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WAKEFULNESS ON THE CIVIL FLIGHT DECK: AN INVESTIGATION OF WRIST ACTIVITY

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WAKEFULNESS ON THE CIVIL FLIGHT DECK: AN INVESTIGATION OF WRIST ACTIVITY

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Executive Summary

This paper reports the second stage of an investigation to identify a practical method of monitoring sleepiness on the civil flight deck. The aim of the work was to recommend the basis of an alerting system to warn pilots of involuntary sleep. Two studies were carried out in three-crew longhaul flights, the first involving flights between London and Miami, and the second between London and Chicago. The subjects in both investigations were twelve British Airways pilots, and they were monitored during outward day and return overnight flights.

The previous study, reported in CAA Paper 95002, examined physiological and physical parameters that were possible indicators of sleep. These were galvanic skin resistance, head and wrist activity and control inputs to the aircraft by the pilot. The presence of sleepiness and sleep were determined objectively from the electrical activity of the brain (electroencephalogram, EEG) and eye activity (electro-oculogram, EOG). In this study, the subjects were allowed to sleep on the flight deck in order to investigate which parameters were sensitive to sleep. The findings were that absence of wrist activity and head movements could identify the occurrence of sleep, and that eye movements were sensitive to both sleep and sleepiness. There is, however, no method currently available to monitor eye movements unobtrusively. Therefore, as a practical approach, a second study was proposed to further investigate the effectiveness of wrist activity to monitor sleep.

In this study, sleep and sleepiness were identified using the EEG and EOG, in a manner identical to that used in the first study. In contrast with the previous instructions, the subjects were requested to attempt to remain awake during the flights, in order to investigate wrist activity under normal flight conditions. This change in instructions to subjects was made because the morphology of sleep when an individual attempts to sleep can differ from when he is asked to remain awake and then falls asleep unintentionally.

The findings indicated that sleep durations of greater than four to five minutes can be identified by detecting wrist inactivity. Sleepiness could not, however, be detected by this method. These observations confirm the findings of the first investigation, in which it was proposed that a cockpit alarm system which detected wrist inactivity would prevent long periods of sleep.

There is concern, however, that an alarm system which allows the pilot to sleep for up to five minutes may result in reduced alertness due to sleep inertia following an abrupt awakening from sleep. There is a lack of definitive information on sleep inertia in the context of short sleeps in operational settings where the subjects are seated rather than lying in bed.

The present study recommends that a prototype alarm system suitable for use in the cockpit is designed based on wrist activity. Optimum ways of sensing and processing wrist activity data should be investigated. The implications in terms of sleep inertia of an alertness alarm that allows sleep to persist for several minutes should also be carefully considered with regard to flight safety.

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1 INTRODUCTION

Sleepiness and reduced alertness and vigilance on the civil flight deck are known to be a cause for concern with regard to flight safety, particularly in the case of longhaul flights. In some instances, aircrew have fallen asleep involuntarily. Many factors combine together to produce fatigue, including irregularity of work and rest, long periods of duty and frequent time-zone transitions. While careful planning of flight schedules and adequate limitation on maximum duty hours for aircrew can minimise these problems, it is difficult to design flight operations where fatigue is completely avoided.

The CAA is therefore considering ways of monitoring alertness on the flight deck, with a view to providing an alarm system to warn aircrew of involuntary sleep. Two separate studies have been carried out to investigate possible methods to detect sleepiness and involuntary sleep, and to provide recommendations on implementing an alarm system. Both studies involved longhaul three-crew operations with each sector lasting approximately 9h. The first involved flights between London and Miami, and the current investigation was between London and Chicago. Each of these operations has a similar lay-over period between outbound and return flights, and aircrew report experiencing fatigue during these operations.

The first study, described in Reference (1), investigated a range of possible parameters that could be used to detect sleep. These were galvanic skin resistance, head and wrist movement and control inputs to the aircraft by the pilot. The presence of sleepiness and sleep were determined objectively from the electrical activity of the brain (electroencephalogram, EEG) and eye activity (the electro-oculogram, EOG). In this study, the subjects were allowed to sleep on the flight deck in order to investigate which parameters were sensitive to sleep.

The investigation indicated that detecting absence of wrist activity and head movements could identify the occurrence of sleep, and that eye movements were sensitive to both sleep and sleepiness. On the other hand, changes in galvanic skin resistance were related more generally to fatigue than to specific instances of sleep. Control inputs to the aircraft by the pilot were separated by long periods of inactivity. They would not, therefore, be a useful method to monitor pilot alertness.

The recommendations proposed two methods for monitoring alertness, the first based on wrist activity and the second on eye movements. A system that detects absence of wrist activity and activates an alarm after a pre-set interval would prevent lengthy periods of sleep. It would not, however, detect sleepiness. An alarm system based on eye movements would, on the other hand, alert the pilot before sleep developed and indicate when sleepiness occurred. However, there is currently no unobtrusive method of monitoring eye movements in a way that could be used on a day-to-day basis in normal operational environments.

The objective of the second study, reported here, was to investigate the efficacy of wrist activity to detect sleep with a view to basing the design of an alarm on this parameter. In contrast with the previous instructions, the subjects were requested to attempt to remain awake during the flights, in order to investigate wrist activity under normal flight conditions. This change in instructions to subjects was made because the morphology of sleep when an individual attempts to sleep can differ from when he is asked to remain awake and then falls asleep unintentionally.

The current paper reports the findings of the second study. The presence of sleep and sleepiness was identified using the EEG and EOG, in a manner identical to that used in the first study. As in the previous study, twelve pilots were investigated on outward day and return overnight flights.

2 METHODOLOGY

2.1 Subjects

The subjects were six Captains between 45 and 54 (mean 48.2) years of age and six First Officers between 31 and 49 (mean 43.0) years of age. All pilots were currently engaged in flying longhaul operations with British Airways. They gave written informed consent to participate following explanation of the purpose and procedures of the study, in accordance with the requirements of the DRA CHS Ethics Committee. The subjects were assured of confidentiality regarding their individual identity. For the purpose of the investigation, subjects were requested not to deliberately attempt to sleep unless it was considered necessary in the interests of health or safety to do so.

2.2 Flights

The study was carried out during six non-stop flights between London and Chicago over the period from February to April 1995, a three-man crew operation covered by Boeing 747-100/200 series aircraft. For the Captain and First Officer, data were recorded from an outbound westward flight during the daytime and the return eastward sector, a predominantly overnight flight. The westward flight departed at 1400h GMT and arrived at 1640h EST (2240h GMT). The return flight departed Chicago at 1800h EST (0000h GMT) and arrived in London at 0845h GMT. The layover period between outward and return sectors was 25.3 hours.

2.3 Procedures

Measurement sensors were attached to each subject before they boarded the aircraft, and were detached immediately after landing. EEG and EOG signals were checked on the flight deck before pre-flight checks were carried out. Data were recorded continuously from each of the subjects from before take-off until after landing, while they carried out their normal pattern of activities as crew members.

Control recordings to assess the physiological state of the subject were carried out on two occasions during each flight, one during the early part of the cruise phase and the second towards the end before descent commenced. Each control period consisted of a recording with eyes open, followed by a recording with eyes closed. Each recording lasted two minutes during which time the subject was requested to remain still and relax. Immediately prior to each control recording, the pilot carried out a subjective assessment of mood by marking a point on each of twelve separate analogue scales, identifying a point which best indicated his mood.

An observer was present on the flight deck at all times to monitor the activities of the subjects and to maintain a written log of events throughout the flight.

A questionnaire was issued to each subject covering wakefulness relating to the outward trip, sleep during the layover period and wakefulness during the return flight. An assessment of sleep quality for the night prior to the trip and during the layover, both main sleep and naps, was requested along with assessments of flight workload and subjective fatigue levels for each flight. Pilots were asked to note any awareness of having slept during the flights, either intentionally or otherwise.

2.4 Measures and sensors

The electroencephalogram (EEG) was recorded from central and left occipital regions of the brain, together with vertical and horizontal electro-oculogram (EOG) and the electro-myogram (EMG) from placements either side of the neck.

Wrist activity was measured using sensors on each wrist. Aircraft motion was recorded by a bi-axial accelerometer mounted in a metal casing and fixed to a shelf on the flight deck. Figure 1 shows a subject with the EEG, EOG and EMG electrodes in position. The left wrist actigraph can also be seen.

The subjects completed subjective assessments of mood[(2)] presented on a hand-held Psion computer. Analogue lines were displayed with a comment relating to various aspects of mood at each end, one end representing 'very bad', the other end 'very good' (Annex A). Subjects used the cursor keys to move a marker to a point on the line which represented their current assessment of the defined mood aspect. The assessments were carried out before take-off, as a baseline level, and immediately prior to each control recording.

The observer monitored general flight deck activities and made written notes of events that might be of relevance to the study including meal times, visitors to the flight deck and periods of turbulence.

2.5 Recording devices

The EEG, EOG and EMG were recorded continuously on a portable 8-channel analogue recorder (Medilog 9200, Oxford Medical Limited) sited adjacent to the seat, and carried when the subject left his seat. Wrist activity was recorded on monoaxial piezo acceleration sensors, the Actigraph Z80-32k V1 activity monitor (Gaehwiler Electronic, Hombrechtikon, Switzerland). The monitors were sensitive to 0.1g acceleration and a built-in band pass filter of 0.25 – 3.0 Hz was applied to the analogue signal. Data were downloaded after each trip, onto an IBM compatible PC via an interface unit. Aircraft turbulence was recorded on a multi-channel ambulatory monitoring system (Vitaport, McRoberts BV) and data were stored on solid state memory cards. Vitaport data were downloaded onto an Apple Macintosh Powerbook after each trip. The Vitaport and Medilog systems were synchronised at the beginning and end of each flight, and at the start and end of each control recording by pressing a marker button simultaneously on each device.

2.6 Analysis

2.6.1 *Signal processing*

All data were analysed by a Hewlett Packard HP720 computer, using a commercially available signal processing package (DATS, Prosig Computer Consultants Limited).

Analogue cassettes containing EEG, EOG and EMG signals were replayed at 60 times real-time using a Medilog 9200 Replay System (Oxford Medical Limited). The signals were digitised at an effective sampling rate of 7680 Hz (equivalent to 128 Hz real-time).

The data were analysed in a manner comparable to the previous study. The EEG, EMG and EOG variables were analysed with a time resolution of 1s. The EEG was described by variables corresponding to frequency ranges known to be related to alertness and sleepiness. The variables delta (δ), theta (θ), alpha (α) and beta (β) were defined as 0.5-3 Hz, 3-7.5 Hz, 7.5-13 Hz, 13-30 Hz respectively. The EOG signal was characterised by absolute activity, defined as the square of the first derivative of signal amplitude with respect to time integrated over 1s. Root mean square (RMS) of EMG amplitude was calculated for 1s epochs and used to indicate artefacts due to body movement.

Wrist activity was sampled at a rate of 8 Hz (125ms) and occurrences of supra-threshold motor activity were integrated over the measuring interval and a single byte value stored for each 30s interval. Durations of periods of movement and periods of no movement were located using level crossing analysis.

2.6.2 *Estimates of alertness at beginning and end of flights*

Estimates of alertness were obtained from the control periods at the start and end of cruise, and during periods of normal flight deck activity ('active recordings') lasting one hour immediately after the first control period and before the second control period of each flight. These estimates were used to indicate the overall alertness of the pilots at various stages of the trip, assuming that the pilots were alert and well-rested at the start of the flights.

Data were analysed by analysis of variance. Values from each control and active recording were compared with the first recording of the outbound flight, the assumption being that the pilots were alert and well-rested at this time.

(a) *Control recordings*. Each of the variables described in paragraph 2.6.1, with the exception of wrist activity, was meaned over the two-minute periods of each of the control recordings. The data recorded with eyes open were analysed separately from data recorded with eyes closed due to the differing characteristics of both EEG and EOG under the two conditions.

(b) *Active recordings.* Data were meaned for the hour to represent the parameters during normal flight operations.

(c) *Subjective assessments.* Subjectively-assessed levels of alertness were analysed relating to start and end of flight. These measures were obtained from the pre- and post-flight questionnaires and are distinct from the Psion tests of subjective assessment of mood.

2.6.3 *Subjective assessment of mood*

A principal components analysis was performed on the subjective assessments of mood, considering data for all subjects, on both outward and return flights and for all three assessment sessions. The first four principal components accounted for 82% of the variance and were deemed sufficient for consideration. The first component represented general level of well-being, and the second component, mental activation. Component 3 was related to calmness and component 4 to physical tension.

An analysis of variance was performed on each of the first four principal components for assessments on each flight, meaned over the twelve subjects.

2.6.4 *Classification of wakefulness and sleep in flight*

For each subject, periods of sleep and sleepiness were identified from the EEG and EOG and subsequently characterised according to a four-point scale of alertness. Levels of alertness were defined using a method based on conventional criteria for the visual analysis of sleep[3]. The data were classified statistically by discriminant analysis using 1s epochs, and the periods identified as sleep or sleepiness were verified visually. The minimum period for classifying alertness levels was 5s to allow for the incidence of short periods of sleepiness seen during the investigation. The four levels of wakefulness and sleep were defined as follows:

0 – alert wakefulness, with no clear evidence of sleepiness. This level is characterised by EEG activity of predominantly alpha and beta frequencies and the presence of saccades and blinks in the EOG.

0.5 – some evidence of sleepiness in both the EEG and EOG, in the form of increased rhythmic EEG alpha activity and slowing of eye movements. These characteristics frequently last only a few seconds, often occur in sequences, and are termed microsleeps when the duration is short. Alternatively, such patterns may appear as the first overt sign in the transition between wakefulness and drowsy sleep.

1 – presence of theta activity in the EEG and slow rolling eye movements. This is analogous to the characteristics of stage 1 sleep according to conventional criteria[3] and represents light, drowsy sleep.

2 – periods of continuous relatively high amplitude theta or delta activity starting either from cessation of slow eye movements or from a K-complex, and lasting until some indication of decreasing depth of sleep, such as an increased frequency of the EEG indicating an arousal or the development of rolling eye movements, saccades or blinks in the EOG. This classification is similar to stage 2 sleep.

The total durations of alertness levels 0.5, 1 and 2 were calculated for all subjects.

2.6.5 *Correlation of wrist activity with wakefulness and sleep*

Periods of inactivity were identified by combining data from both wrists for individual subjects, and then locating periods when both wrists were inactive.

The data from the combined wrist activities were reduced to sequences of 1s (representing movement) and 0s (representing no movement). Then, for each 30s epoch of wrist data, a 'sleep' value was calculated, representing 30s and based on the levels of wakefulness scored for the corresponding thirty 1s epochs of EEG and EOG data. A linear relation between the successive levels of alertness was assumed. Each value of the sleep variable was calculated from the equation

$$\mathrm{SLEEP} = (2 * \mathrm{SS2}) + \mathrm{SS1} + (\mathrm{SS05} / 2)$$

where SS2 was the number of seconds out of 30 classified as level 2, SS1 the number of seconds classified as level 1 and SS05 the number of seconds of 0.5. 'Sleep', therefore, takes a value of 0 when the entire 30s is classified as awake (level 0), and 60 when the thirty epochs are all classified as sleep (level 2).

The variable 'sleep' was calculated for each 30s period of all the recordings, and then converted back into levels of wakefulness according to the ranges given below. As the pilots were requested not to deliberately attempt to sleep unless necessary for safety reasons, the sleepiness profile was biased towards level 0.5 rather than levels 1 and 2, and the ranges selected to represent the levels of wakefulness reflect this.

