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# Aircraft Noise Effects on Sleep: Final Results of DLR Laboratory and Field Studies of 2240 Polysomnographically Recorded Subject Nights

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**Abstract [500]** OBJECTIVES Sleep is vital for the recovery of physical and mental capacities. Environmental noise is a potential disrupter of the sleep process. In order to develop scientifically sound criteria for the operation and restriction of nocturnal air traffic, the DLR-Institute of Aerospace Medicine investigated the influence of nocturnal aircraft noise on sleep, mood and behavior in four representative laboratory and two field studies between 1999 and 2003. METHODS In the lab, 128 subjects aged 18-65 were investigated during 13 consecutive nights (total: 1,664 nights). Between 4 and 128 aircraft noise events with $L_{AS,max}$ between 45 and 80 dB(A) were played back between 11 p.m. and 7 a.m. Results were compared to the findings of two field studies with 64 subjects and 576 nights in total. Here, sound pressure levels were simultaneously measured indoors and outdoors. Electrophysiological signals included polysomnography, EKG, plethysmography, respiration and actigraphy. Synchronous recording with acoustic data assured event related analysis. RESULTS Random effects logistic regression was used for the prediction of noise induced awakenings depending on $L_{AS,max}$ and the calculation of dose–response curves. A comparison of the awakening probability between lab and field revealed striking differences. Based on these results, new criteria for the restriction of nocturnal air traffic were developed and will be presented. CONCLUSIONS The combination of a huge database and new statistical procedures allows the precise prediction of the influence of nocturnal aircraft noise on sleep, which again can be used for the proposal of advanced rules for the protection of residents living near airports.

## 1 INTRODUCTION

Sleep is vital for the recovery of physical and mental capacities. Environmental noise is able to interfere with the sleep process. In order to develop scientifically sound criteria for the restriction of nocturnal air traffic, the DLR-Institute of Aerospace Medicine investigated the influence of nocturnal aircraft noise on sleep, mood and behavior in four representative laboratory and two field studies between 1999 and 2003.

By use of the electroencephalogram (EEG), the electrooculogram (EOG) and the electromyogram (EMG) and after dividing the night into 30-second segments each segment of sleep can be classified into the wake state and five distinct sleep stages [1]: stages 1-4 and REM sleep. Stage 1 and stage 2 sleep are called light sleep, whereas stage 3 and stage 4 are known as deep or slow wave sleep (SWS). REM-sleep and especially deep sleep seem to be very important for the process of memory consolidation, whereas stage 1 sleep seems to contribute only little if all to the recuperative value of sleep.

Environmental noise is a potential disruptor of the sleep process. It may lead to decreases in total sleep time (TST) and changes in sleep structure, to more frequent awakenings and to activations of the vegetative nervous system.
The process of sleep stage classification is time consuming and therefore expensive. Hence, there have only been a few and small studies in the past using polysomnography (EEG, EOG, EMG) for the investigation of the effects of environmental noise on sleep.

## 2 METHODS

### 2.1 Laboratory Studies

128 volunteers free of intrinsic sleep disorders and aged 18-65 (mean age: 38) were examined for thirteen consecutive nights in our soundproof sleep facility, which is situated in the basement of the institute. 8 separate sleep cabins allowed the simultaneous observation of 8 volunteers. 16 subjects served as a control group and did not receive aircraft noise at all during the 13 nights.
Electrophysiological variables were measured continuously during the night and included:

- Electroencephalogram (EEG), Electromyogram (EMG) and Electrooculogram (EOG)
- Electrocardiogram (EKG)
- Finger pulse amplitude (plethysmography)
- Respiration (movements of the rib cage and airflow at mouth and nose)

Control variables were gender, age, educational, psychological and medical status, personal attitude towards aircraft noise and aircraft noise annoyance. Each laboratory study consisted of 4 groups of 8 volunteers each who were examined over a period of 8 weeks (4 x 13 nights). Nights 1 and 2 as well as nights 12 and 13 served as adaptation, baseline and recovery nights respectively.
Lights were turned off at 11 p.m. and again on at 7 a.m. In the noise nights, aircraft noise events (ANE) with varying frequencies of occurrence (4, 8, 16, 32, 64 or 128 events per night with minimum intervals of 3, 7, 14, 30, 60 and 120 min respectively) and noise levels ranging from 45 to 80 dB $L_{AS,max}$ ($L_{AS,eq(3)}$ 31.0-54.5 dB, 8 hours, background $L_{AS,eq(3)}$ 30 dB) were equidistantly presented by loudspeakers. The combinations of frequency and $L_{AS,max}$ over the 9 noise nights were drawn in a random fashion. In each study night, always the same noise event with its characteristic $L_{AS,max}$ was presented to all 8 volunteers. The ANEs had been recorded at homes of residents living in the vicinity of Düsseldorf Airport. In the bedroom, the microphone was positioned near the pillow. The windows were closed or tilted. In order to guarantee realistic playback of ANEs, each sleep cabin was acoustically calibrated. A trigger signal was recorded simultaneously with the electrophysiological data allowing for an event correlated analysis with a resolution of 125 ms. In total, more than 33,000 ANEs were played back in the laboratory studies.

