Statistical assessment of the anti-collision system "AVES-Wind Onshore" for the white-tailed eagle against the background of the LfU-AKS test framework and the "KNE checklist"

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1. OVERVIEW AND SUMMARY OF THE RESULTS

With the AVES-Wind Onshore System, ProTecBird has developed an innovative AI-based anti-collision and monitoring system. As part of a pilot study in 2023, the performance of this system in terms of automatic bird detection and on-demand shutdown was investigated on two Nordex (N149) wind turbines. In particular, the performance of the system was tested against the background of the recently developed LfU-AKS test framework (2024) and in accordance with the KNE checklist (Requirements for anti-collision systems for the protection of birds at wind turbines - checklist for a qualified decision on the applicability of anti-collision systems, 2021) for the red kite (cf. Gross et al., 2024; Mercker, 2023). It was shown that all criteria of the KNE checklist and the LfU-AKS test framework are met for this species.

In this document, a supplementary assessment is carried out for the white-tailed eagle. As this is a supplementary assessment, the rates (detection rate, detection rate, overall rate) in particular are estimated and presented, but not (largely species-independent) points/contents that were already analyzed as part of the initial assessment, such as spatial coverage, evaluation at different locations or timely shutdown.

To determine the detection rate, a wide range of data was collected in advance at a wind farm on two wind turbines (type Nordex N149), analogous to Mercker (2023), which made it possible to assess the performance of the system with regard to the detection rate. The data collected included the following

- spatio-temporal laser rangefinder (LRF) data of the approaching target species (white-tailed eagle);
- spatio-temporal camera-based data of the approaching target species and other bird species from the AKS; and
- local-temporal monocular distance measurements by the AKS.

The results of the analyses of these data **yield a detection rate of 95 % [92 % - 97 %]** (detection range: 300-1000 m distance to the AKS) based on the GLMM method specified in the test framework.

With regard to the detection rate (also called classification rate), this is estimated based on AKS camera data in order to present and apply an accelerated method for the integration of further species, analogous to Reichenbach et al. (2024). We thus follow the suggestions of the LfU-AKS test framework, which states: "*If the determination of the detection rate is based on AKS instead of LRF data, the method must be adapted to enable a statistically correct determination of the overall / protection rate and its confidence intervals*".

In particular, in the present report we compare two different detection rate analysis methods (the method of Reichenbach et al., 2024, with a GLMM method similar to the method specified in the testing framework) and show that both approaches provide highly comparable results.

In particular, the two approaches deliver **detection rates of 87% [82% - 91%] and 86 % [82 % - 89 %]** (in the range up to about 1000 m distance to the AKS) and thus highly comparable results.

With regard to the KNE checklist, it is required that it is shown that the average detection rate is at least 75% for at least the response area (but ideally for at least 500 m around the AKS). In individual cases, i.e. under particularly critical conditions in terms of nature conservation, up to 90 % may be required. With regard to the detection rate, the KNE checklist requires that it significantly exceeds 75 %; ideally, it should be 90 %.

Simple mean value calculations of the rates (based on the LRF data for the detection rate and based on the AKS camera data for the recognition rate) yield 96% (detection rate) and 94% (recognition rate). **The criteria of the KNE checklist are therefore fulfilled for the AVES system and the white-tailed eagle.**

With regard to the LfU-AKS test framework, it is required that the overall rate (evaluated with adequate GLMM methods including consideration of temporal autocorrelation) in the detection area shows a 95% confidence interval whose lower limit ("lower limit of the confidence interval"= UGK) is at least 70%. To meet the requirements, the confidence intervals of the overall rate (combination of detection and recognition rate) must therefore be estimated. As the determination of both rates in the present case is based on different data sources (and they are not used in the "regular" case that both are based on identical LRF tracks, are presumably complex and correlated track by track), this estimation is not trivial.

