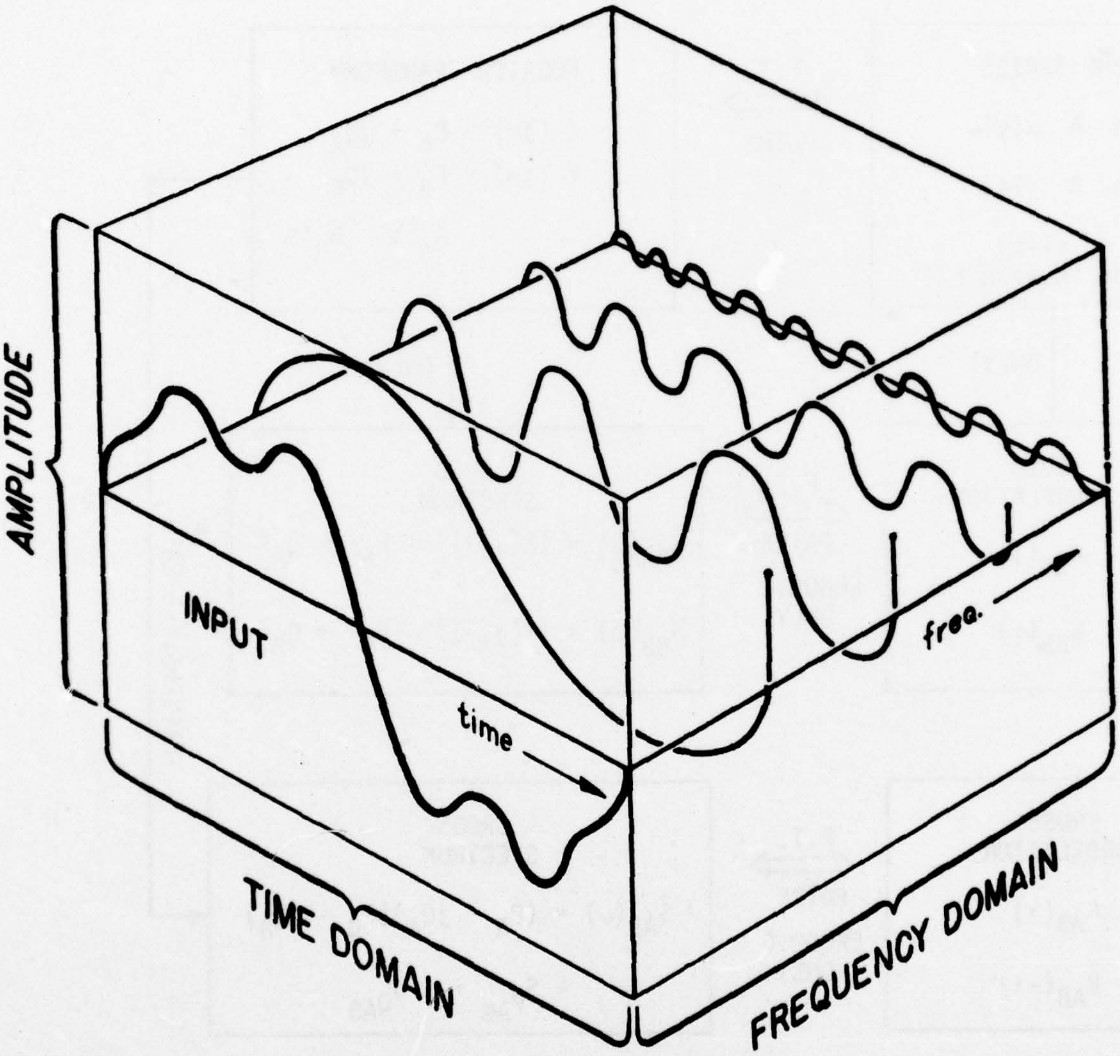


**FIGURE 12 - Time And Frequency Domain**

ently averaging the quantities $G_{xx}(\omega)$, $|G_{yx}(j\omega)|$, and $G_{yy}(\omega)$, the function is also equal to unity where the output and input are related by an amplitude independent linear transfer function. However, values less than unity are obtained where response signals other than those related to the true forcing function are contributing to system output. This is precisely the case in the analysis of the brain as a system where a strobe pulse is the input and the evoked response to that pulse mixed with the subject's normal neurological activity is the output. Systems simulations applying a swept frequency signal as the input and the same signal mixed with noise as the output revealed that the coherence function could be applied in this manner to determine the percentage of output signal produced by the input. (see also figure 11)

The auto correlation function is concerned with the similarity between a wave form and the time shifted version of itself. The value of the function at time zero is obtained by taking a sample of the wave form and its time shifted version at the same instant in time, multiplying the ordinates of the wave forms, and summing the products over the length of the sample. One of the wave forms is held constant to establish a zero time reference while the other is time shifted along the sample interval to produce consecutive values of the function. The resulting auto correlation function represents the relationship between the input wave form and the time shift imparted to the second wave form with each iteration. Because the auto correlation function is computed in this manner, it is obvious that the greatest positive value of the function occurs when the two wave forms are in phase, and the greatest negative value occurs when the wave forms are 180 degrees out of phase. (see figure 13)

The cross correlation function is computed in the same manner as the auto correlation function except that the inputs are different wave forms. The cross correlation is a graph of the similarity of two wave forms as a function of the time shift between them. (see figure 14) By its very nature, it contains only those frequencies common to both wave forms. This function was applied as a neurological signal processing technique during this study to determine the time delay between a flash of the strobe light and the evoked response to the flash in the brain. This time delay for brain waves has been called through-put latency or through-put speed (TPS).

The primary problem in determining through-put latency using the cross correlation function is that the peak value of the function recurs at intervals equal to the period of the reference wave form - the strobe signal. From the cross correlation of an EEG sample with a single frequency strobe input, it is impossible to determine which peak represents the true through-put latency of the brain. By comparing peaks of cross correlation functions of EEG samples at several discrete frequencies for a common peak, however, the through-put latency can be estimated. Although the peaks repeat in each separate correlogram (the cross correlation between a neurological signal and a strobe reference signal) at intervals equal to the period of the strobing frequency, with varying strobe frequencies, and hence varying periods, a common peak will occur in each correlogram at the point equal to the through-put latency. This technique, developed by Midshipman Michael Olson in 1974, is based upon the assumption that the through-put latency is a constant within the frequency range of approximately 11 $H_z$ to 20 $H_z$. The study

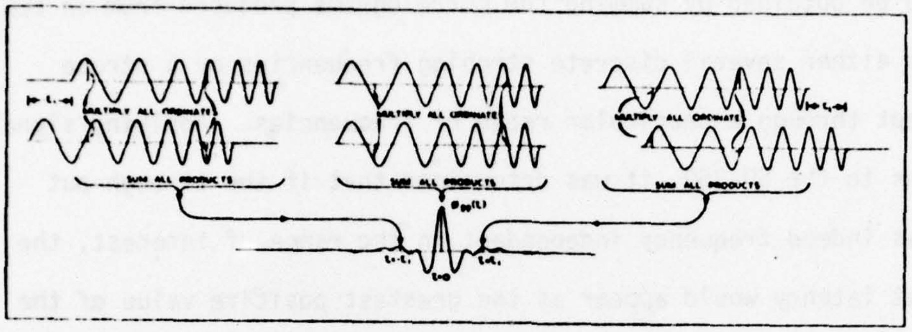
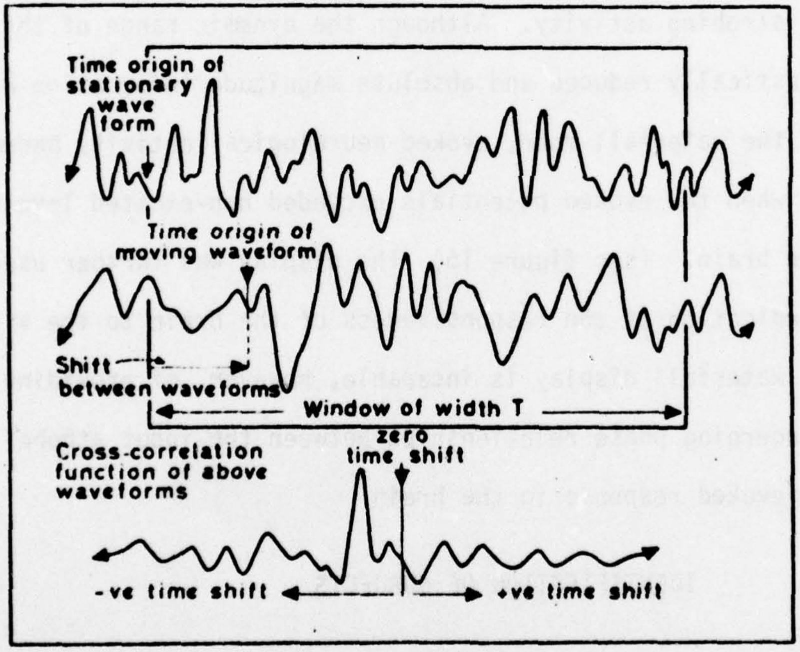


Illustration of the process of constructing the auto-correlation function of a swept-frequency waveform.