### 2.2 Field studies

In the field studies, 64 volunteers aged 19-61 (mean age: 38) were investigated between September 2001 and November 2002 in the vicinity of Cologne Airport, which is one of Germany's airports with the highest number of nocturnal starts and landings. The ANEs occurring during the night were simultaneously recorded outside and inside the bedroom. In total, more than 15,000 ANEs were recorded. The same electrophysiological variables as in the laboratory were continuously sampled in the field. Again, the simultaneous recording of electrophysiological data and a trigger signal allowed for an event correlated analysis with a resolution of 125 ms.

## 2.3 Analysis

### Sleep stage classification

Sleep stage classification [1] was performed visually. All data from one volunteer were analyzed by the same scorer. Prior to the analysis, the data files were renamed and the sequence of the nights was changed in a randomized fashion. In this way, the scorer was blinded, so that he or she did not know if and how many aircraft noise events were played back (laboratory) or recorded (field) during the particular night. In that way, the problem of inter-rater variability was eliminated for intra-individual analyzes as well. In both the laboratory and the field studies, a total of 1,922,194 30-second sleep epochs were visually scored.

### Comparison of sleep stage fractions

The fractions of the different sleep stages were compared intra-individually between baseline and noise nights. The comparison was restricted to the time from sleep onset to the end of time in bed (TIB) of the shorter of both nights. The Wilcoxon signed rank test was used to test for differences in the fractions of sleep stages. A significant result was assumed at alpha = 0.05.

### Event correlated analysis

An event correlated analysis directly connects the incidence of an ANE and the reaction of the sleeper to the ANE. This was made possible by the simultaneous recording of electrophysiological and acoustical data. Changes to sleep stage 1 or awakenings (both from now on simply called 'awakenings') were chosen as the dependent variable of multivariable regression analyzes. Since the dependent variable was dichotomous (awakenings occur (1) or do not occur (0)) logistic regression was used instead of linear regression. Data were not independent, because every subject provided more than one data point (ANEs) for the analysis. Hence, random effects logistic regression was used (EGRET software, version 2.0.31).

Awakenings following an ANE are in that way unspecific, that awakenings are part of normal undisturbed sleep, i.e. they occur spontaneously as well. The probability (P) of noise induced awakenings (risk attributable to aircraft noise alone) can be calculated as:

$$P(\text{induced}) = P(\text{aircraft noise}) - P(\text{spontaneous}) \qquad (1)$$

The time window after the onset of an ANE was chosen in a way maximizing the probability of noise induced awakenings P(induced). This time window turned out to be 60 seconds for the laboratory and 90 seconds for the field studies.

In the field studies, every noise event occurring in the sleeping room (e.g. aircraft noise, snoring, car noise, etc.) was identified and flagged. In that way undisturbed ANEs could be differentiated from ANEs disturbed by other noise events. Only undisturbed ANEs were used for the analysis.

## 3 RESULTS

### 3.1 Comparison of sleep stage fractions

For the laboratory, Figure 1 shows the differences of the time spent in the different sleep stages between all noise nights (n = 966) and the baseline nights (n = 112) during the course of the night irrespective of the number and maximum SPL of the ANEs played back during the night.