This report takes two different approaches to this:

(1) For the red kite, it has already been shown for the AVES system that a detection rate with a UGK of 92 % and a recognition rate with a UGK of 79 % lead to an overall rate with a UGK of 75 % (cf. 380-580 m distance to the AKS in Gross et al., 2024; Mercker, 2023) - with adequate consideration of the above correlation between the two rates. Since in the present case of the white-tailed eagle the UGKs of both rates are at the same level (detection rate) or even several percentage points higher (recognition rate), it can be assumed to a large extent that the UGK of the overall rate is even higher than 75 % and thus meets the minimum criterion of the AKS test framework (> 70 %) - taking into account the complex correlations between the two rates.

(2) In order to investigate the question of the combination of both rates directly by calculation, two variants of the delta method were used to derive an overall rate and its confidence intervals from the mean values and confidence intervals of the individual rates. These two delta method variants were in turn carried out separately for the results of the two possible o.
g. Analysis methods in terms of detection rate. The total of 4 results provided highly similar mean values of overall rates of 82-83% and UGKs of 77-78%. However, it should be noted that the delta method implies that both rates are uncorrelated (which is probably not the case) and

the results may therefore be distorted. However, as the UGKs estimated in this way show a clear gap to the required 70 %, it can be assumed to a high degree that the unbiased value is still above 70 %.

Taken together, the results thus show that the minimum criteria of the LfU AKS test framework with regard to the AKS overall rate validation for the AVES system and the white-tailed eagle are fulfilled.

Finally, it should be noted that although the methods presented under (1) and (2) are, in our opinion, robust and suitable for the present data situation with the white-tailed eagle, this approach cannot be easily transferred to other species or data situations. On the one hand, because in the present case the detection rate was still determined based on LRF tracks (which means a considerable field effort that should be avoided in the future for reasons of simplification and acceleration for supplementary checks), on the other hand, because in the present case of the white-tailed eagle the UGKs of both rates are at the same level (detection rate) or even several percentage points higher (recognition rate) than those of the intensively studied red kite - which is not necessarily the case for other species, so that the same reasoning cannot be followed there. In the present case, the results of the delta analyses also measured a clear distance from the required 70 % of the UGK, so that the simplified assumption of the independence of both rates (and the resulting possible distortions of a few percentage points) can be classified as unobjectionable. Here too, the result for other species may be "narrower", so that the same reasoning cannot be followed here either.

In order to ensure an accelerated and robust analysis of AKS rates for other species under diverse data situations in the future, a methodology should be developed that (1) clarifies under which circumstances it is appropriate from a nature conservation perspective to link AKS data-based detection rates of one species with LRF data-based detection rates of another species, and (2) develops a linking method that takes into account the presumably complex correlation structures between detection and detection rates.

2. DEFINITION AND DETERMINATION OF THE REACTION AND DETECTION RANGE

The reaction area defines the project-specific cylindrical 3D airspace around the WTG rotor center, at the edges of which a bird must have been detected and classified at the latest in order to ensure a timely shutdown of the WTG. The radius of this cylinder is determined, among other things, by wind turbine-specific dimensions and the horizontal flight speed. This area is defined even more specifically in the LfU test framework and its height also depends on the vertical flight speeds (see LfU-AKS test framework, to which the following passages are largely based).

The detection zone, on the other hand, defines the 3D airspace around the AKS, which is used as part of the AKS validation (empirical determination of the rates) and for which a sufficiently high and validly determined detection, recognition (KNE checklist) or overall rate (LfU-AKS test framework) is required. The approval procedure then checks whether the project-specific (cylindrical) response area is protected/covered by the (or one of the investigated) detection area(s).

According to the LfU-AKS test framework, this is the case, for example, if either the reaction area is included in the detection area or if the detection area surrounds the reaction area in a ring shape in such a way that the relevant airspace around the reaction area is monitored and birds entering the reaction area are reliably detected and recognized. This annular view is relevant for the AVES Wind Onshore System, as it specializes in detection and recognition over longer distances and primarily monitors the area surrounding the reaction zone.