The ranges of values for sleep applied to each level of alertness were determined as follows:

To be classified as level 0 (awake), 90% of the 30s must be level 0, and the rest (up to 15%) must be level 0 or 0.5, giving sleep values of 0, 0.5, 1 or 1.5. To be level 2, 85% or more of the 30s must be level 2, giving sleep scores of 50 or more. The boundary between levels 0.5 and 1 is harder to define in terms of the 'sleep' score since differing combinations of the wakefulness levels can result in the same score. However a score of 25 was selected based on examination of the distribution of sleep scores.

Level 0 (awake)	$0 \leq \text{sleep} < 2$
Level 0.5	$2 \leq \text{sleep} < 26$
Level 1	$26 \leq \text{sleep} < 50$
Level 2 (sleep)	$50 \leq \text{sleep} \leq 60$

The occurrences of wrist inactivity of given durations were examined in relation to the variable 'sleep', and the values of 'sleep' determined for any given duration of inactivity.

2.6.6 *Investigation of an alertness monitoring system*

This was carried out by investigating the relationship between the durations of wrist inactivity and the occurrences of sleepiness or sleep. Thresholds of inactivity duration were selected, based on the probabilities of being at a particular level of alertness and the distribution of the sleep variable for each level of alertness, and applied to the data of all subjects. Three subjects (3, 6 and 9) are discussed in detail. The first showed no sleep and very little sleepiness. The second displayed sequences of alternating awake and level 0.5 sleepiness for most of the flight, with periods of sleep at level 1 and level 2. The third displayed sustained sleep at level 2 with little level 1 and some sleepiness level 0.5.

The results were examined in terms of success rates in detecting each level of wakefulness above level 0 and in terms of number of false positive alarms.

3 RESULTS

3.1 Sleep and flight times

Figure 2 shows the pre-flight and layover sleeps for all subjects, along with naps and flight times. All subjects except one took a pre-flight nap as well as a local night sleep during the layover period, although two subjects reported poor or disturbed naps. Three subjects commented on being well rested and one subject reported a poor quality of sleep prior to the outward flight. Five subjects had disturbed or broken main sleeps during the layover.

3.2 Estimates of alertness

Tables 1 and 2 show the mean levels for variables during the control and active recordings respectively. Figure 3 shows subjectively assessed alertness.

Overall, alertness was lower for the return flight than for the outward flight, as would be expected. This effect was reflected in EEG beta activity during active recording ($p<0.05$) and in alpha and beta activity in the control recording with eyes closed ($p<0.1$).

3.3 Wakefulness and sleep during flight

The durations of sleep at levels 0.5, 1 and 2 for all subjects are given in table 3 and the individual sleepiness profiles are shown in figure 4.

There was no evidence of sleep or sleepiness in subjects 1, 5, 7 or 12 in either outward or return flight. Subjects 2, 8 and 11 showed no signs of sleepiness or sleep in the outward flight and only sleepiness (level 0.5) rather than actual sleep in the return flight. Of those showing sleep at levels 1 or 2, four were aware of sleeping. Of three subjects displaying level 0.5 sleepiness, one subject was aware of a reduced level of alertness.

Only three subjects had sustained periods of level 2 sleep. All three were aware of sleep at that time and sleep was intentional.

3.4 Subjective assessments of mood

Assessment 1 was performed before the flight, (pre-flight assessment), and was taken as the control against which all other assessments were compared. Assessments 2 and 3, were completed immediately prior to the EEG control recordings. The results are shown in table 4.

General well-being showed effects due to both flight ($p<0.05$) and time of assessment ($p<0.01$), with a decrease in level over the duration of each flight.

Mental activation showed no significant differences between flights but there were effects due to time of assessment ($p<0.05$). There was an increase in level between pre-flight and start of cruise assessments on both flights, and a drop in level between assessments 2 and 3 on the return flight, reflecting increased mental activation following take-off and preparation for approach and landing.

Calmness showed a significant decrease in level ($p<0.01$) at the end of the outward flight, and a decrease ($p<0.01$) at the start of cruise on the return flight.

3.5 Correlation of wrist activity with wakefulness and sleep

The probabilities of being at a particular level of alertness after any given time are shown in table 5. These probabilities are based on a sleep value for 30s epochs derived as described in paragraph 2.6.4.

The sleepiness profiles for subjects 3, 6 and 9 (return flights) are shown in figure 5, along with their respective wrist activity plots. EEG alpha activity for the occipital region of the brain and eye activity is also shown. Sustained periods of wrist inactivity coincided with changes to the alpha rhythm and the occurrence of sleep. During sleep classified as level 2, wrist activity was generally absent but occasionally broken by brief arousals as can be seen in figure 5c, for example, during transitions between levels of sleep 1 and 2. Shorter periods of inactivity which occurred were associated with all other levels of alertness.

The distributions of the variable 'sleep' for each duration of wrist inactivity are shown in figure 6. Durations of inactivity lasting 6 or more minutes were associated with sleep score above level 0 sleep, with the exception of one instance, whereas durations up to 3.5 minutes were often associated with sleep scores of zero relating to wakefulness.

3.6 Investigation of an alertness monitoring system

The distribution of durations of wrist inactivity is shown in table 6a for all data and for various subsets of the data. It can be seen that the majority of durations of inactivity fall into the 30s (0.5 minute) bin, with longer intervals being observed in subjects showing more signs of sleep and sleepiness. The longest intervals of total inactivity coincided with periods of sustained sleep. Table 6b shows the distribution of durations of wrist inactivity coincident with the different levels of wakefulness. Levels 1 and 2 have been merged to represent conventional 'sleep'. As would be expected, the majority of the shortest durations occurred during wakefulness, and the longest durations were associated with sleep. However, there were instances of relatively long durations of inactivity associated with wakefulness. All inactive periods of longer than four minutes occurred during the return flight, and only one 'long' period (six minutes) occurred in a pilot who otherwise showed no signs of sleepiness or sleep.

Investigation of the distributions of sleep scores and inactivity durations led to an initial inactivity duration threshold setting of 4 minutes. This level was tested on subjects 3, 6 and 9, over the entire return flight. A second test was carried out on the same subjects with the inactivity duration threshold set at 3 minutes for comparison of the numbers of correct and incorrect alarms given or missed.

For subject 3, who showed only brief periods of sleepiness, setting the alarm threshold at 4 minutes produced no alarms, but missed a 2 minute period of sleepiness at approximately 1.5h into flight, a 3 min period of level 0.5 with low 'sleep' scores at about 4h 20 min, and a third 2.5 minute period just before 6h. Setting the threshold at 3 minutes activated the alarm at 5h 46 mins into flight which, although corresponding directly with sleep scores of zero, occurred at the end of a period of wrist inactivity which began 1.5 mins after the third sequence of sleepiness at 4h 20 mins and was therefore counted as a correct positive alarm.

For subject 6, with a setting of 4 minutes, seven alarms were triggered, a false positive at 27 minutes into flight, a correct alarm at 2h 53 mins corresponding to a 7 min segment of sleepiness, a correct alarm at 3h 24 mins, at the start of a period of stage 1 sleep, 2 further alarms at 3h 35 mins and 3h 41 mins respectively occurred during sustained level 2 sleep, caused by a short duration wrist movement which reset the alarm counter. The sixth alarm, at 4h 3 mins occurred in the second sustained level 2 sleep, and the final one at 5h 14 mins corresponding to an 8 min segment of data where sleep scores ranged from one 30s epoch at 0.0 to four 30s (i.e. 2 min) epochs at 30.0 (fluctuating between awake and level 1). Other sequences of fluctuating 0 – 0.5 levels were ignored, due to the occurrence of small wrist movements. Setting the threshold at 3 minutes caused earlier detection of the same seven alarm points, but did not occasion any extra alarms. Figure 7 shows the activation of the alarm on a segment of data for this pilot indicating where wrist inactivity sets the alarm function.

In the case of subject 9, a 4 minute threshold led to the triggering of 2 alarms, one at 3h 17 mins into flight, corresponding to a 6 min period of sleepiness, and one at 4h 31 mins, close to the start of sustained level 2 sleep. Reducing the threshold setting to 3 minutes introduced 2 extra alarms, 1 at 1h 35 mins into flight: a false positive, and one at 4h 59 mins, which was a false positive immediately following arousal from a sustained level 2 sleep.

The results of applying the alarm system to all the available data are shown in tables 7a and 7b. Correct positives were defined as periods of wrist inactivity of longer than 4 (3) minutes coinciding with a sequence of alertness levels of 0.5 and above. False positives occurred where periods of inactivity were associated with sequences of alertness levels of which the majority were level 0. False negatives were defined as sequences of alertness levels where the majority were level 0.5 or above, lasting 2 or more minutes which did not result in activation of the alarm. All such sequences of 4 (3) minutes or more were detected as correct positives during the system testing.

4 DISCUSSION

The present study investigates the use of wrist activity to detect sleep and sleepiness. Wrist activity was recorded continuously during day and overnight flights, and the occurrence of sleep was determined using the EEG and EOG, in a manner identical to that carried out in the first investigation[1]. In general terms, the findings reported here confirm those found previously, and indicate that inactivity recorded from wrist-mounted sensors may be used to detect the presence of sleep. Sleepiness is not, however, detected by this method. Furthermore, the duration and extent of loss of alertness that an alarm system based on wrist inactivity would allow is an important consideration that has implications for flight safety.

The amount of sleep seen in this group of pilots was considerably less than that observed in the previous study[1] since the pilots were requested to remain awake if possible. The limited number of sustained sleeps was, therefore, to be expected. The amounts and patterns of sleepiness varied considerably between the subjects, ranging from no signs of sleepiness in four subjects to intermittent sleepiness throughout the majority of the return flight for one subject. Apart from the three subjects with intentional sleeps on the return trip, no significant durations of sleep levels 0.5, 1 or 2 were displayed. The majority of subjects did, however, show some signs of sleepiness during the return flight.

Short lapses in wakefulness, which are indicated by sleep level 0.5 in this study, often lasted only a few seconds. They were followed either by a return to wakefulness, or by the development of sleep, depending on the subject's current level of fatigue, and on other factors such as current activities in the cockpit. Subject 6 in this investigation and one individual in the previous study progressed from lapses in wakefulness (level 0.5) to deeper sleep. Therefore, an alarm system that activates upon the occurrence of sleep may allow several minutes of low alertness in addition to the duration of sleep allowed by the alarm system before it is activated.

While all incidences of sleep and sleepiness are of potential concern to flight safety, an alarm based on simple measurement of activity cannot be expected to accurately detect lapses in wakefulness without resulting in an unacceptable number of false alarms. Sensitivity of an alarm system based on wrist activity therefore needs careful consideration. While maintaining alertness is the prime objective, a high false alarm rate is equally unacceptable.

The characteristics of a system based on wrist activity need to account for the fact that the wrists may both be inactive for periods of time when the subject is fully alert as well as when he is asleep. Therefore, although periods of sleepiness can be as short or shorter than the 30s epoch used in the activity analysis, any system that activates on this duration of inactivity will have a high rate of false alarms. For example, in this group of subjects, there were 735 instances of inactivity which lasted for 30s.

The present set of data was used to test characteristics of an alarm system using inactivity duration thresholds of four and then of three minutes. With a setting of four minutes, all periods of sustained level 1 and 2 sleep were detected. With one subject, the same period of sleep resulted in several alarms when a single epoch containing movement broke the sequence, corresponding to a brief arousal. Had an actual alarm sounded at the first detection point, it is likely that the subject would have roused sufficiently for wrist activity to recommence, thus preventing subsequent alarm activations. The inactivity threshold setting of four minutes resulted in three false positive alarms, all occurring on the return flight in the non-flying pilot, two during the first hour after take-off. In addition, there were a total of eight false negatives, that is, periods of sleepiness or sleep lasting between two and four minutes which were not detected by the alarm. All except one of these occurred on the return flight.

The three minute threshold resulted in earlier activation of the alarm in all cases than a four minute threshold, and also detected all periods of sustained sleep. While there were fewer false negatives, seven in total, the number of false positives, where there was no evidence of sleepiness, was unacceptably high at sixteen. Once again, all of these except one occurred on the return flight.

The occurrence of false alarms during wakefulness on the return flight suggests that reduced wrist activity is related to fatigue. Intervals where alertness levels fluctuated between 0 and 0.5 were often accompanied by periods of alternating wrist activity and inactivity, when the duration of inactivity was insufficient to trigger the alarm mechanism. This may happen when the subject is trying to stay awake and 'fidgets' to facilitate alertness. However, there is no consistent link between sleepiness as determined by the EEG and EOG and wrist activity, and therefore the occurrence of short periods of sleepiness cannot be detected by wrist activity.

The present study indicates that an alerting system based on wrist inactivity is sensitive to periods of level 1 and 2 sleep and some periods of sleepiness that are sustained. In the majority of cases, wrist inactivity lasting longer than 4 minutes was able to identify periods of sleep. There were, however, two instances of longer periods of inactivity, five and six minutes, which were not related to sleepiness or sleep. This agrees in broad terms with the findings of the first study, although in the previous group of subjects there were no durations of inactivity longer than five minutes while they were awake. This slight difference between the results of the two studies may be genuine, since both involved a relatively small group of individuals. Such long intervals may, for instance, be linked to periods of intense concentration. Alternatively, it could be due to the characteristics of the wrist sensors used in each of the studies, where the signal processing techniques, integration interval and frequency response of the devices were slightly different.

An alarm system that activates after approximately five minutes of sleep may allow loss of alertness to persist for too long a period of time. The question of sleep inertia after the pilot is awoken by an alarm after this duration needs to be considered. While there is much information in the scientific literature on sleep inertia, it has not been thoroughly investigated using modern methods to detect reduced alertness and ability to perform skilled tasks. Further, it relates to sleep in bed in contrast with sleep in a seat. The effect on alertness of sleeps lasting, say, between three and five minutes in cockpit seats therefore needs to be established. The effect is likely to depend on circadian factors, the depth of sleep, as well as extent of fatigue of the pilot.

In summary, the present study confirms that an alarm system to be used in the civil cockpit based on detection of wrist inactivity would prevent the occurrence of sustained sleeps lasting in excess of four to five minutes. Lapses of alertness shorter than this period would occur without activating the alarm. Setting a lower threshold would result in an unacceptable incidence of false alarms. As indicated in the previous paper(1), there is clearly a trade-off in using a simple measure such as wrist activity. Short lapses in wakefulness could be detected by more sophisticated methods, such as measurement of eye movements or brain activity. However, these cannot as yet be implemented in a way that is suitable for day-to-day use in the civil cockpit.

5 CONCLUSIONS

Detecting periods of wrist inactivity can be used to identify periods of sustained sleep lasting four to five minutes. The method is, however, insensitive to sleepiness, unless the alarm is set to activate after a short duration. This results in an unacceptably high number of false positive alarms.

Wrist activity is a suitable basis for a cockpit alarm system that prevents long periods of sleep. However, the implications for alertness of awakening a pilot who has been asleep for up to five minutes needs to be assessed. This is likely to have implications for flight safety.

6 RECOMMENDATIONS

1 The characteristics of a wrist-mounted activity sensor and aspects of signal processing should be investigated. It may be possible to improve upon the duration of four to five minutes determined by the two in-flight studies carried out so far.

2 A prototype alarm system, consisting of sensors and signal processing hardware, should be designed for use in the cockpit. This would initially be trialled in the laboratory before being tested in-flight.

3 The implications of an alertness alarm that allows sleep to persist for several minutes should be considered in terms of sleep inertia. This is an important factor with respect to flight safety.