FIGURE 13 - The Auto Correlation of a Swept Waveform*



The upper two traces represent the waveforms being cross correlated. The bottom trace is the cross-correlation function; the maximum in it shows that for the indicated value of time shift there is a marked similarity between the waveforms, even though this is barely visible to the eye.

FIGURE 14 - The Cross Correlation of Two Different Waveforms*

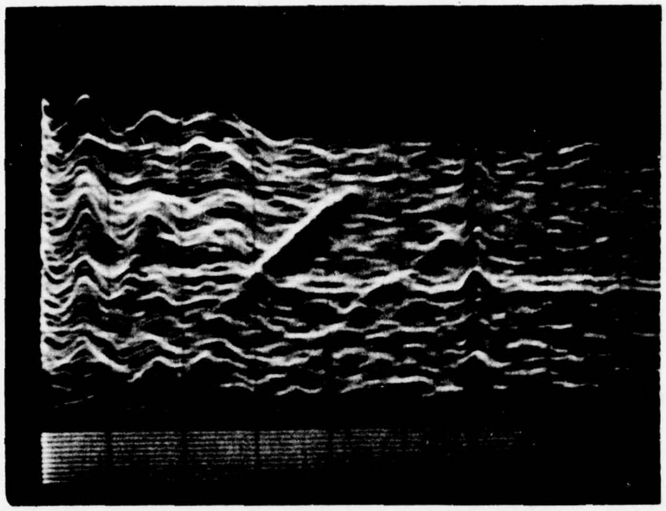
*Ref: N. A. Anstey, "Correlation Techniques - A Review," Journal of the Canadian Society of Exploration Geophysicists, Vol. 2, No. 1, December 1966.

described herein further attempted to determine if the through-put latency could also be obtained by summing the correlograms produced from an EEG signal and either several discrete strobing frequencies or a strobe signal swept through a particular range of frequencies. Applying signal simulations to the SD-360, it was determined that if the through-put latency was indeed frequency independent in the range of interest, the through-put latency would appear at the greatest positive value of the cross correlation function.

The waterfall display capabilities of the SD-360 were developed to present successive four second averages of the auto spectrum during the 256 seconds of strobing activity. Although the dynamic range of the display was drastically reduced and absolute magnitude information was unavailable in the waterfall mode, evoked neurological activity became quite apparent when the evoked potentials exceeded non-excited levels of activity in the brain. (see figure 15) The display was further used as a general indication of the responsiveness of the brain to the visual stimulus. The waterfall display is incapable, however, of providing information concerning phase relationships between the input strobe signal and the evoked response in the brain.

## IDENTIFICATION OF SUBJECTS

At the inception of this project, it was assumed, based upon the investigator's experience as a flight instructor, that a significant degradation in pilot performance could be induced using low-time, private pilots during a simulated instrument flight of approximately one hour in duration. This assumption was considered valid by many other experienced



FATIGUED

NOTE: Magnitude of Mode and 60 $H_z$ Peaks and Subject's Response to Strobe Fundamental and First Two Harmonic Frequencies

RESTED

NOTE: Increase in High Frequency Activity has Buried Mode and 60 $H_z$ Signals and Response to Strobe is Not Apparent

FIGURE 15 - Rested and Fatigued Auto Spectrum: Waterfall Display of Neurological Activity During Log-Sweep of Strobe

(NOTE: Same Subject, Same Scales - 10 $H_z$/Division) aviators and flight instructors as well. Preliminary testing, however, did not produce the levels of degradation (between 10 and 30 percent) desired in this study.

It was further assumed that experienced aviators would be capable of flying longer instrument flights than low-time pilots before equivalent levels of degradation in pilot performance would occur. Although this assumption proved to be valid, the test plan finally adopted was capable of inducing equivalent levels of degraded pilot performance in both experienced and unexperienced aviators.

For the reasons stated here, and because of time and scheduling constraints at the Naval Academy, it was decided that eight civilian pilots from the Brigade of Midshipmen and four fleet aviators from the Naval Academy staff would form the group of subjects used for this study.

## DEVELOPMENT OF THE EXPERIMENTAL TEST PLAN

There is little that can be done to prevent accidents resulting from pilots undertaking tasks above their normal level of flying skills. However, most of the National Transportation Safety Board (NTSB) accident reports citing "pilot fatigue" as a significant factor involved flight operations normally within the pilot's capabilities. It was therefore decided to place the emphasis of this study upon the examination of pilot neurological changes as individual pilot performance degraded.

It was further decided that the difficulty of the problem given to each subject should be varied in order to achieve approximate equality in terms of the mental difficulty of the problem. This was done by changing the stability and performance characteristics of the aircraft used and by varying the types of flight operations required of each subject based upon his level of pilot skills. The difficulty of the problem remained unchanged, however, during each graded portion of the flight.

In order to achieve approximately equal mental problems for each member of the test group, the researcher varied the difficulty of the flying problem in order to force each pilot's rested flight performance grade into the range of 50-95 percent in accordance with the grading system outlined in this chapter. The underlying assumption is that all pilots in an environment where their performance is being monitored by a flight instructor will attempt to maintain established military or FAA standards as appropriate to their background. The assumption has yet to be proven, as the proof involves many complex variables such as age, aviation background, motivation, and current experience. However, the experience of many flight instructors and FAA examiners and the applicability of the Hawthorne effect - i.e., subject performance improves in a testing environment - tend to support the validity of the assumption.

Having decided upon the basic principles and objectives governing the experimental portion of this project, a basic test plan was conceived and modified through several iterations. Although it was originally intended that each subject make a single flight in the simulator of sufficient duration that his performance at the end of the flight was significantly (more than 10 percent) different from the beginning, it was found that the time required to obtain these results was prohibitively long (in excess of 3 hours). Flights at such duration were impractical at the Naval Academy because of scheduling problems. An alternative solution was therefore formulated.

Assuming that a pilot's neurological activity during periods of rested and degraded performance was the key element in determining the relationship between individual pilot performance and neurological functions, it was decided that activities between these two periods of interest was irrelevent to the question at hand. The activities of each subject during this period were noted by the researcher, but by allowing this activity to be somewhat random, chances of similar changes in aviator's neurological activity being related to the interim activity rather than pilot performance were reduced.

It was determined through preliminary investigation that significant degradations in pilot performance could be induced by requiring subjects to remain awake during the period from 6 P.M. until 6 A.M. prior to their being retested. This effect was partly enhanced by the structured nature of Naval Academy life. It was further found that the effect became most pronounced during flights in a simulated night instrument flight environment.

Applying the assumptions and results of preliminary investigation to the original test plan, a final version of the experimental procedure was derived. Subjects were first tested in a rested state during the evening 7-9 P.M. after a day of normal activity and then required to remain awake until they were again tested the following morning at 6 A.M. All testing was conducted in a simulated night instrument flight environment with the stability of the aircraft and the difficulty of the problem the same for both testing periods. The investigator tailored the difficulty of the problem to each subject based upon his knowledge of the subject's aviation background in order to keep the rested flight performance grades at all subjects within the range of 50-95 percent.

## IMPLEMENTATION OF TEST PROCEDURES AND DATA COLLECTION

The testing of subjects using the test plan described previously took place over a three week period. The development of the testing equipment and experimental test procedures had taken six months.

Each subject reported to the flight simulation lab for rested performance testing between 7 P.M. and 9 P.M. after normal daily activities. At this point the objectives of the project were explained and a short pre-flight briefing conducted while the electrodes were being placed upon the subject's scalp. The pilots were told that their performance was determined by the precision with which they followed the desired flight path as indicated by their instruments. The investigator determined the aircraft performance parameters and pilot operations briefed based upon the experience of the aviator being tested, the objective being to establish a rested flight performance grade between 60 and 95 percent.

After the pilot was thoroughly briefed, he was placed in the simulator, the electrodes were connected to the EEG recording system, and the room lights were turned out. After allowing the subject approximately three minutes to become settled in his new environment, the researcher recorded 256 seconds of resting EEG data with the subject's eyes closed and 256 seconds of EEG data while the subject was being flashed with the strobe. The strobing took place with the pilot's eyes closed, looking through the eyelids in the direction of the strobe. The frequency of the strobe was logarithmically swept between 13 $H_z$ and 26 $H_z$ (one octave) in order to produce a uniform input power spectrum over the 256 seconds at recorded strobing activity. At the same time the subject's neurological activity was being recorded, the power spectrum of the left and right hemisphere signals were computed, averaged, and recorded in hard copy form using the SD-360.