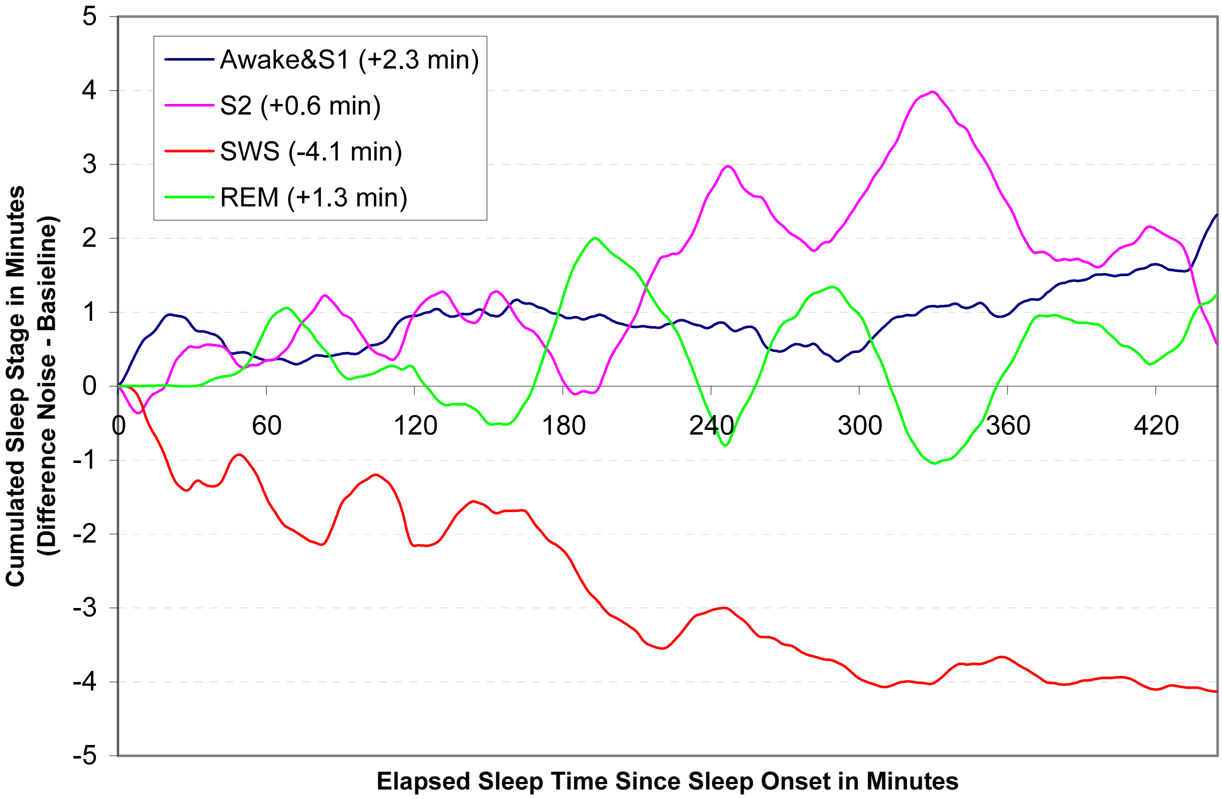


Figure 1: *Differences in sleep stage distributions between noise and baseline nights depending on elapsed sleep time (for explanations see text)*

On average, 7 hours and 24.5 minutes after sleep onset were compared. Totals sleep time was non significantly reduced by only 1.8 minutes ($p = 0.262$). Nevertheless, changes in the structure of sleep were obvious. The amount of slow wave sleep was reduced by –4.1 minutes ($p = 0.057$) especially in favor of the time spent awake or in sleep stage 1 (+2.3 minutes, $p = 0.132$).
The amounts of SWS were further analyzed depending on number and maximum SPL of ANEs. In 21 of 30 different combinations a reduction in SWS amount compared to noise free baseline nights was seen (expected if aircraft noise did not influence SWS: 15). The differences varied between the extremes of +7.7 minutes at 4 x 55 dB(A) and –18.0 minutes at 32 x 60 dB(A). Even these extremes represented non significant changes after Bonferroni correction of alpha (0.0017).
No significant differences in sleep stage amounts could be seen between noisy and less noisy nights (median split) during the field studies.

## 3.2 Event correlated analysis

### Laboratory studies

The final analysis consisted of 25,408 ANEs and of 112 subjects. Figure 2 shows the results of a multivariable random effects logistic regression model with the statistically significant independent variables:

- maximum SPL of the ANE
- maximum SPL * maximum SPL
- time after sleep onset (TaSO)
- sleep stage prior to the start of the ANE (PSS)

In Figure 2, TaSO was chosen as the middle of the more sensitive second half of the night (601 epochs). PSS was chosen as the most sensitive sleep stage S2.