7 ACKNOWLEDGEMENTS

This study was supported by the United Kingdom Civil Aviation Authority

We would like to thank the British Airways Senior Captains and First Officers who took part in the study as volunteer subjects, and the Senior Flight Engineers of the participating crews for their considerable assistance. We would also thank Steven Foster and Sue Mills for carrying out the studies with us, and Brodie Gillibrand for technical support.

8 REFERENCES

(1) Wright NA, Coldwell J, McGown AS, Nicholson AN. Wakefulness on the civil flight deck CAA Paper 95002 April 1995.

(2) Nicholson AN, Stone BM, Borland RG, Spencer MB. Adaptation to irregularity of rest and activity. Aviat Space Environ. Med. 1984;55:102-12.

(3) Rechtschaffen A, Kales A. A manual of standardised terminology, techniques and scoring system for sleep stages of human subjects. Bethesda: United States Department of Health, Education and Welfare, Public Health Service 1968.

Table 1 Variables during control recordings (mean values for 10 Subjects) (Subject 11 using central EEG regions, all others occipital regions)

Variable	Day Flight Start	Day Flight End	Night Flight Start	Night Flight End	Std Error
Eyes Open					
EEG Theta	2.909	7.084	2.424	2.537	2.447
EEG Alpha	3.299	6.058	3.322	2.942	1.729
EEG Beta	4.047	5.457	4.491	3.381	0.866
Eye Activity	42.978	37.051	35.089	39.764	3.274
Eyes Closed					
EEG Theta	3.829	6.531	2.817	2.774	1.201
EEG Alpha	6.551	9.053	5.112	4.284 (+)	1.004
EEG Beta	4.922	6.799	4.585	3.339 (+)	1.060
Eye Activity	35.194	37.335	34.756	30.371	3.182

The recording made at the start of the day flight was taken to be the control measure, and all other recordings were compared to this.

(+ effect slightly short of significance)

Table 2 Variables during 'active' recordings (mean values for 10 subjects)

Variable	*Day Flight*		*Night Flight*		
	Start	*End*	*Start*	*End*	*Std Error*
EEG Theta	5.740	5.925	4.062	5.122	0.396
EEG Alpha	5.590	5.985	5.236	4.913	0.278
EEG Beta	8.492	9.470	8.496	7.414 (*)	0.417
Eye Activity	87.071	114.053	78.377	78.204	11.239
Left Wrist Activity	16.048	17.099	15.607	15.150	1.299
Right Wrist Activity	25.093	23.586	22.608	20.030	1.243

(* p<0.05)

Table 3 Durations of sleep for subjects during day and night-time flights

Subject	*Day Flight*					*Night Flight*				
	Duration of sleep level (min)					*Duration of sleep level (min)*				
	0.5	*1*	*2*	*1+2*	*Total*	*0.5*	*1*	*2*	*1+2*	*Total*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.9
3	0.3	0.0	0.0	0.0	0.3	2.1	1.7	0.0	1.7	3.8
4	0.8	0.3	0.0	0.3	1.1	1.9	1.8	0.0	1.8	3.7
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	5.7	0.3	0.6	0.9	6.6	29.7	14.4	35.2	49.6	79.3
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	6.7	0.8	0.0	0.8	7.5
9	0.0	0.0	0.0	0.0	0.0	5.0	3.4	21.9	25.3	30.3
10	0.0	0.0	0.0	0.0	0.0	14.4	5.2	21.1	26.3	40.7
11	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	3.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4 Subjective assessments of mood – means

	Outward flight			*Return flight*			
	Pre-flight Assessment (Control)	*Assessment at start of cruise*	*Assessment at end of cruise*	*Pre-flight Assessment*	*Assessment at start of cruise*	*Assessment at end of cruise*	*Std. Error*
Well-being	1.222	1.393	0.291	0.633	–1.060 ***	–2.479 ***	0.293
Mental activation	–0.357	0.260	0.238	–1.096 *	0.712 **	0.242	0.173
Calmness	0.429	0.005	–0.417 **	–0.019	–0.265 *	0.265	0.126
Physical tension	0.299	0.339	–0.232	–0.057	–0.067	0.053	0.159

The pre-flight assessment for the outward flight was considered as a control assessment. All other assessments were compared to the control assessment. Scores were meaned over the 12 subjects.

(* P<0.05 ** P<0.01 *** P<0.005)

Table 5 Probabilities of being at a particular level of alertness after a given duration of wrist inactivity

Duration of Inactivity	*Awake level 0*	*Probability of being in* *Drowsy level 0.5*	*Drowsy sleep level 1*	*Sleep level 2*
0 – 1 minute	95.5	4.2	0.1	0.2
1 – 2 minutes	97.5	2.5	0.0	0.0
2 – 3 minutes	86.7	13.3	0.0	0.0
3 – 4 minutes	62.5	37.5	0.0	0.0
4 – 5 minutes	50.0	0.0	0.0	50.0
5 – 6 minutes	33.3	0.0	0.0	66.7
6 – 7 minutes	0.0	0.0	0.0	100.0
7 – 8 minutes	0.0	0.0	0.0	100.0
8 – 9 minutes	0.0	0.0	0.0	100.0
9 – 10 minutes	0.0	0.0	0.0	100.0

Table 6a Distributions of durations of wrist inactivities over different combinations of subjects and flights

Durations of inactivity (min)	*Outward and return flights All data*	*Outward flight All data*	*Outward with sleepiness only*	*Outward with no sleepiness or sleep*	*Return flight All data*	*Return with sleepiness and/or sleep*	*Return with sleepiness only*	*Return with no sleepiness or sleep*
	(24 subj)	*(12 subj)*	*(2 subj)*	*(10 subj)*	*(12 subj)*	*(8 subj)*	*(5 subj)*	*(4 subj)*
0.5	757	374	71	303	383	292	170	91
1.0	195	87	17	70	108	89	53	19
1.5	110	57	11	46	53	45	23	8
2.0	40	13	2	11	27	24	14	3
2.5	13	6	2	4	7	6	4	1
3.0	7	1	0	1	6	4	2	2
3.5	14	5	2	3	9	6	4	3
4.0	6	2	2	0	4	2	1	2
4.5	0	0	0	0	0	0	0	0
5.0	1	0	0	0	1	1	0	0
6.0	2	0	0	0	2	1	0	1
7.0	1	0	0	0	1	1	0	0
8.0	2	0	0	0	2	2	0	0
9.0	1	0	0	0	1	1	0	0
10	1	0	0	0	1	1	0	0
10–15	0	0	0	0	0	0	0	0
15.5–20	2	0	0	0	2	2	0	0
20.5–25	1	0	0	0	1	1	0	0
25.5–30	0	0	0	0	0	0	0	0
30.5 +	0	0	0	0	0	0	0	0

Note. The 5 subjects on the 'return flight with sleepiness only' are also included in the 8 subjects 'Return with sleepiness and/or sleep'.

Sleepiness here refers to actual sleepiness as determined by analysis of the EEG and EOG.

Table 6b Distributions of inactivities over levels of alertness for all data

Duration of inactivity (min)	*Awake level 0*	*Sleepiness level 0.5*	*Sleep levels 1 and 2*
0.5	735	20	2
1.0	181	13	1
1.5	103	7	0
2.0	37	3	0
2.5	11	1	1
3.0	6	1	0
3.5	14	0	0
4.0	4 *	2	0
4.5	0	0	0
5.0	1 *	0	0
6.0	1 *	1	0
7.0	0	0	1
8.0	0	2	0
9.0	0	1	0
10	0	0	1
10–15	0	0	0
15.5–20	0	0	2
20.5–25	0	0	1
25.5–30	0	0	0
30.5 +	0	0	0

Alertness levels were based on 30 second epochs. For 0.5 minute periods of inactivity, the corresponding alertness level was scored. For all other durations, the alertness level was taken to be the level at which the largest percentage of the inactivity duration was spent. Where percentages were equal, the highest level was scored.

* These inactive durations were compared with the original alertness levels determined from the EEG and EOG. Two of the 4.0 minute intervals occurred during the outward flight, the remaining intervals occurred during the return flight. One 4-minute inactivity contained a 15 second sequence of alertness level 0.5. All remaining inactivities occurred wholly during wakefulness.

Table 7a Activations of alarms by the alerting system set at 4 minutes

	Outward flight			*Return flight*		
Pilot	*Correct positives*	*False positives*	*False negatives*	*Correct positives*	*False positives*	*False negatives*
1	0	0	0	0	1	0
2	0	0	0	0	1	0
3	0	0	0	0	0	3
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	1 *	6	1	2
7	0	0	0	0	0	0
8	0	0	0	0	0	1
9	0	0	0	2	0	1
10	0	0	0	1	0	1
11	0	0	0	0	0	0
12	0	0	0	0	0	0

False negatives refer to durations of sleepiness or sleep of between 2 and 4 minutes.

Table 7b Activations of alarms by the alerting system set at 3 minutes

	Outward flight			*Return flight*		
Pilot	*Correct positives*	*False positives*	*False negatives*	*Correct positives*	*False positives*	*False negatives*
1	0	0	0	0	5	0
2	0	0	0	0	2	0
3	0	0	0	1	0	2
4	0	2	0	0	3	0
5	0	0	0	0	2	0
6	0	2	1 *	6	1	2
7	0	1	0	0	0	0
8	0	0	0	0	0	1
9	0	0	0	2	2	1
10	0	0	0	1	1	1
11	0	2	0	0	0	0
12	0	0	0	0	0	0

False negatives all refer to durations of sleepiness or sleep of between 2 and 3 minutes.

Note. All positive detections are based only on wrist inactivity, with no reference to alertness level determined from the EEG and EOG. These levels are used to ascertain whether the positive alarm is genuine, i.e. related to sleepiness or sleep, or false, occurring during wakefulness.

* Refers to sequence of 37 minutes of levels 0 and 0.5, where sub-sequences of 0.5's of up to 17 seconds were split by durations of 0's of between 20 seconds and 9 minutes.

Figure 1 The pilot on the flight deck, showing the EEG, EOG and EMG electrodes in position. The left wrist actigraph is also visible

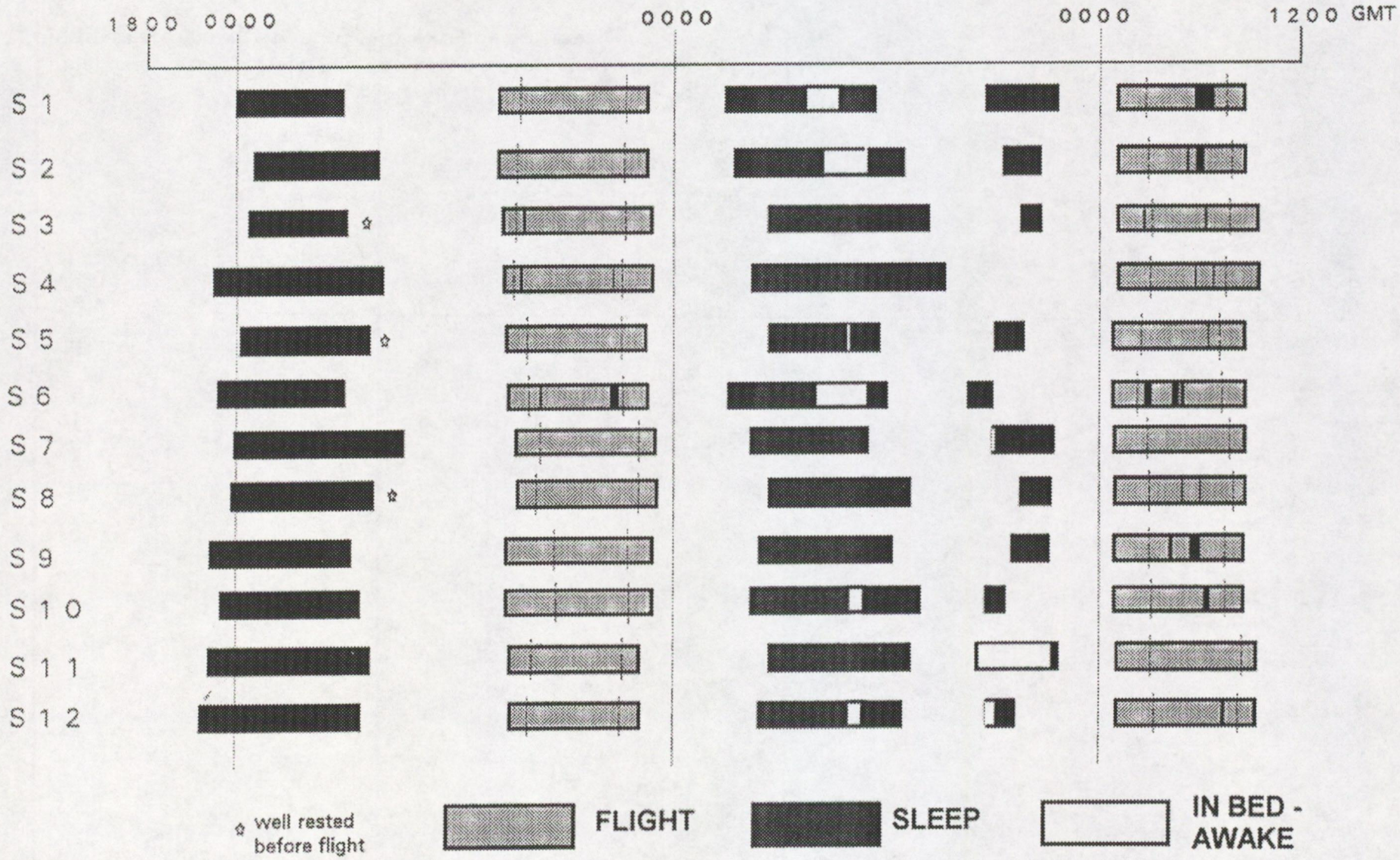


Figure 2 Pre-flight and layover sleeps, naps and flight times. Sleeps and naps are shown in black, intervals of wakefulness during sleeps are shown in white. Fllights are shown in grey