After the pilot's resting neurological activity was recorded, he opened his eyes, started the aircraft, and began the simulated night instrument flight as briefed. The first twenty to thirty minutes of the flight were ungraded and used to familiarize the aviator with the aircraft and his environment. During the next twenty to thirty minutes, three 256 second samples of pilot performance and neurological activity were averaged and recorded while the pilot performed the activities briefed prior to the flight. The pilot landed the aircraft after the graded portion of the flight, was debriefed in the manner of most supervised flights, and the electrodes were removed from the scalp.

After the first testing period, the subject was required to remain awake through the night until he was again tested using the same procedures as for the rested flight at approximately 6 A.M. the following morning. The fatigued testing procedure was identical to the rested procedure with the exception that in performing the pre-briefed flight operations a right turn might be substituted for a left turn or a climb for a descent. Personal bias was removed, however, by including equal numbers of right and left turns, and climbs and descents in the graded portion of the flight.

Although allowed to engage in activities of their choice during the period between rested and fatigued testing, most subjects used the time to pursue academic activities such as reading, completing homework, or grading quizzes. The subjects were not allowed to drink alcohol but were allowed to drink coffee or soft drinks. Excessive physical exercise was also discouraged to reduce the effects of physical fatigue upon the subject's neurological activity (see Trident Scholar Report #69, 1974).

## ANALYSIS OF COLLECTED DATA

Using the cassette recordings of each subject's neurological activity and the hard copy records obtained on-line, the following functions were evaluated using the SD-360:

(1) the auto spectrum (power spectrum) from zero to 180 $H_z$ for both left and right hemispheres of the brain, while (a) inactive, eyes closed; and (b) flying the aircraft, eyes open, during each 256 second graded period (see figure 16).

(2) the cross correlation between the strobe signal, log-swept for 256 seconds from 13 $H_z$ to 26 $H_z$ and both the left and right hemispheres of the brain (see figure 17).

(3) the coherence of an evoked response in both hemispheres in the brain triggered by strobe pulses during the 256 second log sweep (see figure 18).

(4) the waterfall display of the subject's left and right auto spectrum during the 256 second strobe log sweep (see also figure 15).

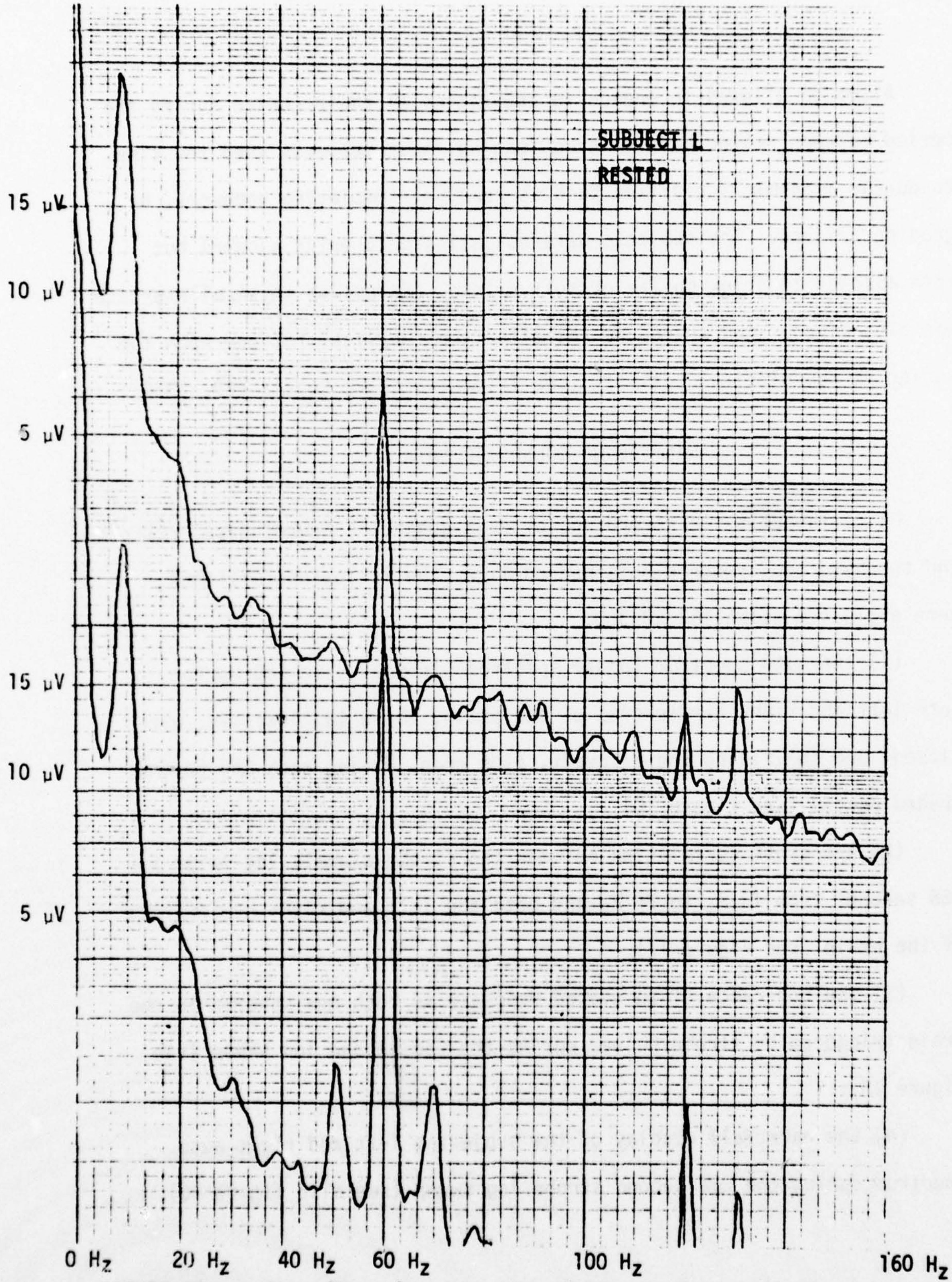


FIGURE 16 - Auto (Power) - Spectrum of Neurological Activity

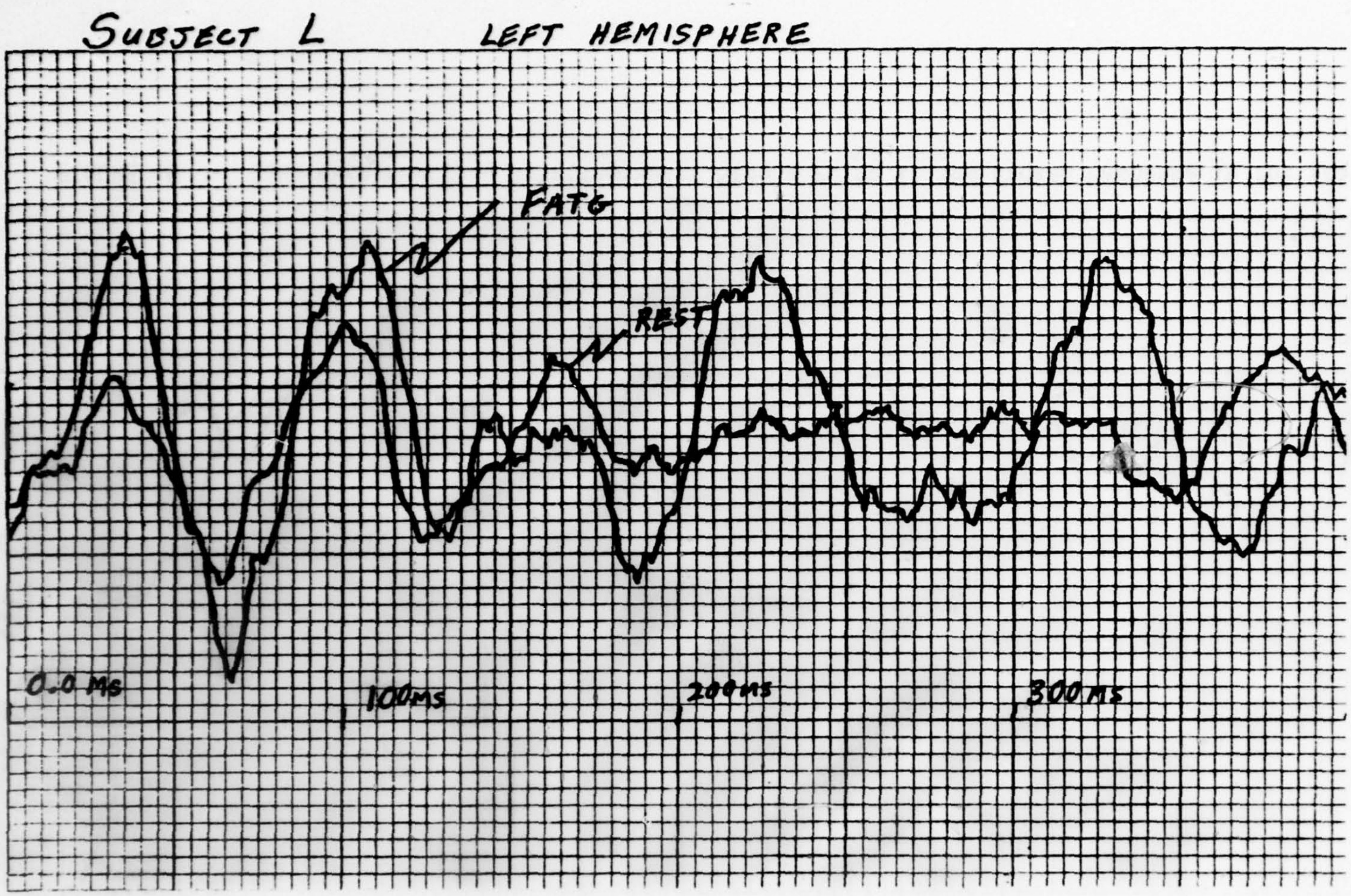


FIGURE 17 - Cross Correlation Between Swept Strobe and Left Hemisphere Brain Wave