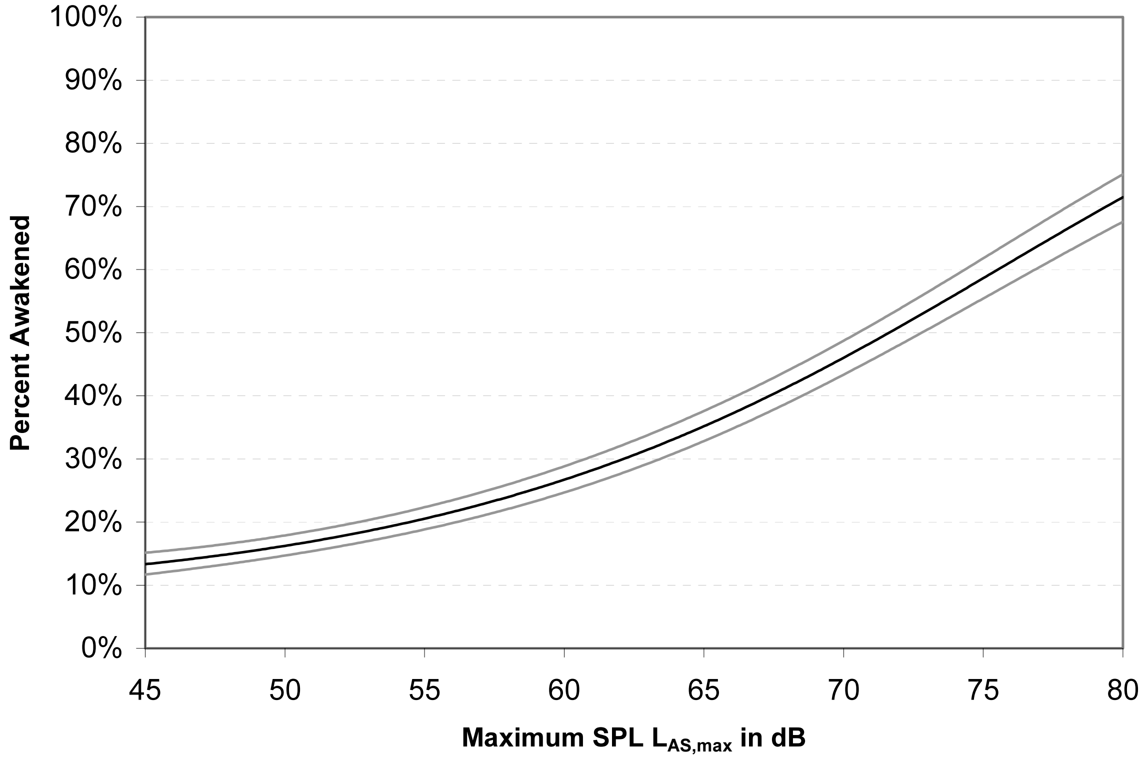


Figure 2: *Random effects logistic regression model based on the data of the laboratory study (includes 95% confidence intervals, for explanations see text)*

Awakening probability rises with increasing maximum SPL in a non-linear fashion. The model predicts an awakening probability of 13.3% at 45 dB(A) and 71.5% at 80 dB(A) respectively. The precision can be read from the width of the 95% confidence intervals. Because of the large sample size the precision of the prediction is very high and varies between 3.2% at 49.5 dB(A) and 7.5% at 80 dB(A).

## Field studies

We were able to use 10,658 ANEs of 61 subjects for the final analysis. Figure 3 shows the results of a multivariable random effects logistic regression model with the following statistically significant independent variables:

- maximum SPL of the ANE
- background noise level ($L_{AS,eq}$) one minute prior to the start of an ANE (BNL)
- maximum SPL * BNL (interaction)
- time after sleep onset (TaSO)
- sleep stage prior to the start of the ANE (PSS)

For Figure 3, TaSO was chosen as the middle of the more sensitive second half of the night (601 epochs). PSS was chosen as the most sensitive sleep stage S2. Background noise level (BNL) was set to 27.1 dB(A), which equals the median BNL found in the field.