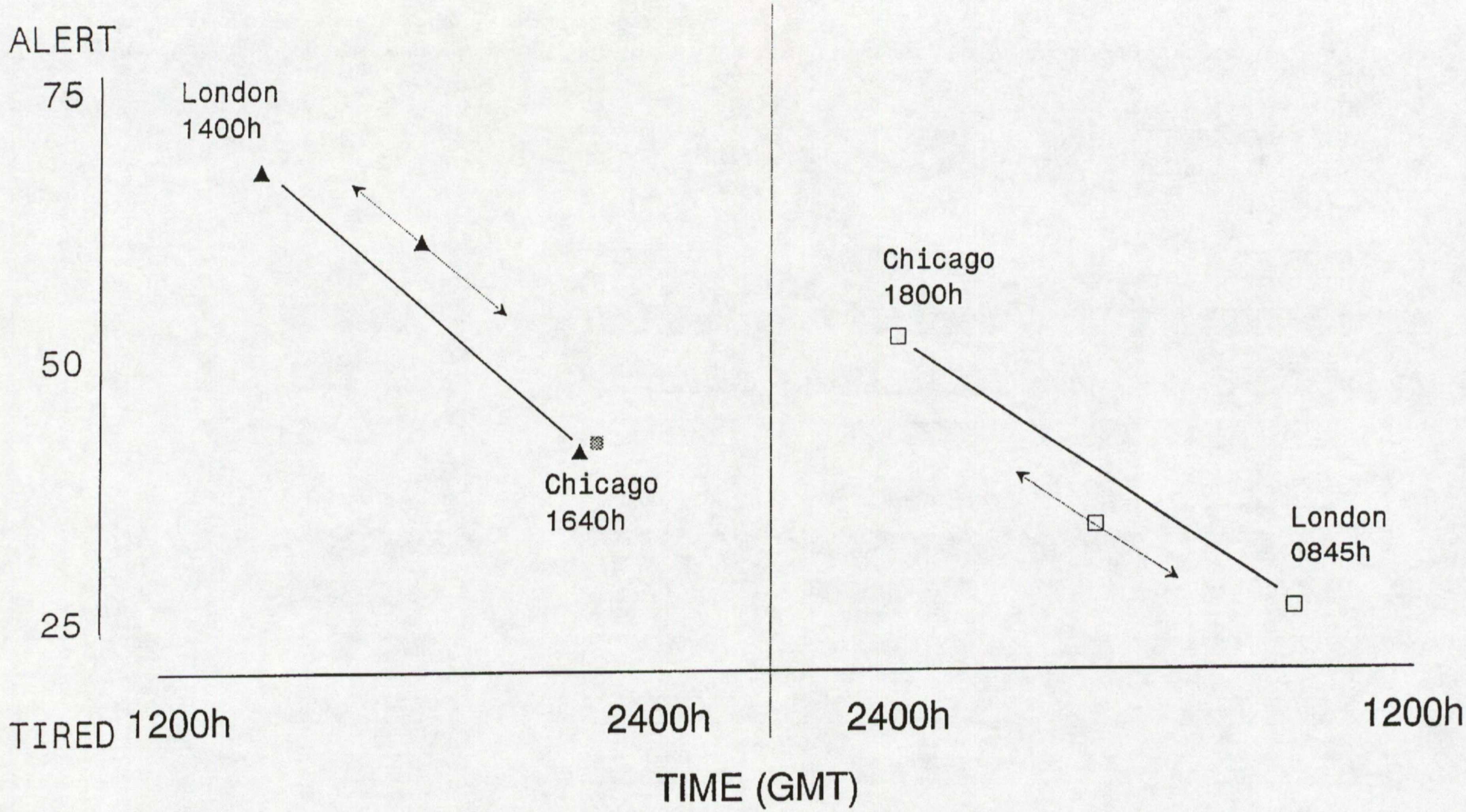


Figure 3 Subjectively assessed alertness assessed at the start and end of flights, meaned over subjects. Retrospective estimates of alertness are shown as points with extended arrows

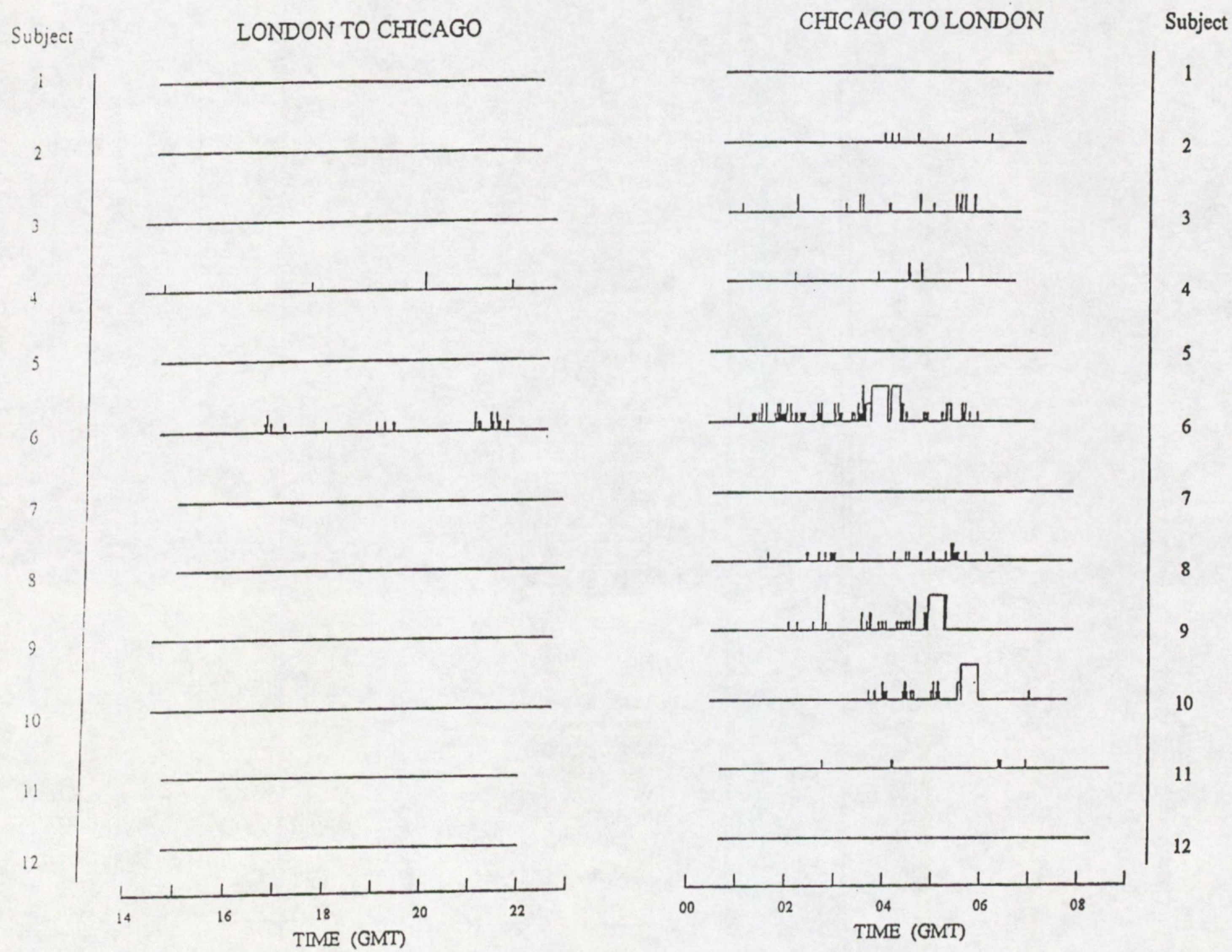


Figure 4 Sleepiness profiles during flight for all subjects. Each line has 4 levels corresponding to awake (0), sleepiness (0.5), drowsy (1) and sleep (2)

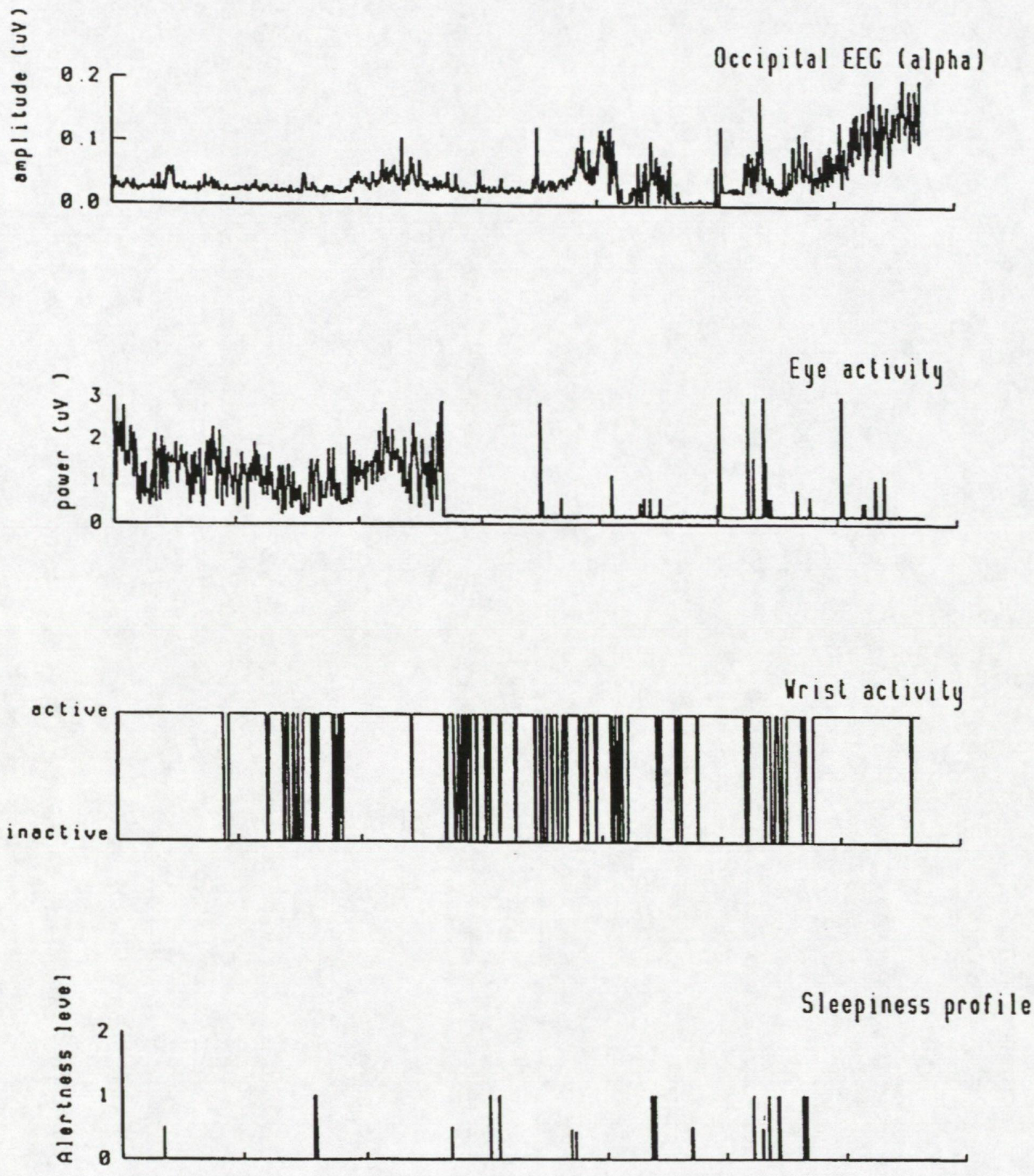


Figure 5a Subject 3 – return flight

Figure 5 Data for 3 subjects showing occipital EEG (alpha frequency), eye activity, presence/absence of combined wrist activity and sleepiness profiles

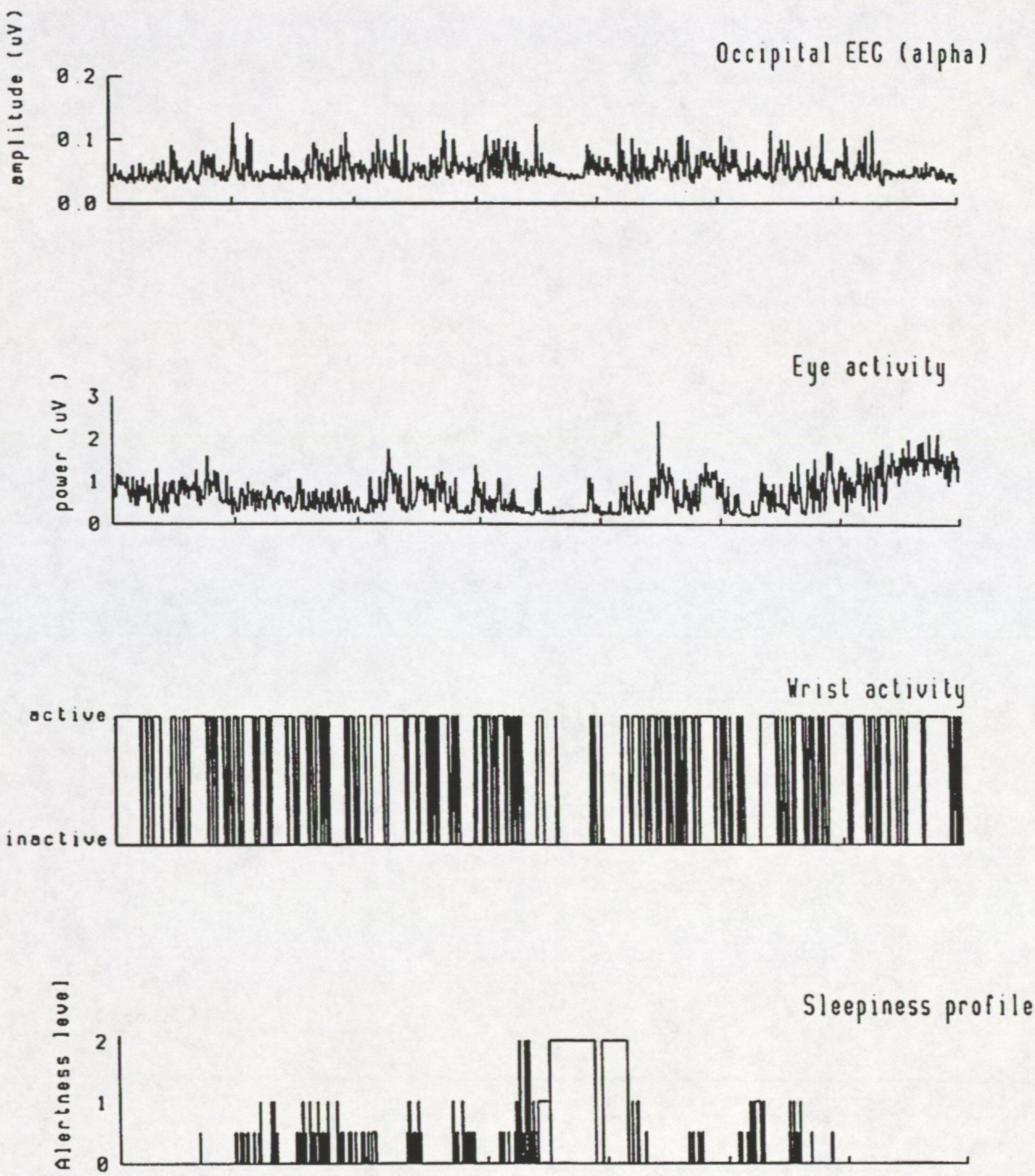


Figure 5b Subject 6 – return flight

Figure 5 (continued)