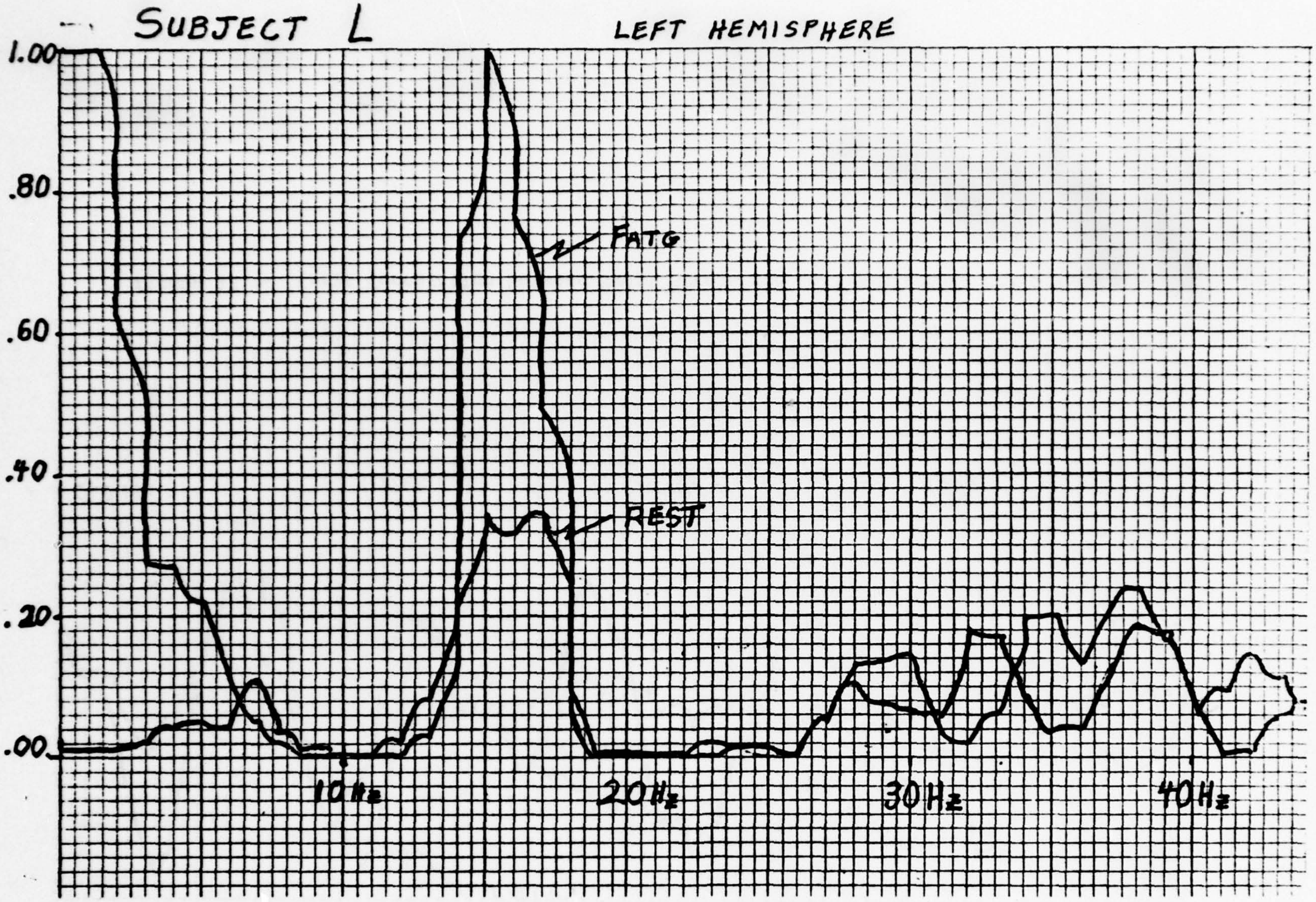


FIGURE 18 - Coherence Function Relating Swept Strobe Pulse to the Evoked Response in the Brain

# CHAPTER IV. RESULTS AND DISCUSSION

## FLIGHT PERFORMANCE ANALYSIS

This study determined that it is possible to quantify various elements of pilot performance using the techniques outlined in Chapter II of this report. Pilot performance data collected during the execution of the experimental test plan further indicated that it was possible to force initial (rested) pilot performance grades into the range from 50 to 95 percent by adjusting the difficulty of the problem for each subject. Fatigued grades however, depended upon the individual's ability to compensate for lack of sleep.

Table 2 tabulates the four elements comprising the overall Flight Performance Grade (FPG) for each subject. Table 3 presents the combined FPG's in addition to the ratio of fatigued to rested grades and the percent difference between the two. Had the investigator had the time to become more familiar with the aviation background and skills of each subject, it is anticipated that initial grades could have been forced into a band less than ten percent in width. Yet the value of this capability would be of questionable utility as no research has been conducted to determine if any correlation exists between the rested FPG and the mental difficulty of a pilot's problem.

It is significant to note that although each subject was deprived of approximately the same amount of rest, the changes in individual pilot performance are not at all similar. This observation tends to support the original premise that arbitrary pilot duty cycle criteria are inadequate to insure safe pilot operations under all circumstances.

TABLE 2 INDIVIDUAL ELEMENTS OF PILOT PERFORMANCE DATA
(In Percentage Scores)

| SUBJECT | REST | | | | FATIGUE | | | |
|---|---|---|---|---|---|---|---|---|
| | ABSOLUTE DEVIATIONS | ALT. BIAS | SLOPE | GROSS ERROR INSTRUCTOR EVALUATION | ABSOLUTE DEVIATIONS | ALT. BIAS. | SLOPE | GROSS ERROR INSTRUCTOR EVALUATION |
| A | 58.7 | 95 | 49 | 100 | 50.3 | 90 | 52 | 100 |
| B | 93.3 | 100 | 79 | 100 | 72.7 | 85 | 81 | 100 |
| C | 42.0 | 90 | 43 | 100 | 29.0 | 40 | 51 | 100 |
| D | 76.3 | 100 | 64 | 100 | 73.3 | 90 | 63 | 70 |
| E | 31.3 | 50 | 51 | 100 | 19.3 | 0 | 54 | 100 |
| F | 84.3 | 100 | 70 | 100 | 25.3 | 100 | 47 | 50 |
| G | 47.3 | 80 | 49 | 100 | 51.0 | 90 | 41 | 100 |
| I | 70.3 | 100 | 63 | 100 | 46.0 | 100 | 54 | 100 |
| J | 47.7 | 100 | 48 | 100 | 24.0 | 100 | 38 | 100 |
| L | 55.3 | 80 | 57 | 100 | 49.0 | 92.5 | 53 | 100 |

TABLE 3 ANALYSIS OF COMPUTED FLIGHT PERFORMANCE GRADES (Rest vs. Fatigue)

| SUBJECT | REST | FATIGUE | FATIGUE/REST | % DIFF. (- Indicates Degradation) |
|---|---|---|---|---|
| A | 70.8 | 67.7 | .96 | - 4. |
| B | 91.7 | 81.6 | .89 | -11. |
| C | 62.5 | 46.0 | .74 | -26. |
| D | 82.1 | 74.9 | .91 | - 9. |
| E | 49.7 | 32.0 | .64 | -36. |
| F | 86.3 | 56.7 | .66 | -34. |
| G | 62.9 | 64.6 | 1.03 | + 3. |
| I | 80.0 | 70.0 | .88 | -12. |
| J | 68.7 | 58.6 | .85 | -15. |
| L | 62.7 | 68.4 | 1.01 | + 1. |

NOTE: 1) Subject K has been eliminated as the investigator underestimated his level of pilot skills and created too easy a problem indicated by his abnormally high (98 percent) FPG's.

2) Subject H has also been eliminated as subject H was the researcher himself and his knowledge of the experiment might possibly have biased the results.

Each individual reacts to a particular set of circumstances in his own unique manner.