In the case of the AKS camera data with regard to the analysis of the detection rate, it was not possible to precisely locate the tracks in the direct vicinity of the AKS; therefore, only those tracks were selected that showed a distance of < 1000 m to the AKS. This consideration of a circular instead of a ring-shaped detection area with regard to the detection rate therefore represents a conservative approach from a nature conservation perspective with regard to the AVES system, as it is - as mentioned above - not specialized in the close range. In the case of the analysis of the detection rate (in the context of which an exact localization of the LRF tracks was also possible at close range), the annular area with a distance of 300-1000 m to the AKS was considered in this report. In both cases, therefore, up to a distance of 1000 m is analyzed in order to be able to cover the widest possible range of future/real reaction areas in the context of approval procedures. In addition, the coverage areas examined in this report are not limited either upwards or downwards, but all LRF or AKS camera tracks are analyzed that are within the coverage areas when viewed horizontally. In this way, even birds flying from the ground or far above into the response area are reflected in the determined rates; this is therefore also a conservative approach in terms of species conservation.

As the present project is a multi-camera AKS system that adapts the number of cameras to the specific project, a total of four cameras were used in the present field experiments for the rates/validation. The detection area was adjusted accordingly (one "pie slice" per camera).

3. DATA & FIELD AND STATISTICAL METHODS

3.1 Data basis LRF data

The LRF data were collected on 10 different days between 19 September 2024 and 7 October 2024 at two different locations (but only about 70 m apart) and contain a total of 1,860 measured LRF points from 71 different sea eagle flight tracks at distances between 70 and 2,189 meters. These were restricted to the range between 300 and 1000 m from the AKS. In addition, only those LRF tracks were used (in accordance with the LfU-AKS test framework) that comprised at least 4 different points in the analyzed survey area, as they can lead to a disproportionately large increase in variance or to biased results in the context of the regression methods (see below) with often very small proportions of the total data. In addition, LRF / GPS tracks with only a few points are usually flights with no risk of collision, where the bird only appeared briefly in the detection area. In total, 55 different LRF tracks of the white-tailed eagle remained in the analyzed detection area.

3.2 Methodology of field trials and allocation of AKS vs. LRF

The concept for investigating the detection rate is based on the comparison of birds detected in the field (spatially and temporally located) by ornithologists with those detected by the AVES Wind Onshore System. The observers used laser rangefinder (LRF) devices, which can locate the birds relatively precisely (Ransom & Pinchak, 2003). For this reason, it is assumed in the following (simplified) that the LRF data are in principle not subject to any significant spatial and/or temporal error. The local error of the AVES-AKS has already been quantified in Mercker (2023).

An a priori pre-selection of the LRF points was carried out exclusively with regard to the question of whether or not they were located in the "pie slice" in front of the camera (see above). These "pie slices" contain more airspace than the wedge-shaped cones of view of the cameras can capture when viewed from the side. This automatically results in the consideration of the technically required "coverage rate".

For this and for the assignment of LRF point vs. AKS signal ("matching"), the
The following considerations/work steps were carried out:

1. Using the LRF coordinates, the camera positions and the calibrated camera angle scale, theoretical angles (pan, tilt) were generated for each point at which the bird can be seen;
2. The detection area is a circular ring around the camera (which is attached to the WTG) with a fixed inner and outer radius and a fixed height. Horizontally, the detection area extends over a viewing angle of 30° per camera ("pie slice");