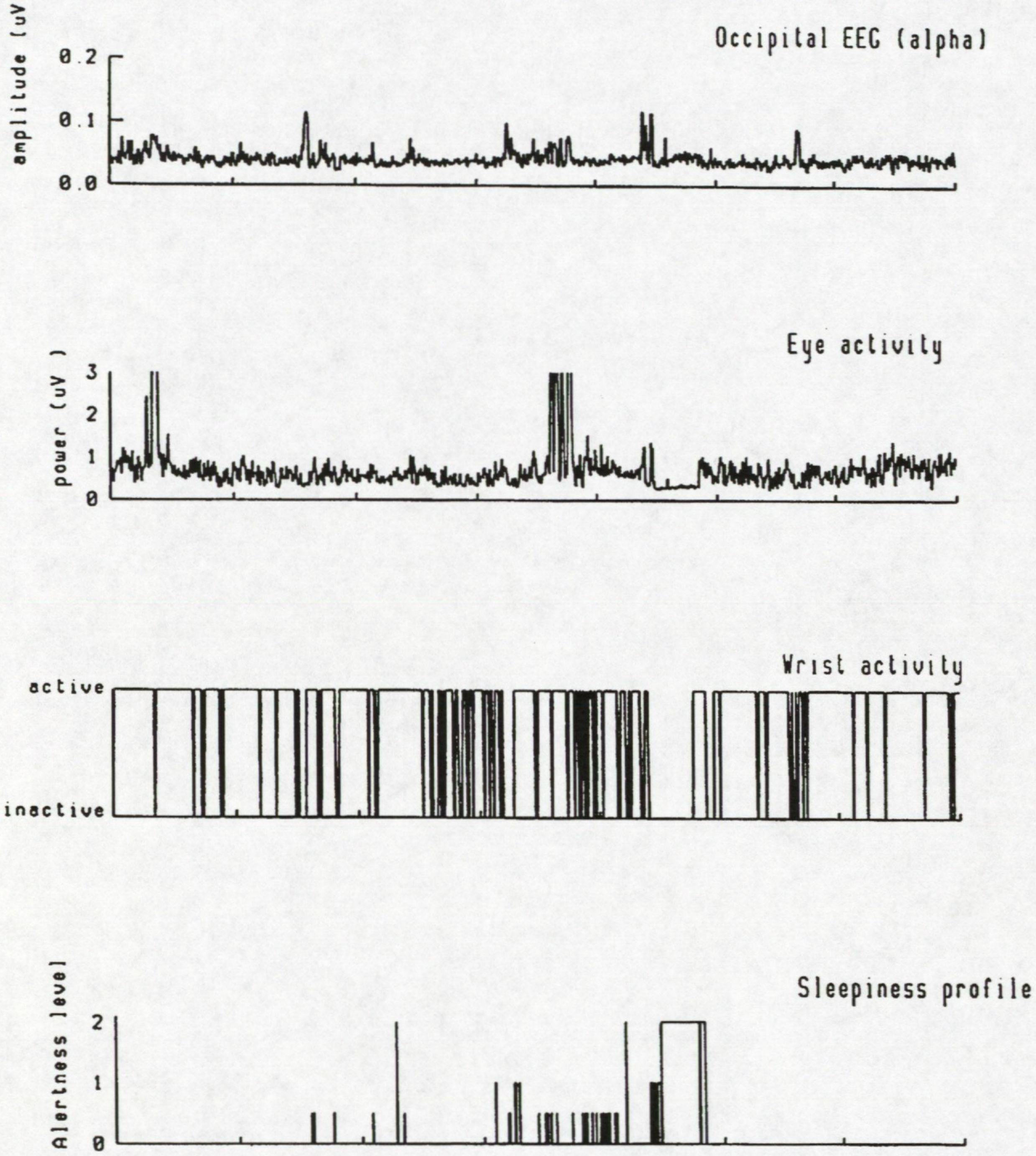


Figure 5c Subject 9 – return flight

Figure 5 (continued)

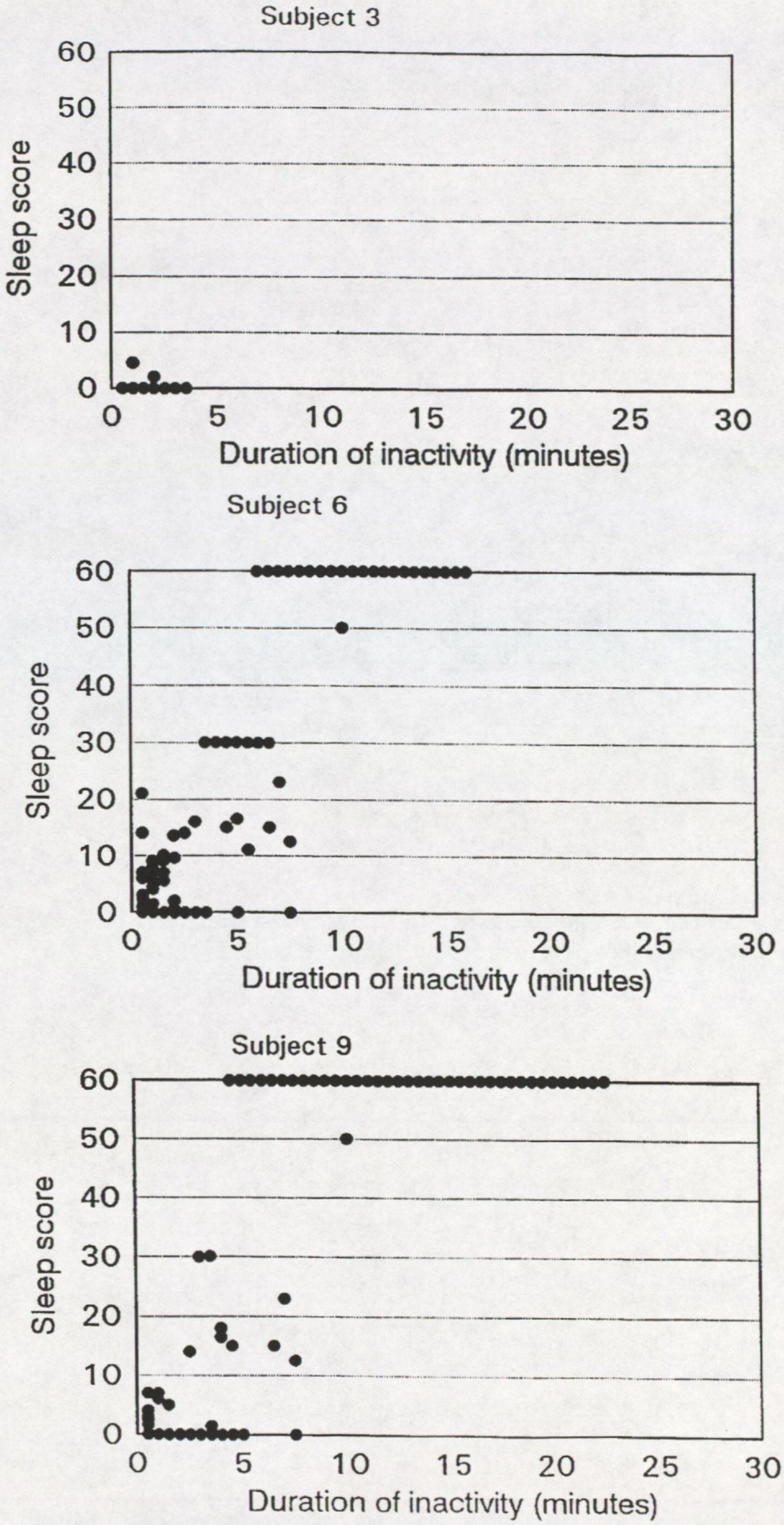


Figure 6 Distributions of the variable sleep for 3 subjects showing the calculated sleep value for differing durations of wrist inactivity

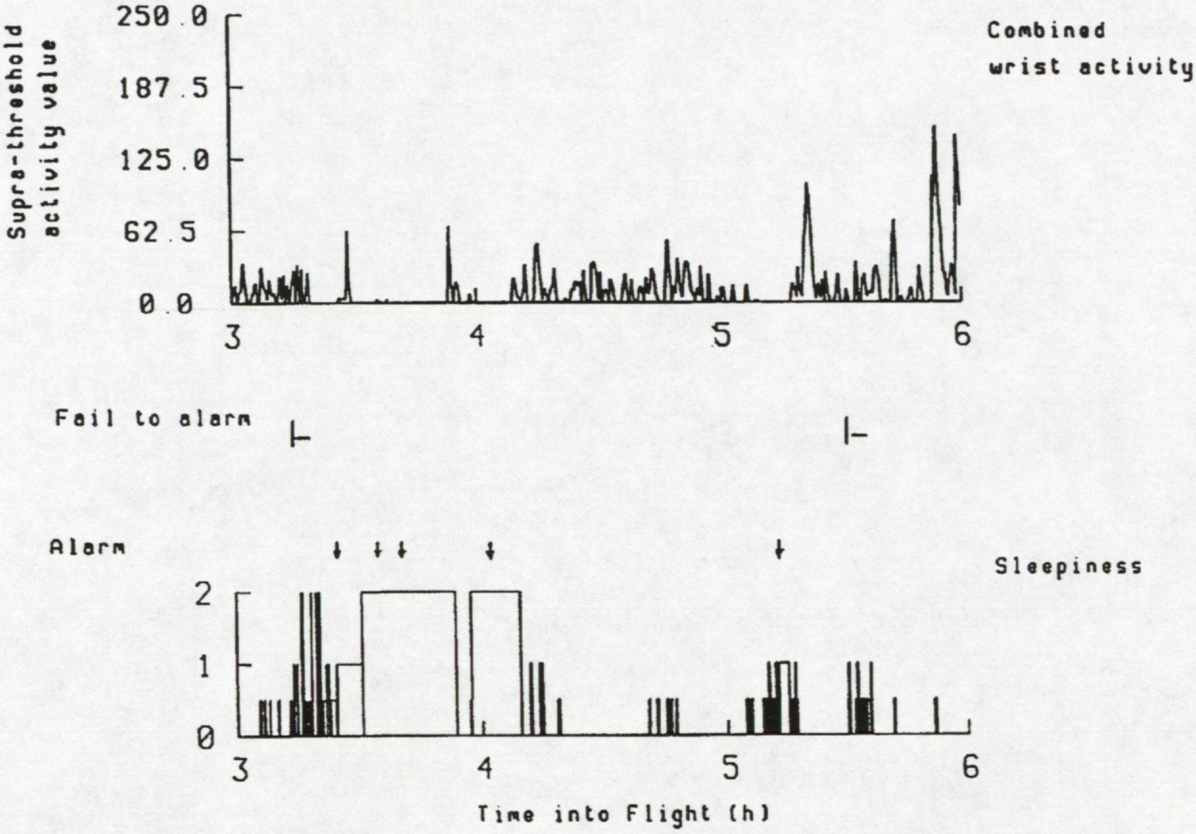


Figure 7 An example of an alarm system based on wrist inactivity for a segment of data from subject 6, return (night) flight

Combined wrist activity (30 second time resolution)

Incidence of false negative alarms indicated at the start of sleepiness by the symbol I–

Activation of the alarm is shown by a downwards pointing arrow

The sleepiness profile derived from the EEG and EOG

Annex A Subjective Assessment of Mood

I feel
Absolutely carefree — extremely anxious

I am
extremely aggressive — extremely passive

I am
ecstatically happy — in the depths of depression

With regard to carrying out general duties
I feel that I am
absolutely useless — extremely efficient

I feel
extremely sociable — extremely withdrawn

I am
extremely irritable — not at all irritable

I am
absolutely relaxed (physically) — extremely tense (physically)

I am
extremely sleepy — extremely wide awake

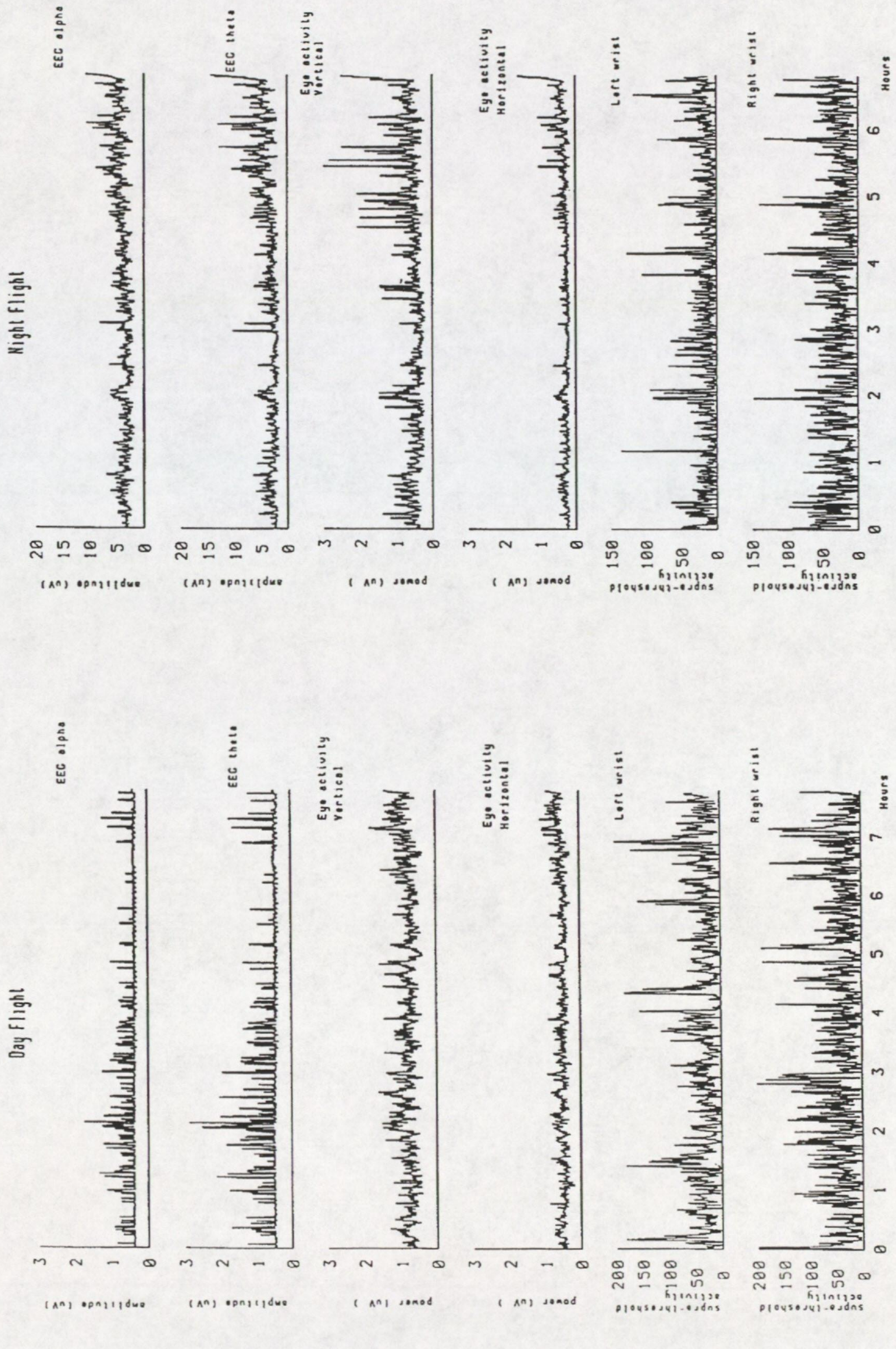
I am
extremely energetic — extremely lethargic