The preliminary investigation leading to the development of the final test plan also revealed the significance of the Hawthorne effect in relation to this study. If the pilot in any way perceived that his performance was being monitored by the flight performance analysis system, his performance improved dramatically. Familiarity with the limitations of the system used for this project allowed some pilots to achieve artificially high FPG's by "playing" the simulator "like a pinball machine." Improvements in the test plan removed this advantage, however, by preventing the pilot from knowing which flight instruments and what portions of the flight were being monitored. Pilot briefings prior to test flights gave the impression that performance monitoring was continuous throughout the flight using all instrument indications appropriate to the maneuver in progress. This modification to the test plan appeared to produce more uniform pilot performance throughout the test flight and eliminate the tendency of the subjects to "play the machine." Although there was no way to determine if overall pilot performance improved as a result of the Hawthorne effect, such an improvement should not detract from the validity of the observed pilot performance data provided the pilot's attitude toward the flight test remained the same while rested and fatigued. On the contrary, such an effect would provide a good indication of the pilot's maximum level of performance for his current neurological state.

Another significant effect observed in the development of the pilot performance analysis portion of this project was related to the pilot's learning curve. When presented a relatively new task, most subjects tended to operate on the most vertical portion of the learning curve and performance improved significantly from one flight to the next and even during a single flight in spite of fatigue effects. For this reason, it was necessary to design flights composed of elements familiar to the test subject both in terms of principles and recent experience in order to force pilot operations along the relatively level portions of the learning curve.

It is important to note that each of these observations is strictly limited by both physical constraints and the subjective nature of many of the required assumptions. The small sample size (ten subjects) and the time limitations involved (only two flights of approximately one hour in duration) in this study do not provide enough information to statistically analyze pilot performance according to groups of various experience levels and aviation backgrounds. Nor does the sample necessarily represent a cross section of the aviation community as a whole.

The analysis of altitude data alone further limits the validity of pilot performance data by examining only one of the parameters describing the flight path of an aircraft. The assumption must be made that an aviator's attitude toward altitude control relative to other indications of flight path control remains unchanged for this information to be valid.

Finally, the pilot performance information obtained from this study was limited by the subjective nature of the criterion function used to compute the overall Flight Performance Grade. Non-uniformites in pilot training programs made it necessary to make allowances for differences in pilot attitudes among the subjects tested. Bias and deviation information were included with absolute tolerance data in computing the FPG. Further, because altitude information describes the aircraft flight path in the vertical plane alone, an instructor's subjective evaluation was required to include any gross safety errors made in a horizontal plane or in operational procedures. The criteria function described in Table 1 of Chapter II represents a consensus of attitudes among several experienced military and civilian aviators in applying significance to each element of flight path control. By its nature, the function assigns high grades for safe and precise flight path control and low grades for unsafe and poor control with safety being paramount in both cases. The function further tends to emphasize changes in flight path control to make degraded pilot performance readily apparent. Therefore, in spite of the fact that the criterion function is subjective in nature, it is not without logical and objective basis. However, it must still be considered a limiting factor in determining the validity of the pilot performance data in this study.

## NEUROLOGICAL SIGNAL ANALYSIS AND CORRELATION

Figures 16 - 18 depict actual copies of neurological records analyzed using the Auto spectrum, Cross correlation, and Coherence functions respectively. Various quantities measured from these hard copy records are presented in Table 4.

From resting Auto (power) Spectrum records, the amplitude of the subject's mode frequency was measured in microvolts. The mode frequency

TABLE 4 MODE DATA

| SUBJECT | RIGHT RESTED* | RIGHT FATIGUED* | LEFT RESTED* | LEFT FATIGUED* | RIGHT: FATG/REST | LEFT: FATG/REST |
|---|---|---|---|---|---|---|
| A | 9.5 | 15.1 | 8.2 | 14.0 | 1.59 | 1.71 |
| B | 14.0 | 18.0 | NON-EXISTENT | 15.5 | 1.29 | - |
| C | 33.5 | 45.0 | 30.0 | 40.0 | 1.34 | 1.33 |
| D | 7.8 | 9.0 | 10.5 | 14.0 | .85 | .72 |
| E | 15.0 | 35.0 | 10.0 | 34.0 | 2.33 | 3.40 |
| F | 29.5 | 20.0 | 28.5 | 20.1 | .68 | .71 |
| G | 45.5 | 38.5 | 51.0 | 36.5 | .85 | .72 |
| I | 18.0 | 22.0 | 31.0 | 31.5 | 1.22 | 1.19 |
| J | 48.0 | 36.0 | 28.5 | 20.1 | .75 | 1.02 |
| L | 76.0 | 51.0 | 54.0 | 49.0 | .67 | .91 |

*Units are in microvolts

is a characteristic low-frequency (generally 8 - 13 $H_z$) peak in an individual's neurological power spectrum. The mode is most probably caused by the periodic charging and discharging of brain cells not actually being used for their primary function.[13] As an individual closes his eyes, for example, the average magnitude of the mode builds as cells normally used in the optic sensory system no longer perform that function but continue to exchange electrical charges at the mode frequency. (see figure 15) Little correlation was found between changes in the mode and pilot performance (the correlation coefficient, $r_r$ = .53 and r = .54 for left and right hemispheres respectively). (see figure 19)

The frequency of the mode was also noted, as was an estimate of the average dB (decibel) difference between rested and fatigued spectrum in the range from 60 to 180 $H_z$. (Note that on these spectral plots microvolts can be read from the logarithmic scale and dB from a linear scale.) It was found, however, that the frequency of an individual's mode generally remained unchanged with fatigue and that there existed practically no correlation (r = .264 and r = .009 for left and right hemispheres respectively) between percent changes in pilot performance and dB changes in high frequency neurological activity. (see figures 20 and 21) As the microvolt levels of high frequency activity continued to roll off, there was no means of expressing these changes in absolute terms or ratios.

Analysis of recorded data further revealed that because of some unknown process by which the brain responds to the strobe pulse, the strobing technique failed to consistently produce a single maximum peak in the cross correlation function. Instead, there were generally three large peaks of nearly equal magnitude provided with approximately