3. The log files of the AVES Wind Onshore system provided the actual angles at all times. It was also possible to derive what the default orientation is, which defines the location of the fixed detection area. The default orientation was determined algorithmically from the log files to avoid (error-prone) hard-programmed angles. As the cameras can only return to a default value with a limited tolerance even after tracking a bird, the horizontal angle of the default orientation may fluctuate by up to 1° over the course of a session;
4. Check that each point can be recorded:
    a. All points in the area defined above were considered detectable (hereafter "detectable" is synonymous with "within the pie slice" - see above for the consideration of the technical coverage rate at this point);
    b. The cameras can be automatically panned to track birds. This results in an additional "dynamic" field of view of a camera, which can be limited to a width of less than 30° by zooming. An LRF point whose angle was within this dynamic field of view was considered detectable if it was within the inner and outer edges of the circular ring. LRF points were considered detectable if an angle match was achieved (see below). This is necessary because the calculation of whether an LRF point is within the dynamic field of view often leads to errors, as the angle interval of the field of view at maximum zoom is < 4°, which is well below the accuracy of the angle calculation. Example: a bird is tracked and zoomed in to a viewing angle of 3°. The calculation using the angles shows that the bird can theoretically be seen at pan=34°. The dynamic camera range is Pan= [37° -1.5°, 37°+1.5°]. According to the figures, the LRF point is therefore not in the camera's field of view. The system indicates a tracked bird at 37.3°. The difference between the two angles is 3.3°. This is within the assumed tolerance of 11°. The bird is considered tracked and therefore also trackable. As a result of the checks described above, birds detected to the side and above the detection range were included in the analysis. However, the radial distance condition was strict, i.e. LRF points with a radial distance lower than the inner radius or higher than the outer radius of the circular ring were never considered detectable;
5. Check detection/angle matching:
   In the event that a track entry was available at the LRF time, it was checked whether the theoretical angles (LRF pan, LRF tilt) correspond to the angles of the tracked object (track pan, track tilt). A tolerance of 11° (pan) or 9° (tilt) was used in the calculation. If the conditions described above are met, the LRF point is counted as detected.
6. Determine AI classification:
   A time interval was set around each LRF point. This went up to half the time until the next LRF point of the same track. For LRF points at the beginning or end of an LRF track ID, 3s were added before or after the LRF time point. Within the time interval determined in this way, the classifications of the AI were collected from all log file entries and the most frequent entry under 'final

class' was the AI class of the LRF point. The AI classes are given by the classes "target" (here white-tailed eagle), "non-target" (all other bird species) or "bird" (undetermined bird). The "final class" is already an averaging of all previous individual classifications of the currently recorded bird, specially adapted for the application purpose. Side note: it is also possible to read out an AI classification without a suitable angle matching, e.g. if the system is tracking a different bird than the one mapped by the LRF.

7. Determination of the final variable "white-tailed eagle detected and recognized" vs. "not detected or recognized":
   If an LRF point produced a successful angle match with the system data and the Kl classification matched the actual bird species, the bird was considered correctly detected and recognized.

The correct realization of the assignment between LRF and AKS camera data was randomly checked using the LRF vs. AKS raw data.

3.3 Data basis AKS camera data

In live operation of the AVES Wind Onshore system, all birds are tracked and a video is automatically saved for each detection. Normally, these videos show how a bird that is initially far away is continuously tracked and gradually zoomed in on. The video ends as soon as AVES stops tracking,
i.e. as soon as the live AI no longer consistently recognizes a bird. Numerous videos were recorded during the recording period. The actual bird species in the videos was subsequently determined by ornithologists.

This results in a series of videos in which a sea eagle can actually be seen, regardless of the classification by the live AI. This video series represents the test data set for validation. The videos have now been analyzed frame by frame offline using a renewed AI. For this purpose, all calculations and parameters are selected in such a way that they simulate live operation. This provides one AI class of the bird per video frame, analogous to live operation. The detection rate can then be calculated from the list of AI classes per frame. It is important to note that the updated AI was not trained with the videos from the test data series. This was ensured by excluding videos from the acquisition period from the AI training data.

Since the videos in the test data series correspond exactly to the conditions in real operation in terms of perspective, zoom level, etc., the offline processing by the renewed AI realistically simulates live operation.

A total of 64 different camera tracks of the white-tailed eagle were available with 600,737 individual images from 11 different recording days between 18.09.2024 and 07.10.2024.