I am
mentally very dulled — extremely alert

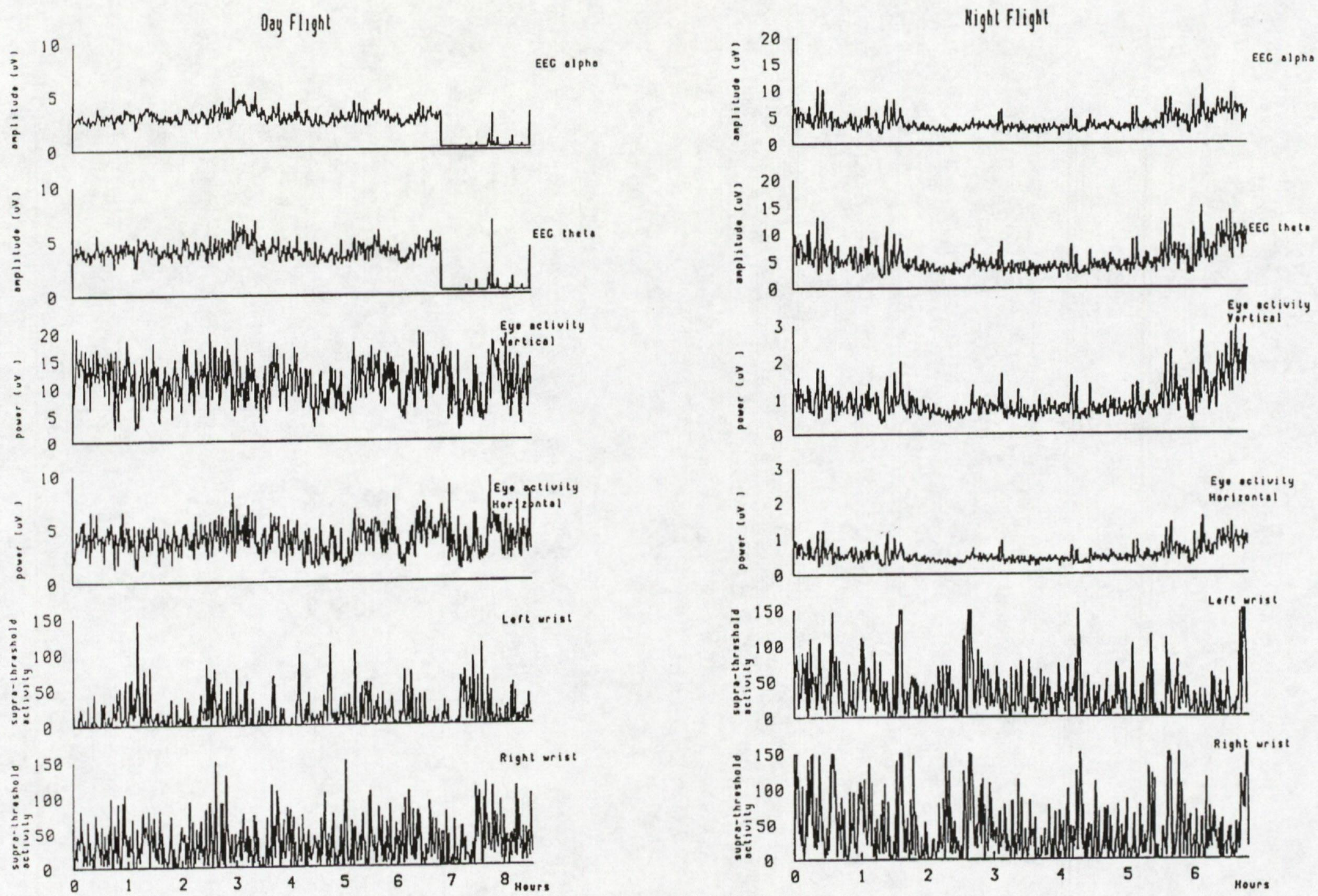
I am
absolutely calm — extremely agitated

I have
no ability to concentrate — complete ability to concentrate

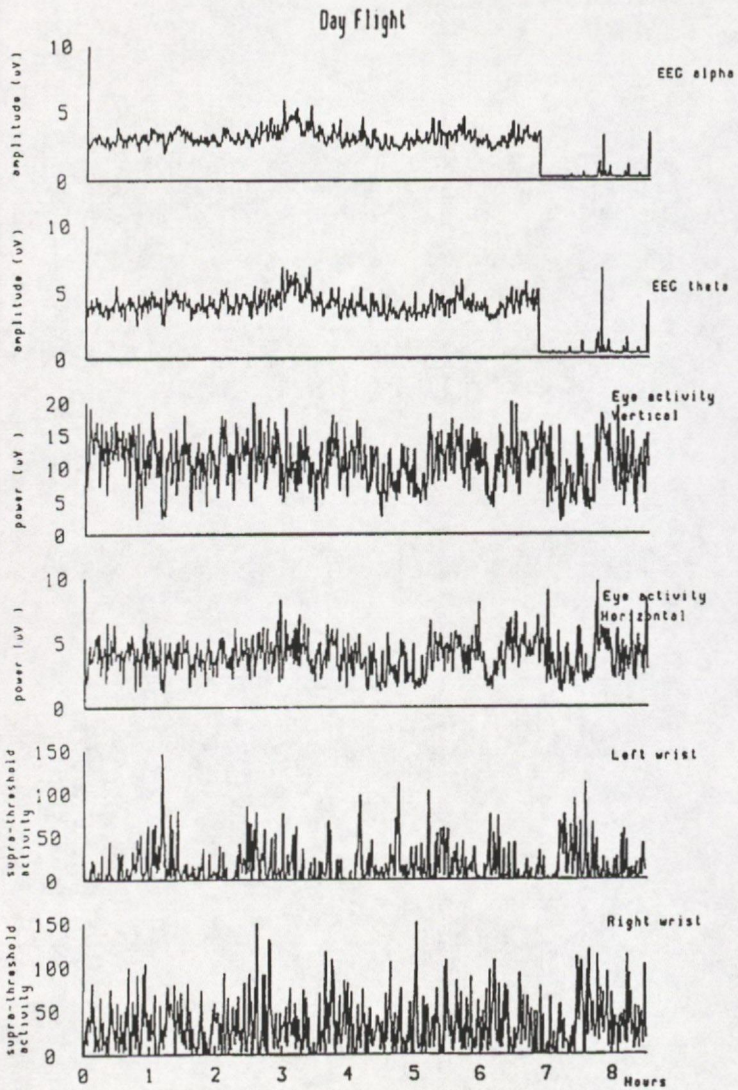
Annex B Brain, Eye and Wrist activity for 12 subjects showing outward (day) and return (night) flights.

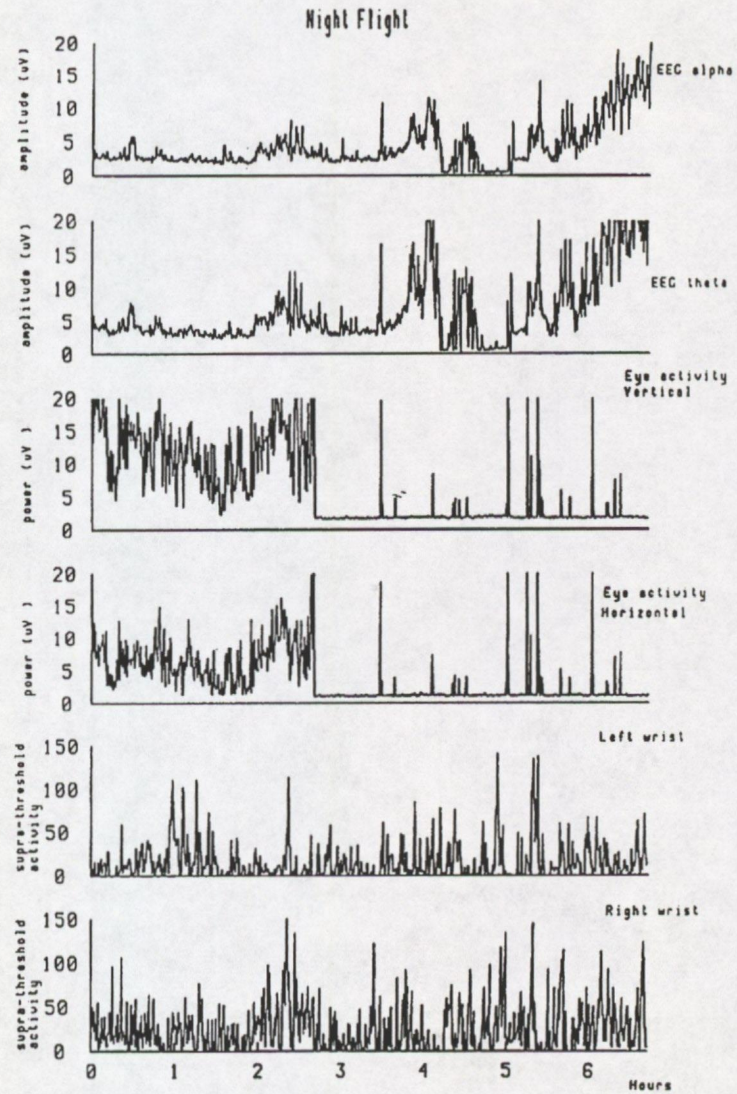


Subject 1

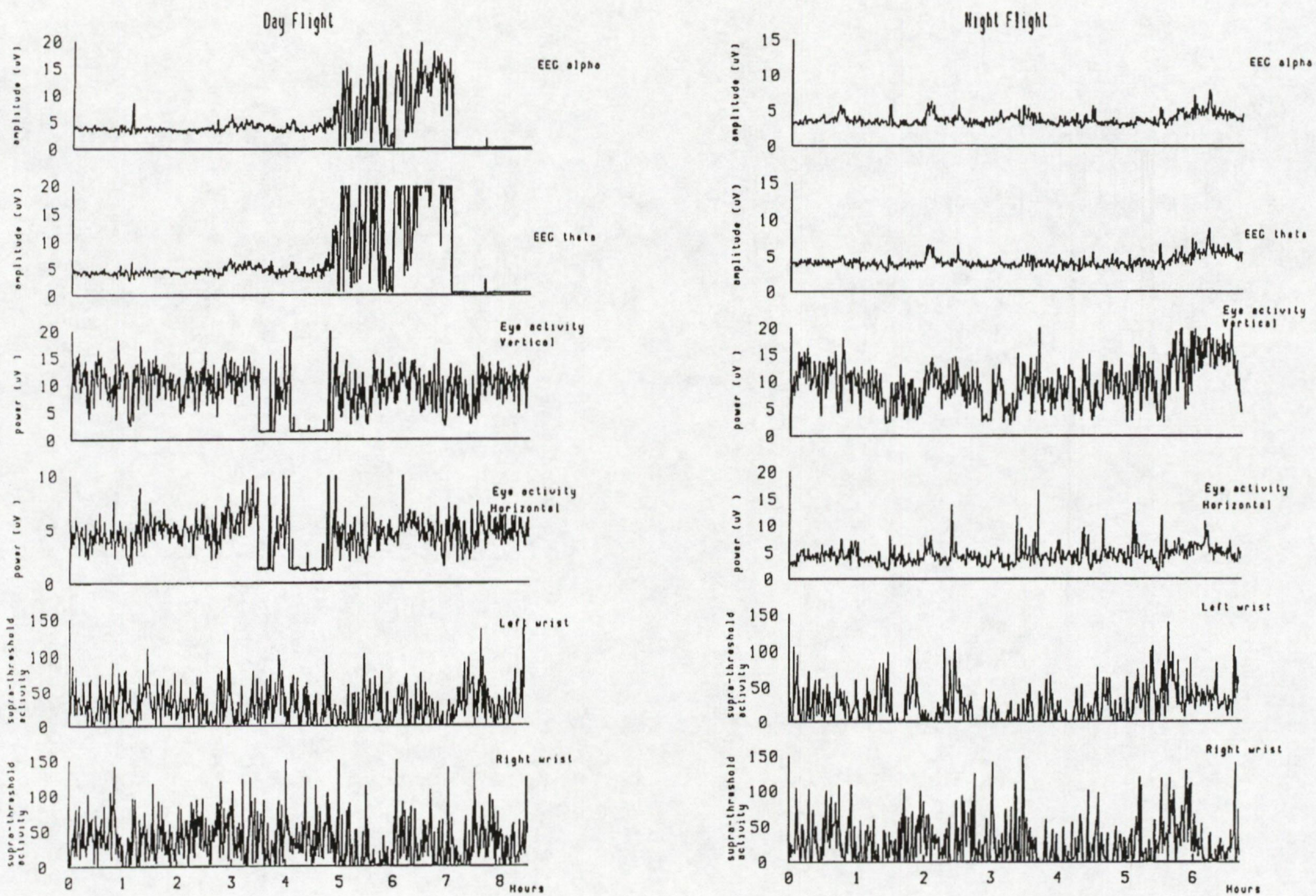

Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 2

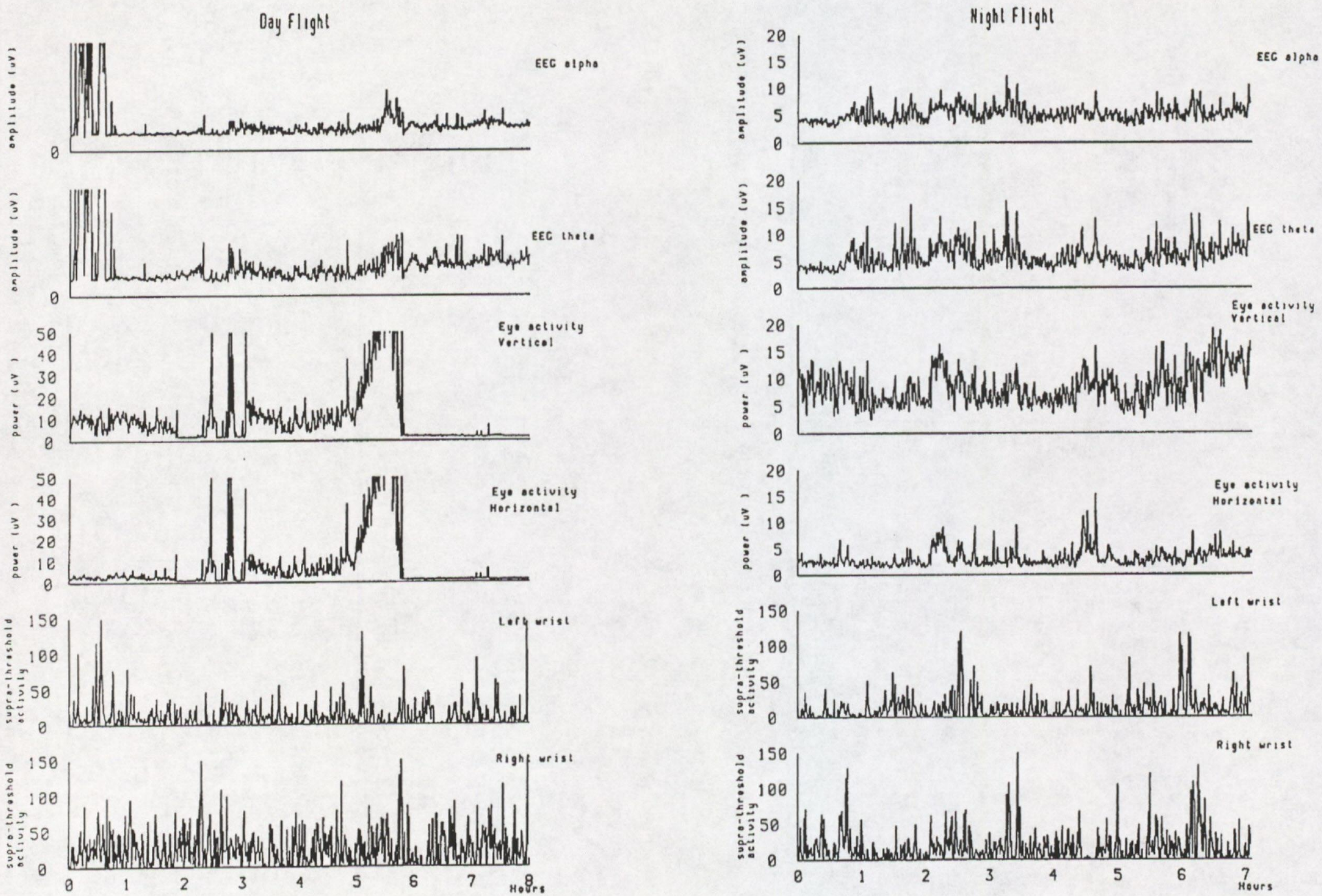

Day Flight
amplitude (uV)
EEG alpha
EEG theta
power (uV)
Eye activity
Vertical
Eye activity
Horizontal
supra-threshold activity
Left wrist
Right wrist
Hours


Night Flight
amplitude (uV)
EEG alpha
EEG theta
power (uV)
Eye activity
Vertical
Eye activity
Horizontal
supra-threshold activity
Left wrist
Right wrist
Hours