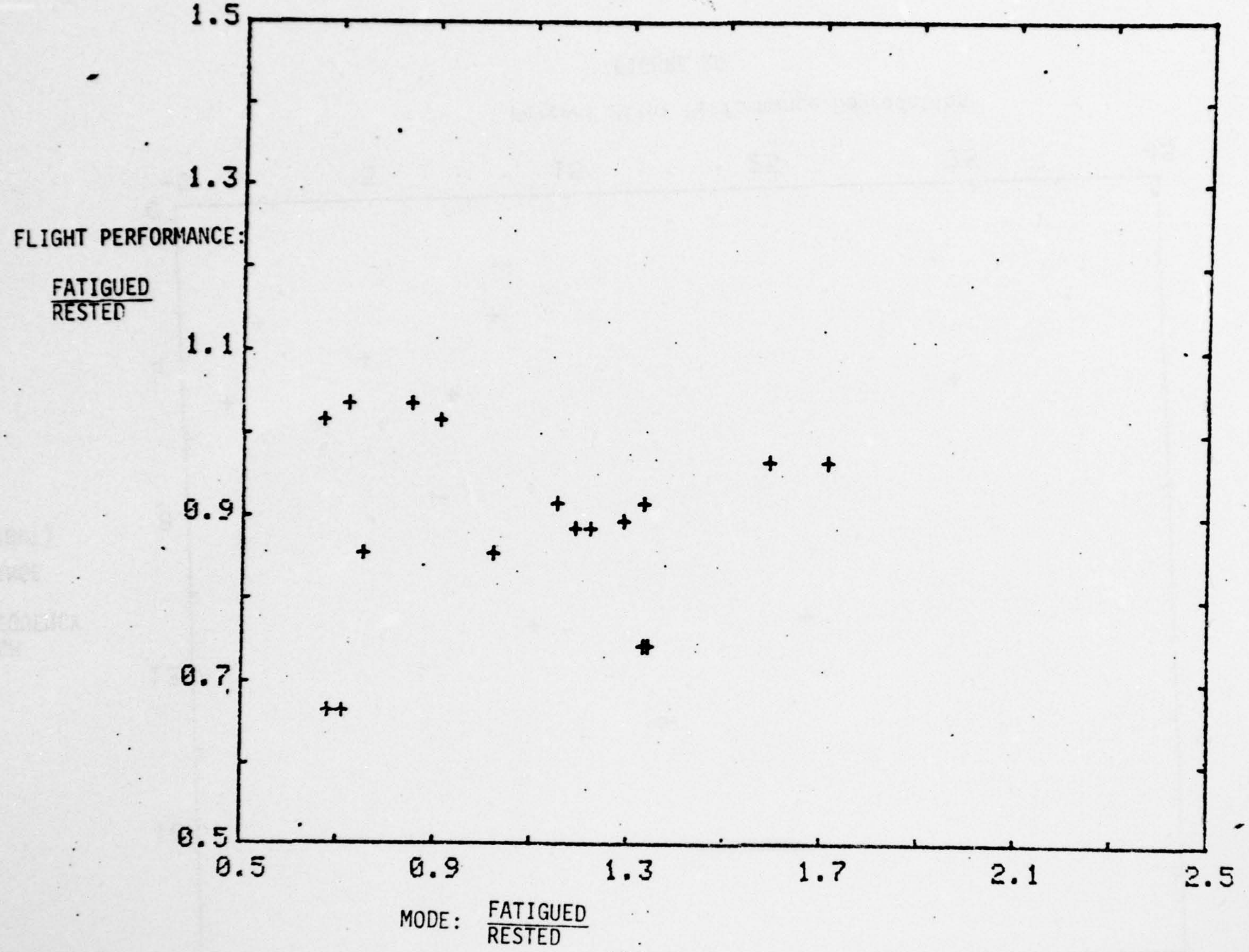

FLIGHT PERFORMANCE:
FATIGUED / RESTED
1.5
1.3
1.1
0.9
0.7
0.5
0.5
0.9
1.3
1.7
2.1
2.5
MODE: FATIGUED / RESTED

FIGURE 19

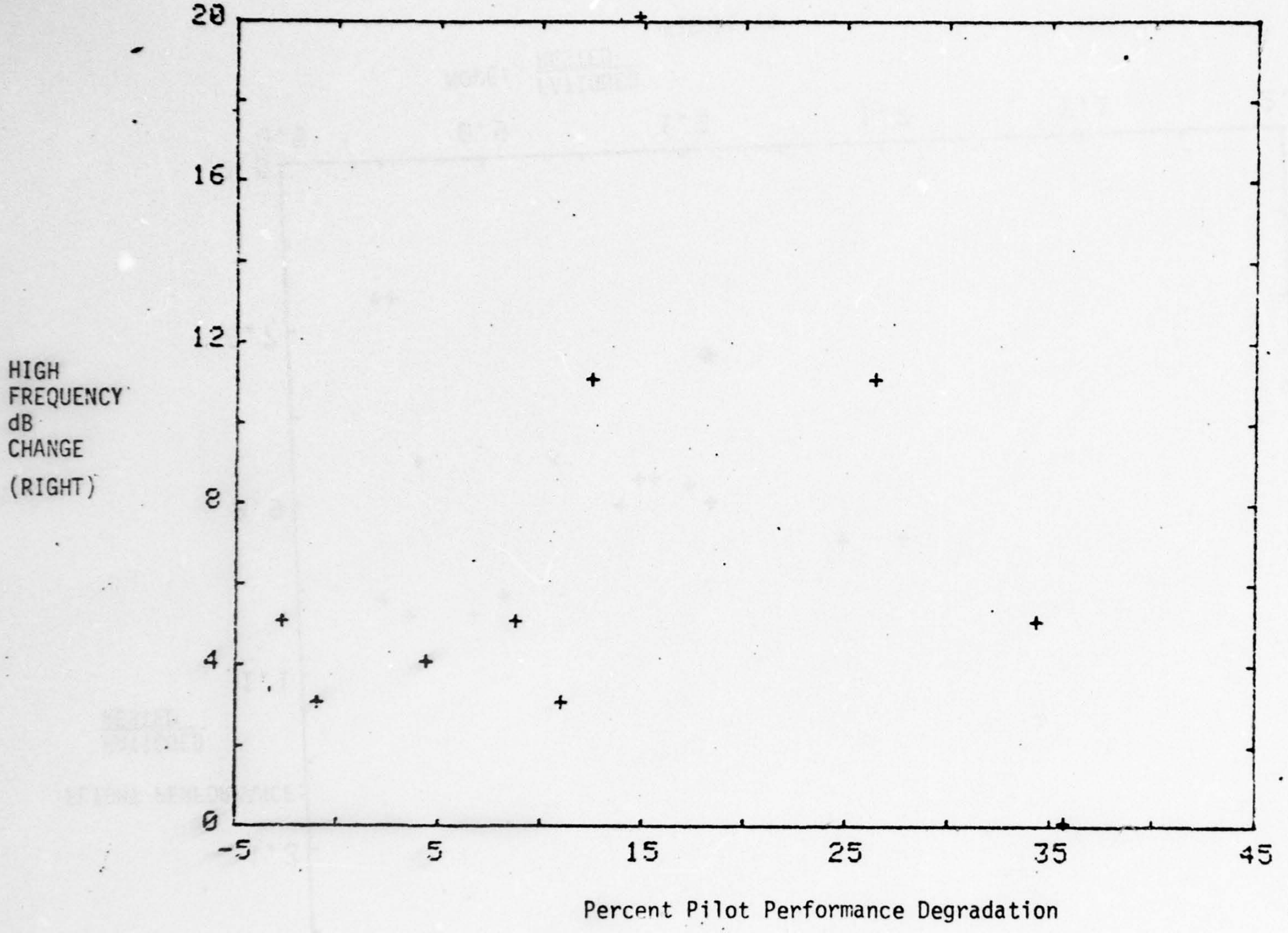

HIGH
FREQUENCY
dB
CHANGE
(RIGHT)
20
16
12
8
4
0
-5
5
15
25
35
45
Percent Pilot Performance Degradation

FIGURE 20

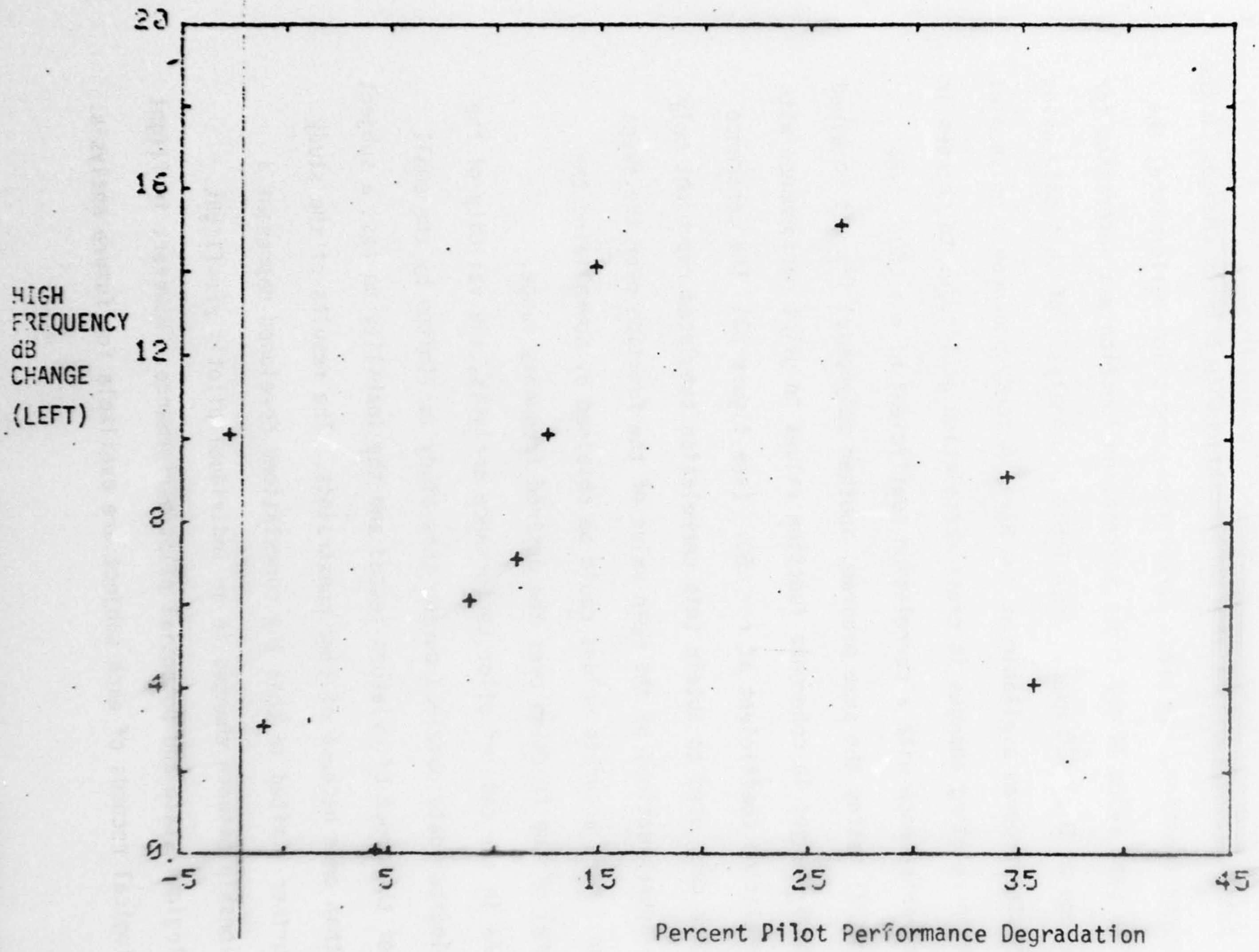

HIGH FREQUENCY dB CHANGE (LEFT)
20
16
12
8
4
0
-5
5
15
25
35
45
Percent Pilot Performance Degradation

FIGURE 21

60 msec. spacing (1/60 msec ≈ 16.5 $H_z$ - the mean frequency in the typical range of greatest coherence function values between peaks). It was therefore impossible to determine conclusively from a single cross correlation, the time delay between a strobe pulse and the corresponding evoked response in the brain.