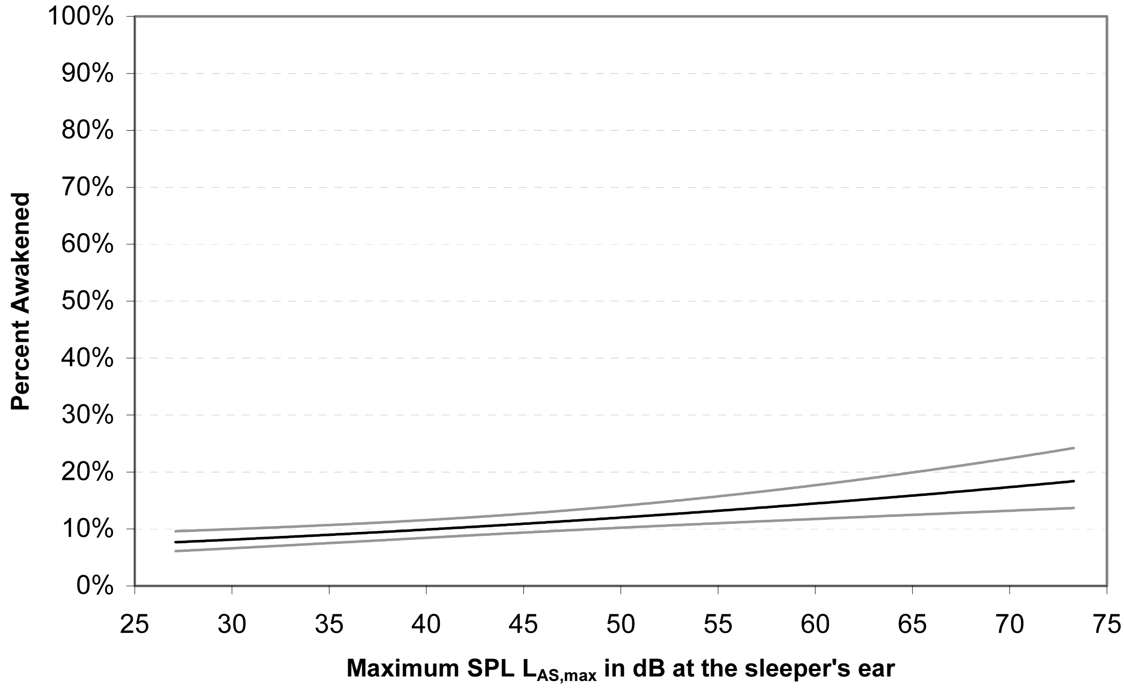


Figure 3: *Random effects logistic regression model based on the data of the field study (includes 95% confidence intervals, for explanations see text)*

Like in the laboratory studies, awakening probability rises with increasing maximum SPL, but in a much less steeper way. The model predicts an awakening probability of 7.7% at 27.1 dB(A) and 18.4% at 73.2 dB(A) (laboratory: 54%), respectively.
The differences between laboratory and field were observed over the whole range of maximum SPL values and rose with increasing SPL values.
The probability of spontaneous awakenings was calculated with a separate random effects logistic regression model, based on so called virtual ANEs [2]. Using similar values for TaSO and PSS, a spontaneous awakening probability of 8.6% was estimated. This value is surpassed only by ANEs with maximum SPLs higher than 32.7 dB(A), which means that a threshold value of 32.7 dB(A) was found in the field. In the laboratory, up to values of 45 dB(A) no threshold was found (spontaneous awakening probability in the laboratory = 6.3%).
The precision can be read from the width of the 95% confidence intervals. Because of the large sample size the precision of the prediction is high and varies between 3.1% at 39 dB(A) and 10.5% at 73.2 dB(A).

## 4 DISCUSSION

Total sleep time in the laboratory studies was only marginally influenced by aircraft noise. Possible reasons are adaptation mechanisms, leading to changes in sleep structure between two ANEs or the influence of an elevated sleep pressure induced by aircraft noise in preceding nights. Nonetheless, changes in sleep structure in form of reductions of SWS amounts were obvious, although not statistically significant. With actigraphy alone, it would not have been possible to observe these subtle changes in sleep structure.
Dose-response relationships between maximum SPL of ANEs and awakening probability revealed striking differences between laboratory and field studies. Reactions were much less frequent in the

field than in the laboratory. These differences have already been reported as the result of a meta-analysis by Pearsons [3]. We were able to confirm these results in our study.
Subjects sleeping in their familiar environment, including their own bed, is one possible reason for the differences observed in the laboratory and the field. Hume and Whitehead [4] showed in a study where subjects were exposed to ANEs via loudspeaker in the laboratory as well as in the field, that awakening probabilities at home were less pronounced than those observed in the laboratory. The different locations were the only reason for this difference, because the same ANEs were played back in both situations. The awakening probabilities at home were still higher than those reported by Pearsons [3] in the field, which may support the thesis that there is no general adaptation to aircraft noise, but rather an adaptation to the specific aircraft noise scenario experienced at home.