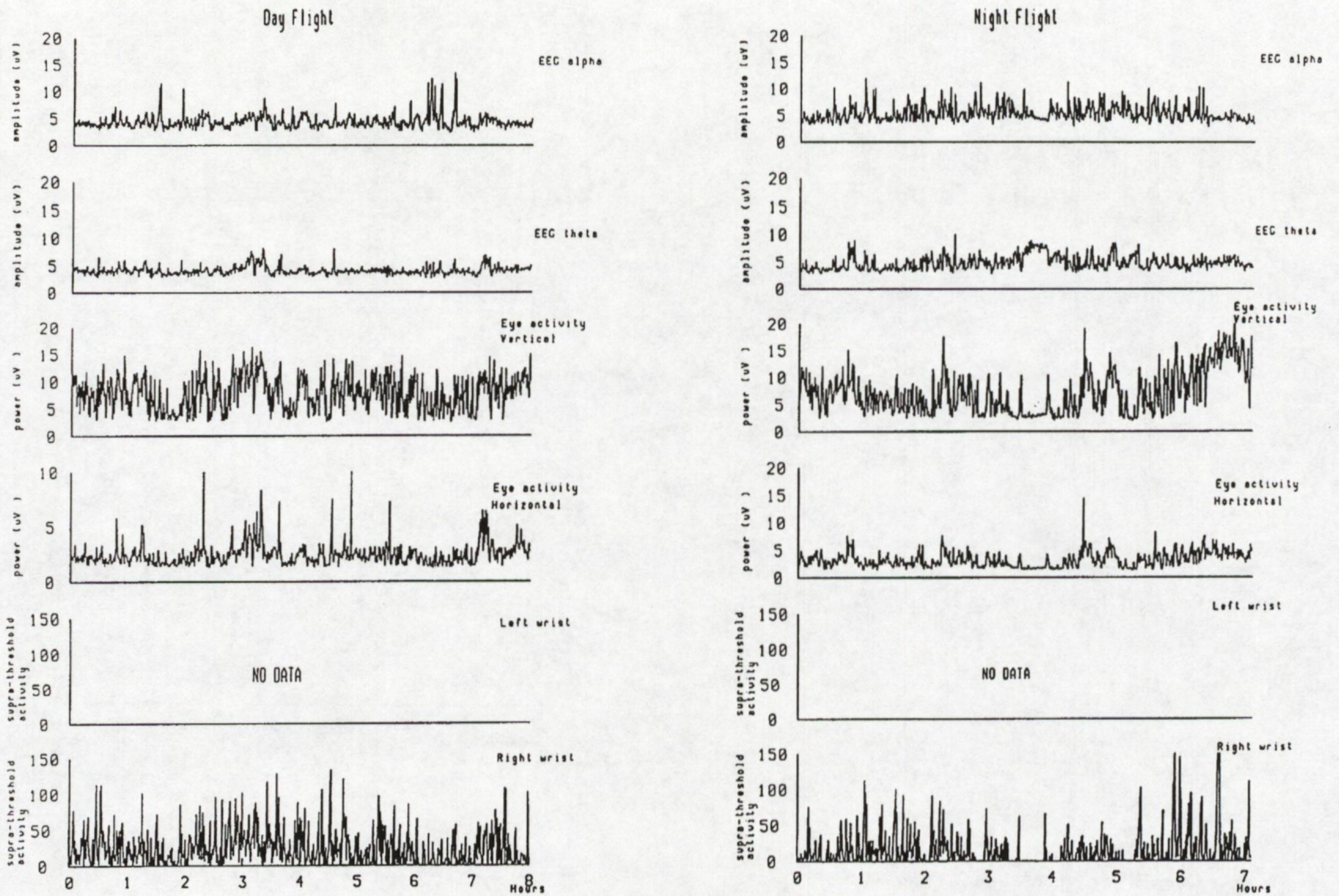
Subject 3


Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity
Vertical
Eye activity
Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold
activity
Hours

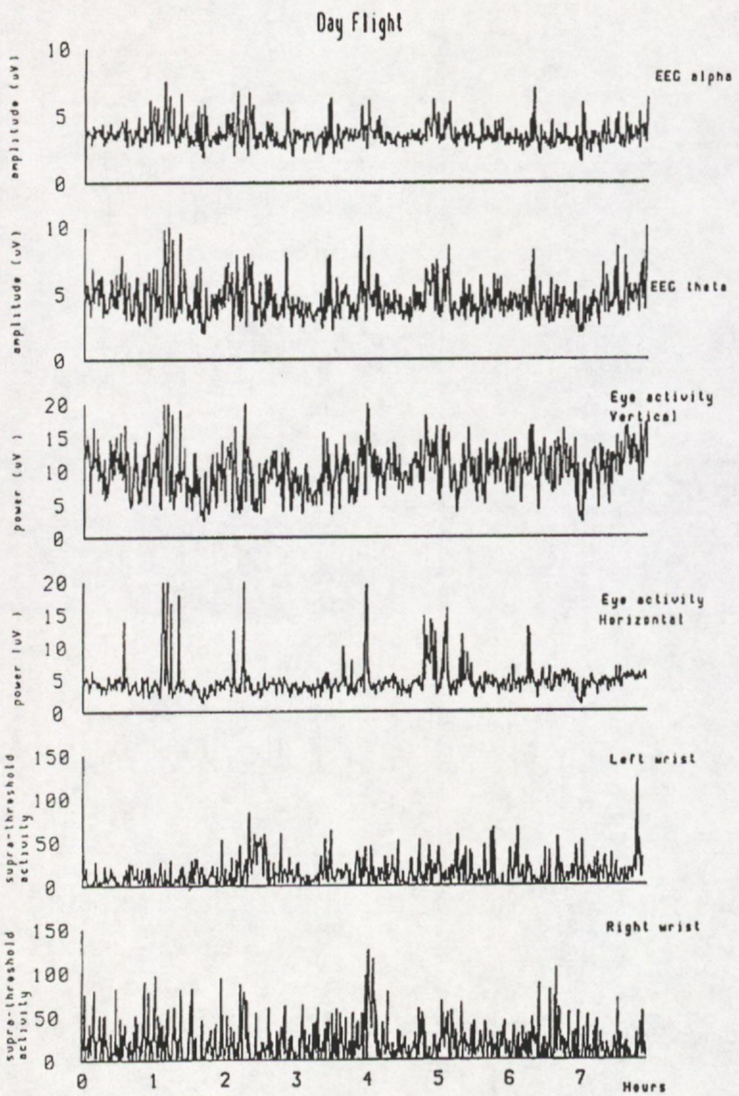
Subject 4

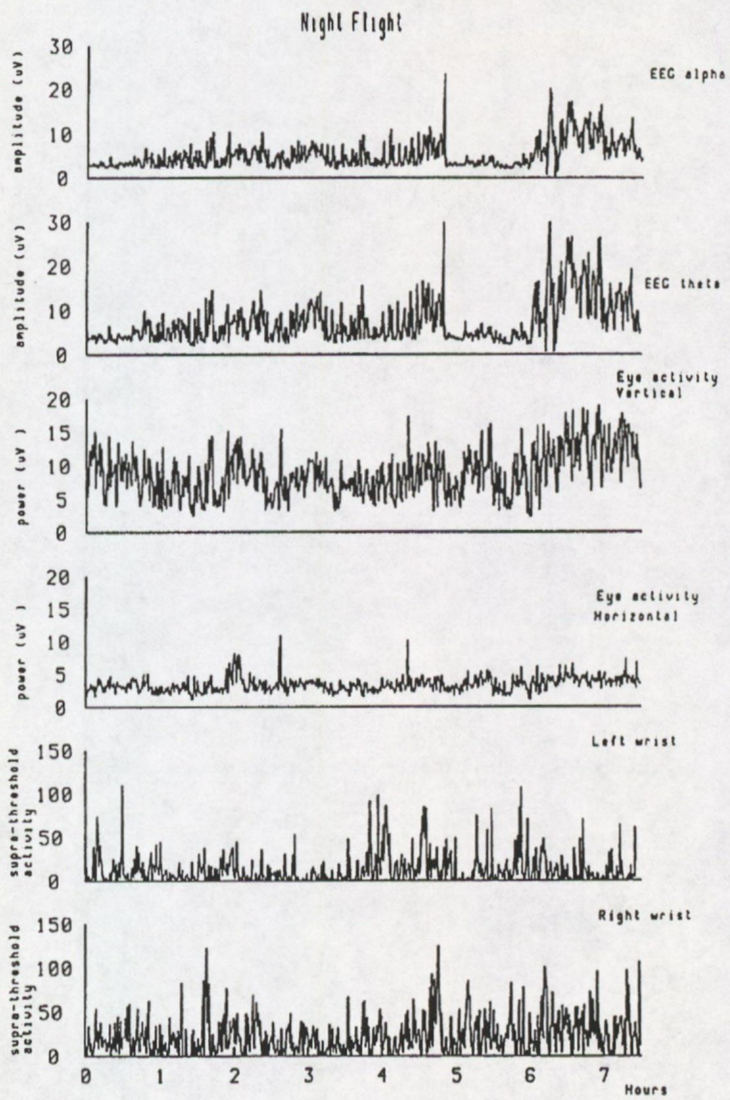

Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity
Vertical
Eye activity
Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 5

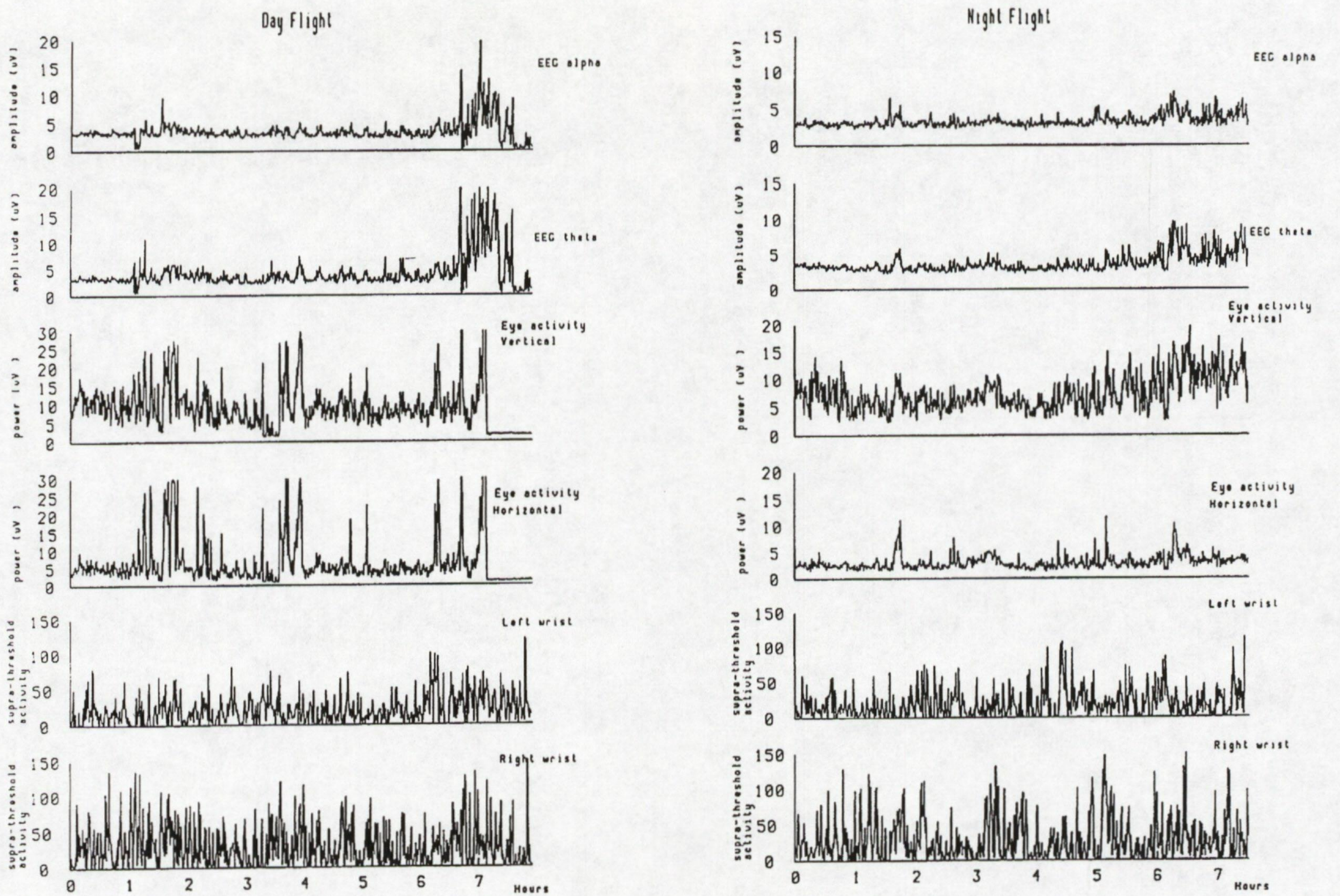

Day Flight
EEG alpha
amplitude (uV)
EEG theta
amplitude (uV)
Eye activity Vertical
power (uV)
Eye activity Horizontal
power (uV)
Left wrist
NO DATA
supra-threshold activity
Right wrist
supra-threshold activity
Hours
Night Flight
EEG alpha
amplitude (uV)
EEG theta
amplitude (uV)
Eye activity Vertical
power (uV)
Eye activity Horizontal
power (uV)
Left wrist
NO DATA
supra-threshold activity
Right wrist
supra-threshold activity
Hours

Subject 6

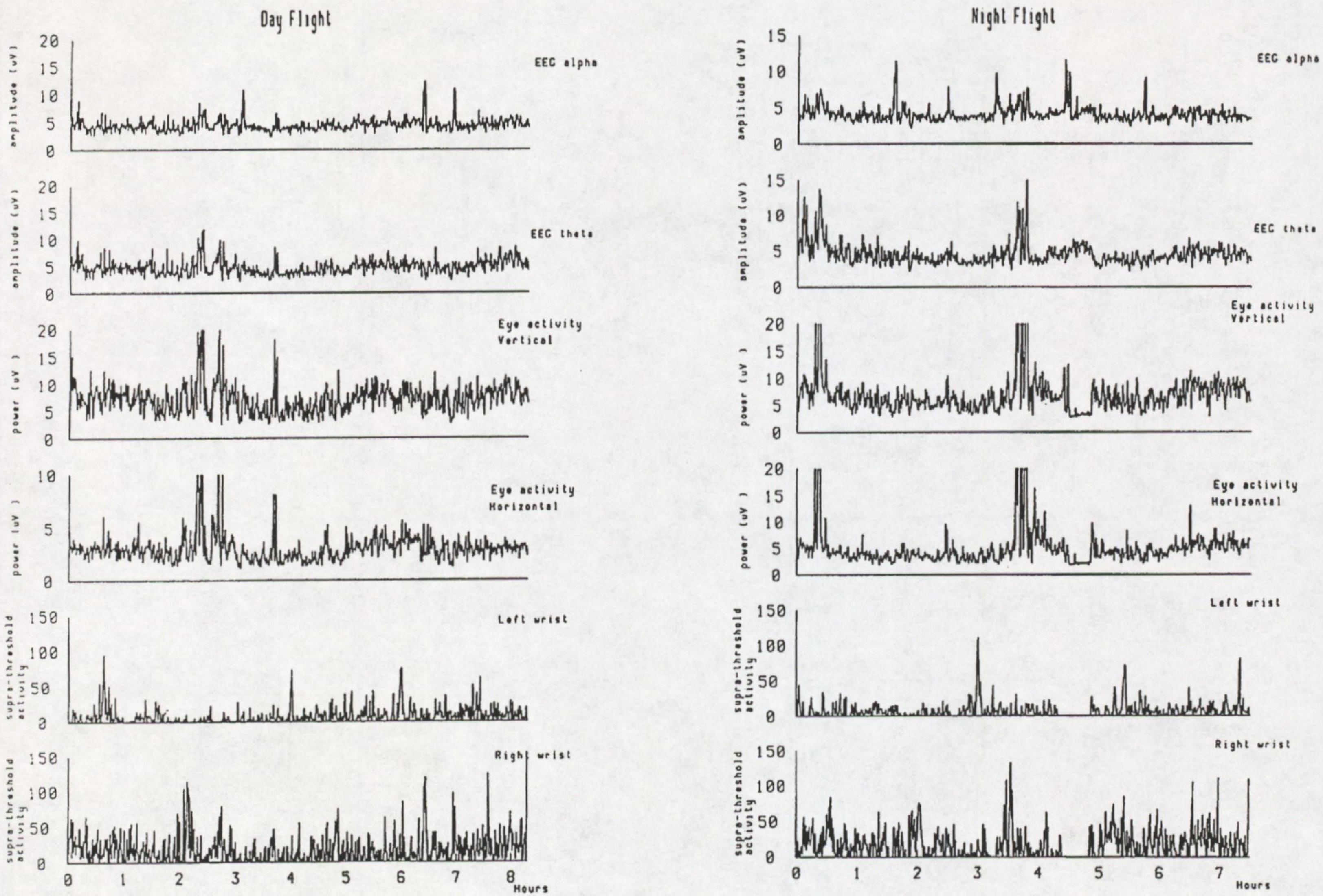

Day Flight
amplitude (uV)
EEG alpha
amplitude (uV)
EEG theta
power (uV)
Eye activity
Vertical
power (uV)
Eye activity
Horizontal
supra-threshold
activity
Left wrist
supra-threshold
activity
Right wrist
Hours