Anticipating the existence of a relationship between changes in the coherence function, the cross correlation, and pilot performance, the peak to peak value of the cross correlation function was determined for the range of 0 to 400 msec. (see Table 5) Analysis of this data using a computer program available at the Naval Academy produced a polynomial equation relating changes in cross correlation amplitudes to changes in pilot performance with a correlation coefficient of $r = .80$. (see figure 22) Using the same program, another polynomial fit was obtained relating changes in coherence function values to pilot performance with a correlation coefficient at $r = .80$. (see figure 23) The coherence function data used to obtain this correlation tabulated represent only rough approximations of the mean value of the function over the swept region. More accurate values could be obtained by normalizing the integral of the function over the desired frequency range.

As in the case of pilot performance analysis, the validity of the neurological data obtained during this study is limited by the small size of the group of aviators tested and the inability to test a subject more than once because of time constraints. The results of the study are further limited in that the correlations developed represent a relationship between changes in an individual pilot's pre-flight neurological state and potential pilot performance. However, in-flight neurological records of each subject are available for future analysis.

## TABLE 5 CROSS CORRELATION DATA

| SUBJECT | RIGHT RESTED* | RIGHT FATIGUED* | LEFT RESTED | LEFT FATIGUED* | RIGHT: $\frac{\text{FATG}}{\text{REST}}$ | LEFT: $\frac{\text{FATG}}{\text{REST}}$ |
|---|---|---|---|---|---|---|
| A | 1.7 | 2.0 | 2.0 | 1.6 | 1.18 | .8 |
| B | 3.1 | 1.4 | 1.7 | 1.5 | .45 | .88 |
| C | 3.7 | 1.9 | 2.5 | 1.8 | .51 | .72 |
| D | 1.6 | 2.0 | 1.8 | 1.7 | 1.25 | .94 |
| E | 4.2 | 4.8 | 3.8 | 2.8 | 1.14 | .74 |
| F | 1.6 | .7 | 1.8 | 1.0 | .44 | .56 |
| G | 1.0 | 1.1 | .7 | 1.1 | 1.10 | 1.57 |
| I | .04 | 2.0 | 2.5 | 2.2 | .50 | .88 |
| J | 3.1 | 1.5 | 2.6 | 1.7 | .48 | .65 |
| L | 1.6 | 2.8 | 1.6 | 2.6 | 1.75 | 1.63 |

*Relative units of magnitude

## TABLE 6 COHERENCE DATA

| SUBJECT | RIGHT RESTED* | RIGHT FATIGUED* | LEFT RESTED* | LEFT FATIGUED* | RIGHT: FATG/REST | LEFT: FATG/REST |
|---|---|---|---|---|---|---|
| A | .54 | .54 | .70 | .50 | 1.0 | .71 |
| B | .80 | .05 | .50 | .05 | .06 | .1 |
| C | .40 | .10 | .34 | .12 | .25 | .35 |
| D | .35 | .55 | .30 | .55 | 1.57 | 1.83 |
| E | .7 | 1.0 | .7 | 1.0 | 1.43 | 1.43 |
| F | .20 | .01 | .25 | .01 | .05 | .05 |
| G | .07 | .30 | .08 | .25 | 4.29 | 3.13 |
| I | .01 | .20 | .40 | .25 | 20 | .63 |
| J | .20 | .06 | .35 | .08 | .30 | .23 |
| L | .44 | .96 | .35 | 1.0 | 2.18 | 2.86 |

*Normalized magnitudes

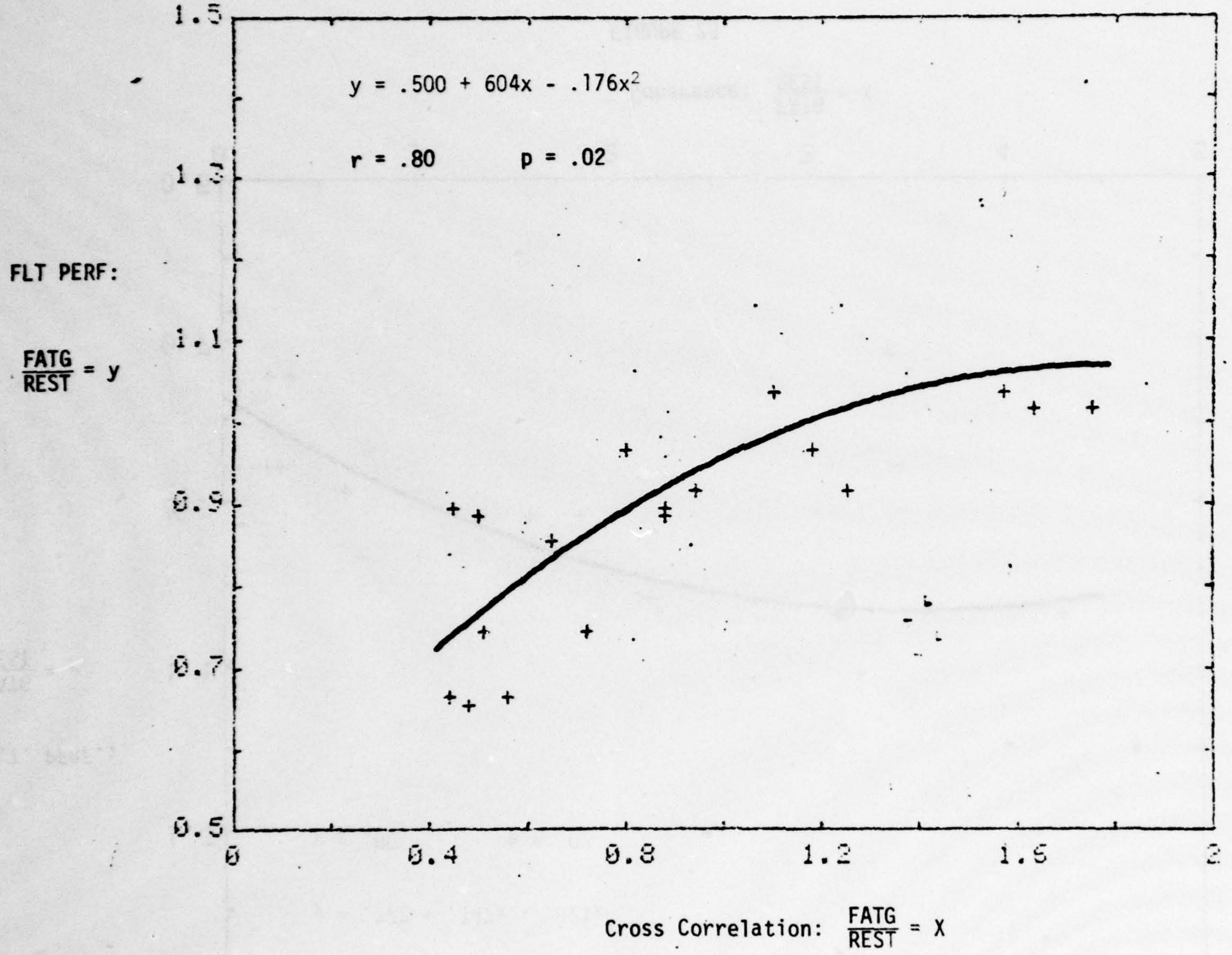

y = .500 + 604x - .176x²
r = .80
p = .02
FLT PERF:
FATG/REST = y
1.5
1.3
1.1
0.9
0.7
0.5
0
0.4
0.8
1.2
1.6
2
Cross Correlation: FATG/REST = X