## 5 CONCLUSIONS

The world's largest polysomnographic study on the effects of nocturnal aircraft noise on human sleep was carried out by the DLR-Institute of Aerospace Medicine between 1999 and 2003. 192 subjects and 2,240 subject nights provided extensive data for the development of precise dose-response relationships between maximum SPL of ANEs and awakening probability. In connection with acoustical prognosis, these relationships will be used to precisely predict population groups who do not additionally wake up, exactly wake up one time, exactly wake up two times and so on by aircraft noise. This is shown exemplary for Frankfurt Airport in Figure 4.

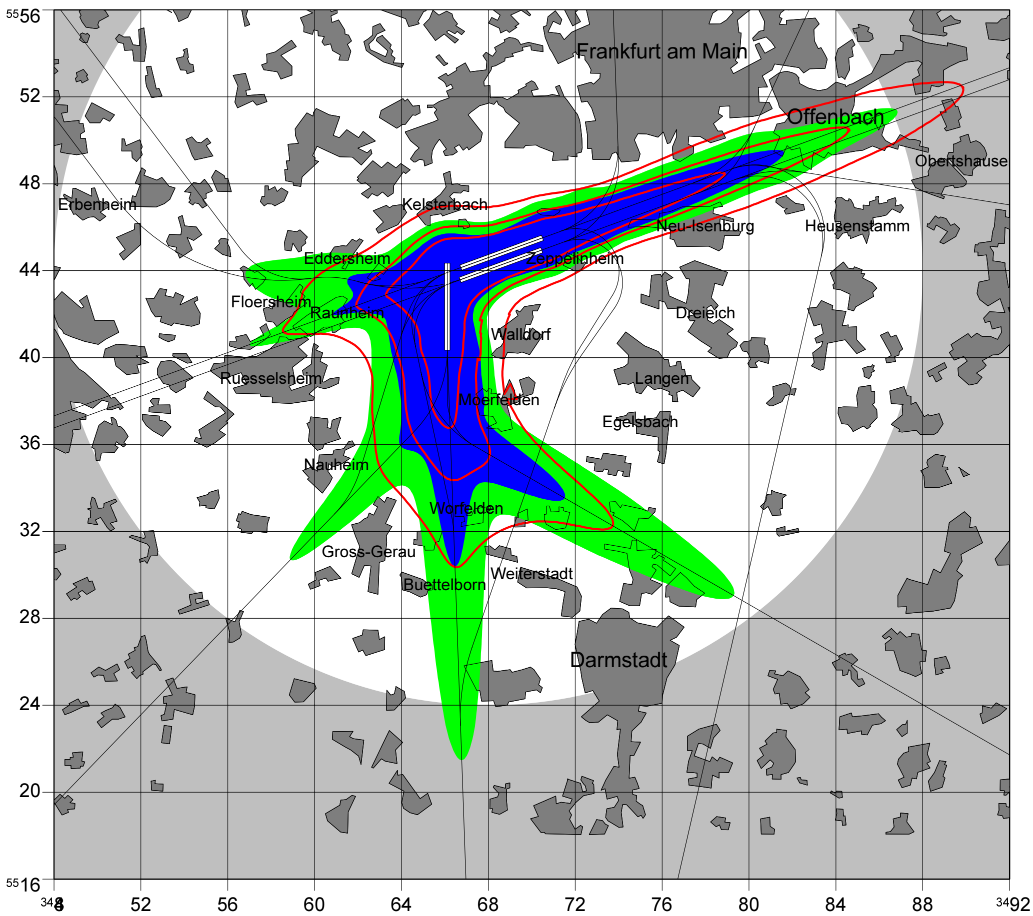


Figure 4: *Combination of acoustical prognoses and the dose-response relationship between maximum SPL and awakening probability found in the field for the prognosis of areas in which more than 3, 2 or 1 awakenings induced by aircraft noise are expected to be observed at Frankfurt Airport (see text).*

The green and yellow zones represent areas where an $L_{AS,eq(3)}$ of 50 dB (green) and 55 dB (blue) is expected to be exceeded. The red lines on the other hand represent areas outside of which less than 3 (inner area), less than 2 or less than 1 (outer area) additional awakenings induced by aircraft noise are expected. Clearly, qualitative differences of shape and size of the different areas can be seen.

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