Night Flight
amplitude (uV)
EEG alpha
amplitude (uV)
EEG theta
power (uV)
Eye activity
Vertical
power (uV)
Eye activity
Horizontal
supra-threshold
activity
Left wrist
supra-threshold
activity
Right wrist
Hours

Subject 7

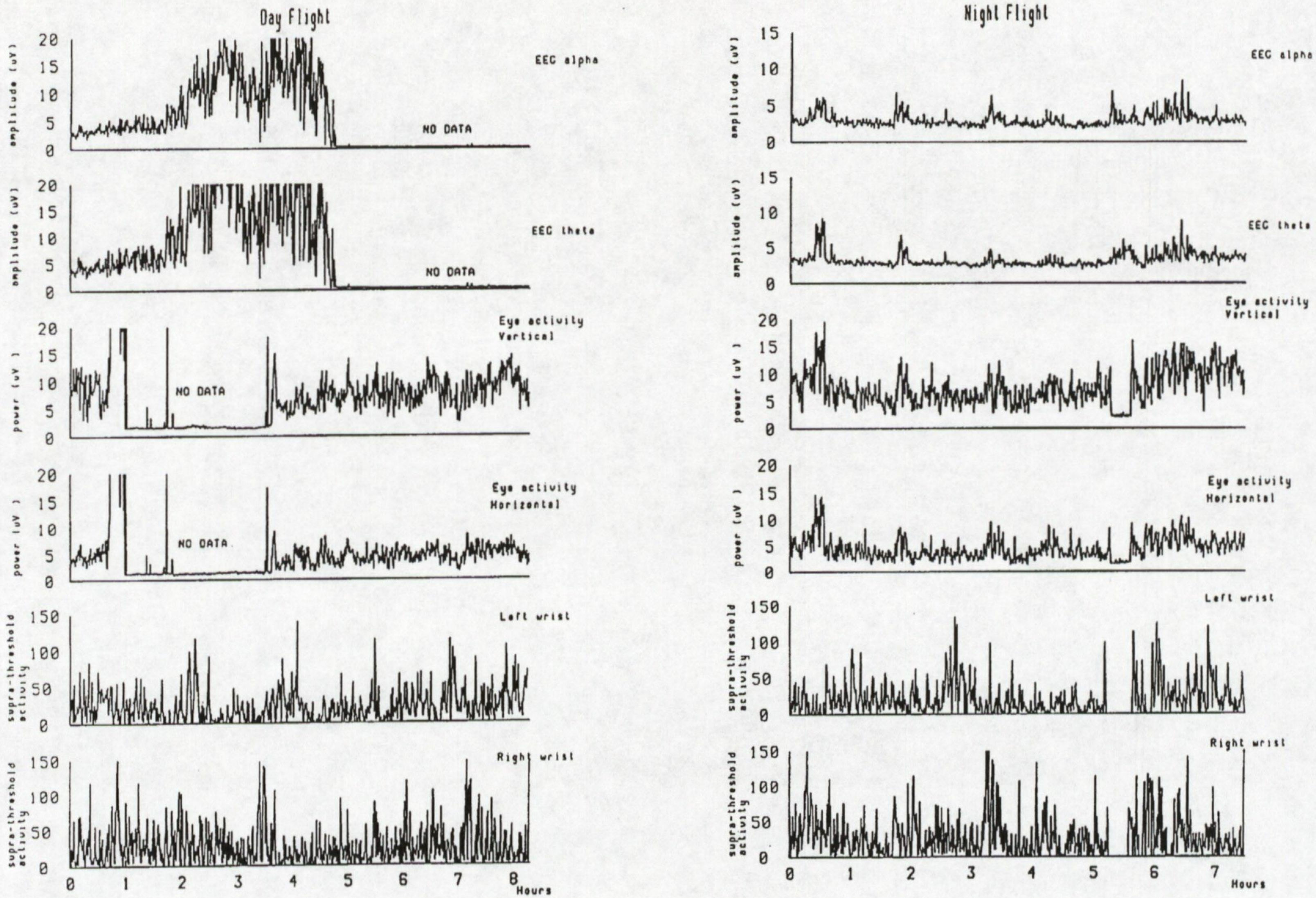

Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity
Vertical
Eye activity
Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold
activity
Hours
0
1
2
3
4
5
6
7

Subject 8



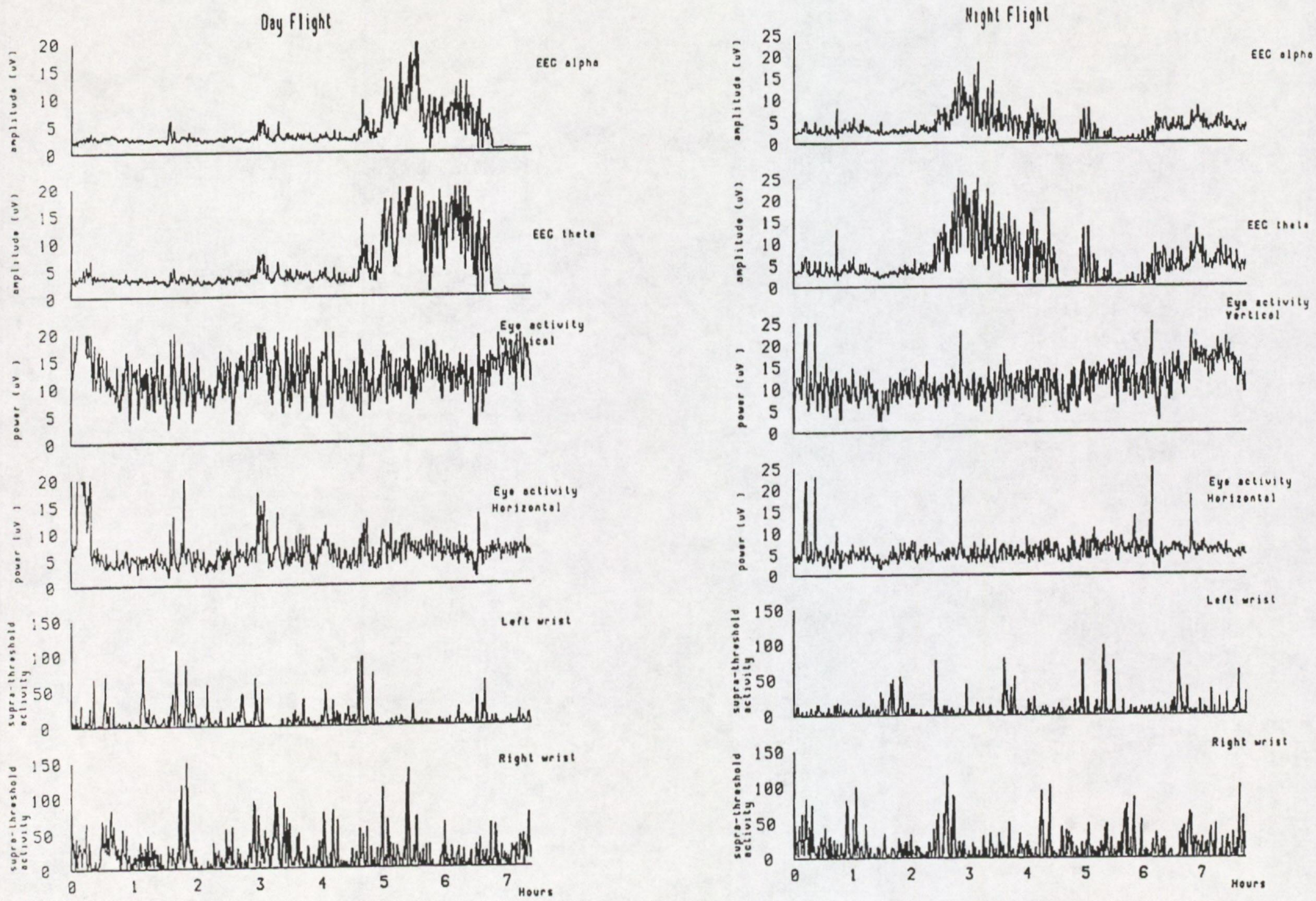
Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 9



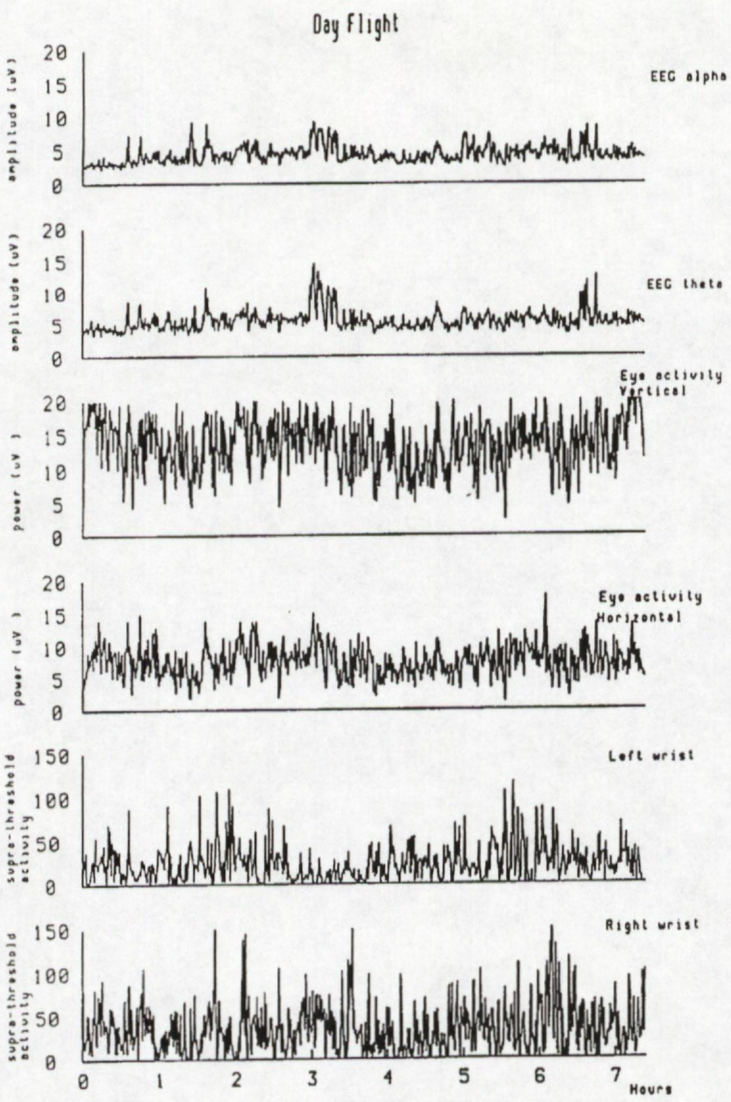
Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
NO DATA
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 10

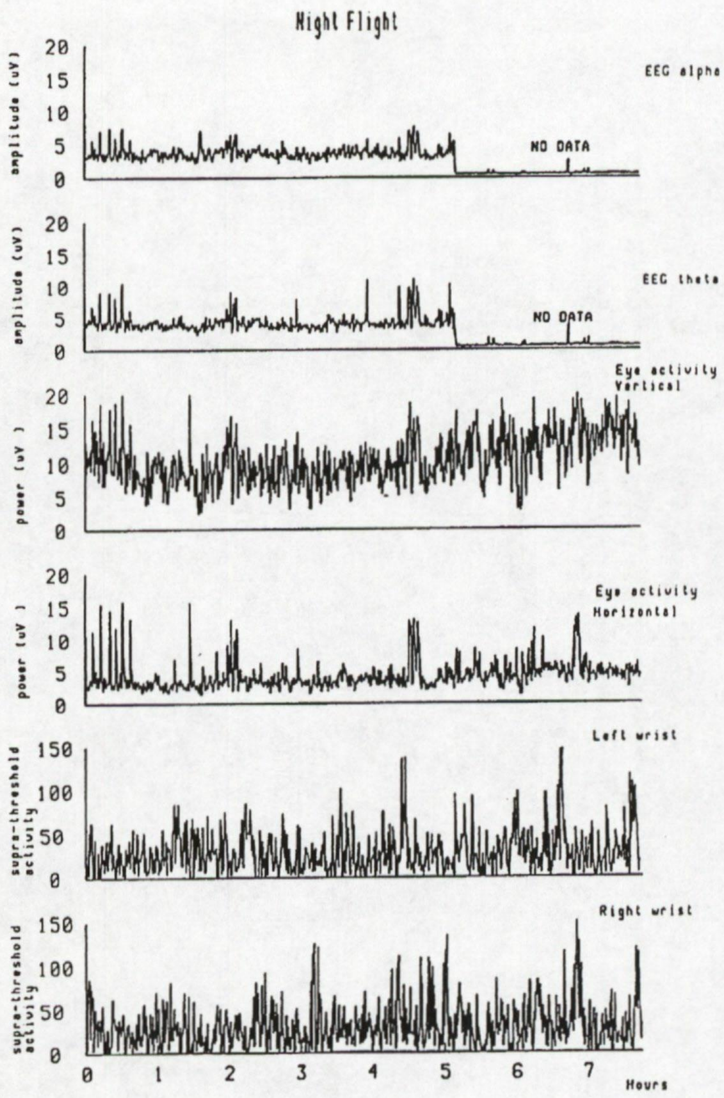


Day Flight
Night Flight
EEG alpha
EEG theta
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 11



Day Flight
EEG alpha
EEG theta
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours



Night Flight
EEG alpha
EEG theta
NO DATA
Eye activity Vertical
Eye activity Horizontal
Left wrist
Right wrist
amplitude (uV)
power (uV)
supra-threshold activity
Hours

Subject 12