FIGURE 22

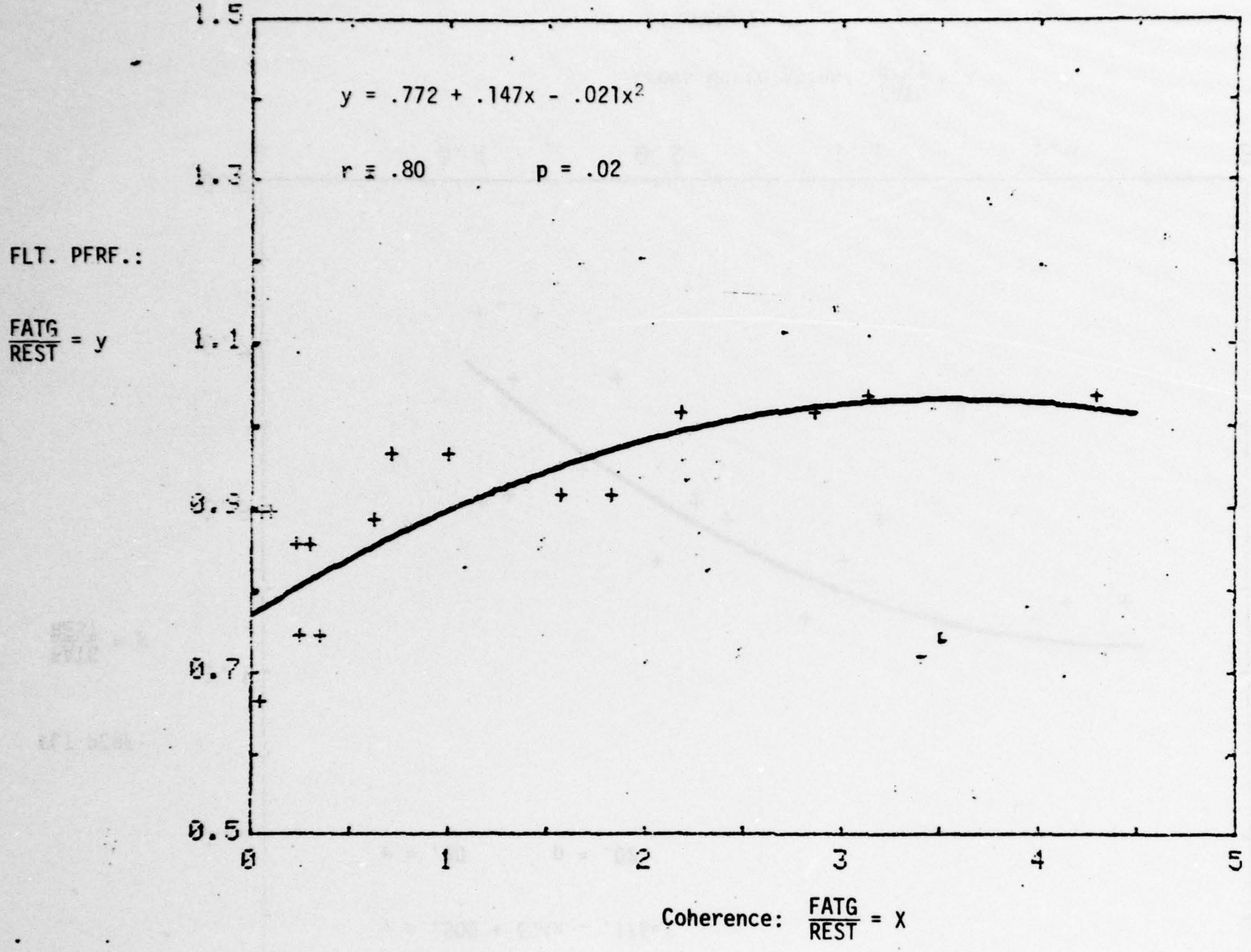

$y = .772 + .147x - .021x^2$
r ≡ .80
p = .02
FLT. PFRF.:
$\frac{FATG}{REST} = y$
1.5
1.3
1.1
0.9
0.7
0.5
0
1
2
3
4
5
Coherence: $\frac{FATG}{REST} = X$

FIGURE 23

The value of the recorded neurological data is also limited by the very nature of the data itself. The decision to use a flashing strobe to evoke responses in the brain during neurological testing was based upon previous research and equipment constraints. The use of the strobe gave meaning to the application of the cross correlation and coherence functions to neurological signal analysis. The frequency range (one octave) was determined by limitations of the coherence function algorithm on the SD-360; while the sweep rate (one octave/256 seconds) was determined by the time required for the SAI-43 to produce a meaningful pilot performance record. The sweep limits (13 - 26 $H_Z$) were based upon coherence function data to include those frequencies at which most individuals appeared to respond best to the strobe stimulus. Optimum techniques for measuring and recording neurological signals have yet to be determined.

# CHAPTER V. CONCLUSIONS

As a result of this study, the following accomplishments were realized:

1) A new and unique system was developed for quantifying pilot performance.

2) A system was developed for monitoring and recording pilot neurological functions in a cockpit environment. The system did not impair the pilot's ability to fly the aircraft and had the capability of being used in both flight simulators and real aircraft.

3) The components of the two systems described above were successfully integrated in order to provide control by a single individual in executing the project test plan.

4) Significant changes in pilot performance and neurological functions were observed as a result of the execution of the experimental test plan. Pilot performance was generally degraded as a result of sleep deprivation holding all other factors as constant as possible. It is therefore logically inferred that the observed degradation in pilot performance were a result of the subject's "mentally fatigued" state.

5) An apparent trend relating changes in a pilot's pre-flight neurological state to changes in his subsquent flight performance was observed and a polynomial fit to the data representing this trend was developed.

6) In accomplishing point number five, the ground work was laid for further investigation into the possibility of predicting pilot performance based on a comparison of the pilot's current neurological state to a

previously recorded baseline and developing neurologically based criteria for pilot duty cycles.

# CHAPTER VI. RECOMMENDATIONS

As a result of observations made during the course of this study, the following recommendations are made as a guide to further research in this area:

## PILOT PERFORMANCE ANALYSIS

1) With respect to the system developed and used for this study, research should be conducted to determine optimum weighting and normalizing criteria to produce the best possible correlation between computed pilot performance grades and actual pilot performance (i.e., how well does the FPG approximate the pilot's ability to track the desired flight path).

2) An automated version of the system used in this project should be developed. The system could utilize preset selector buttons to automatically null correct instrument indications to zero when selected. Such modifications would vastly improve the present system and allow a single operator the capability of monitoring and recording all the parameters appropriate to the flight regime being observed. These modifications, combined with the explanation of the system grading criteria to each subject would make the criteria grading function a purely objective system.

3) A monitoring system having the same capabilities as point 2) of this section should be designed for military and commercial training aircraft. The system should provide the flight instructor/examiner with the capability of recording pilot performance records on cassette tape for post-flight analysis on the ground.

## NEUROLOGICAL SIGNAL PROCESSING

1) Because of the significant changes noted in an individual's neurological functions as a result of sleep deprivation it is recommended that in future investigations, subjects be tested more than once at each desired physiological state to determine the reproducibility of recorded neurological data. Research should be conducted to determine the validity of classifying an individual's neurological characteristics based upon a single "baseline" observation.

2) From neurological data collected using the procedures outlined for this study, the significance of high-frequency coherence (above the swept region of the fundamental strobe frequencies) should be investigated. Particular emphasis should be placed upon examining response at the higher harmonic frequencies of the strobe repetition rate.

3) The significance of the triple peak effect in the cross correlation function between a logarithmically swept strobe and the corresponding neurological activity should be further examined. Signal simulations using a filtered pulse sequence to represent the strobe and the same pulse delayed and buried in random noise to represent the evoked response in the brain produced, as would be expected, a single large peak in the cross correlation function. The location of this peak on the time axis indicates the time delay between stimulus and response. It is hypothesized that the triple peak effect is related to variations in the process that transmitts evoked responses through the brain. The transfer function relating the strobe stimulus to its evoked response in the brain appears to be variable in nature, but further research is necessary to verify this observation.

4) Waterfall displays of auto spectrum on the SD-360 should be examined to determine a) the significance of the display in terms of coherence and cross correlation function measurements and b) the optimum technique for utilizing the display to extract meaningful information.

5) Further investigation should be conducted to determine optimum techniques for recording an individual's neurological activity with primary emphasis placed upon the evaluation of neurological functions.

## FURTHER CORRELATIONS

1) The possibility of relationships between quantifiable elements of a pilot's pre-flight neurological activity not examined in this study, and potential pilot performance should be investigated.

2) In-flight pilot neurological data should be examined to determine the possibility of a correlation between a pilot's performance and neurological activity during the same period.

3) The possibility of grouping aviators according to the effect of various tasks upon neurological functions and pilot performance should be investigated. Such a study would prove useful in providing scientific basis for new pilot duty criteria.

4) Finally, the possibility of determining potential for success among aviation candidates based upon neurological characteristics should be examined.

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4. A-7E 2F 111 Flight Simulator Operator's Manual, and A-7E NCLT Operator's Manual.

5 This information is the result of a search and inquiry for NAVAIR instructions concerning criteria for pilot grading involving the Naval Aviation Training Command units at Pensacola, Florida and the A-7 aircraft Replacement Air Groups in Jacksonville, Florida and Lemoore, California.

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The purpose of this study is to determine whether a meaningful correlation exists between some quantifiable element of a pilot's neurological activity and his performance at the controls of an aircraft.

A new, unique system for quantifying pilot performance was developed using the Singer GAT-1B Link Flight Simulator. A system was also developed for monitoring and recording pilot neurological functions in a cockpit environment.

Significant changes in the pilot performance and neurological
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functions were observed. - An apparent trend was observed also relating changes in pilot performance to changes in a pilot's pre-flight neurological state.

Ground work was laid for further investigation into the possibility of predicting pilot performance based on a comparison of the pilot's current neurological state and developing neurologically based criteria for pilot duty cycles.