3.4 Statistical determination of rates

Statistical models

The data to be analyzed are binary variables that, for example, distinguish between "detected" and "not detected" or "detected" and "not detected" (1 vs. 0). In the simplest case, mean values of the corresponding rates can be determined here. However, this evaluation method is not adequate from a statistical point of view, as several underlying conditions are violated (see below) and it therefore provides distorted results. Nevertheless, it was used in parallel with the statistically adequate methods described below, as previous/earlier analyses (such as those based on the KNE checklist) have used these or similar methods, thus ensuring comparability in principle. This method is referred to below as the "**mean value**" and the calculation of the 95% confidence intervals is based on the application of suitable linear "intercept-only regression models".

However, the statistical situation is actually somewhat more complex: on the one hand, the binary variable is obviously non-normally distributed data, so that regression models with an appropriately adjusted random distribution must be used ("generalized models"). Secondly, time series are investigated (i.e. consecutive measurement points are potentially strongly correlated), and finally, the LRF points can be assigned to different individuals, so that the independence of the individual measurement points is violated in several respects and thus a problem of "pseudo-replication" exists (Hurlbert, 1984), which can lead to a (possibly significant) underestimation of confidence intervals and to distorted determined rates. Although temporal autocorrelation is also part of the system performance (it reflects the ability of the system to track detected birds), not taking temporal autocorrelation into account can, among other things, lead to the influence of very long (or "well tracked") tracks being given a very high weighting compared to the important criterion of detection and recognition. This "attenuation" of the influence is achieved by adequately considering the autocorrelation.

For this reason, an analysis strategy was used that adequately takes this data situation into account (see method specification and motivation in the LfU-AKS test framework). In particular, the analysis (as motivated above) was carried out using suitable regression methods, the "logistic regression methods", which belong to the "generalized linear models" (GLMs) (Bolker et al., 2008; Field et al., 2012; A. Zuur et al., 2007). The affiliation to different individuals/tracks was taken into account here by using the track ID as a "random intercept" in the context of "mixed modelling", which led to the class of "generalized linear mixed models" (GLMMs) (Bolker et al., 2008; Pinheiro & Bates, 2000; A. F. Zuur et al., 2009). In addition, the strength of the temporal autocorrelation was analyzed using pACF plots and integrated as a suitable autoregression structure (Korner-Nievergelt et al., 2015; A. Zuur et al., 2007; A. F. Zuur et al, 2009). Further details on the method and its motivation can be found in the LfU-AKS test framework (2024). This method is referred to below as "**GLMM_AC**" ("generalized linear mixed model with temporal autocorrelation") and the calculation of the 95%-

Confidence intervals were based on the application of the "intercept-only regression models" of this model class. This method was used in the analysis of the detection rate; but also (as an alternative to the "bootstrap track-mean" method - see below) in the analysis of the recognition rate. In the latter case, the closely timed AKS camera tracks were thinned to such an extent that the residuals of the subsequently used GLMM showed an autocorrelation of strength 1 (and not yet 2); an AR-1 structure was then integrated into the model.

In the case of the analysis of the detection rate, the recently published method by Reichenbach et al. (2024) was also established and applied as an alternative approach. In particular, the detection rate was analyzed separately for each track, its mean value was calculated, and 95% confidence intervals were calculated using suitable percentiles of 10,000 bootstrap samples at track level. This method is described below as "**Bootstrap track-mean**" designated.

The open source software **R** was used for all statistical analyses (R Core Team, 2024).

Since the AVES Wind Onshore System is a multi-camera AKS system, an evaluation of tracks or rates was carried out in which the overall system was considered as a recording unit. This is permitted as all cameras (through data exchange) together generate a clear reaction of the overall system (i.e. a shutdown signal if necessary) or each camera is able to send a shutdown signal on its own (without prioritizing individual cameras).

Model validation

The model was validated using various model residual plots, as described in Korner-Nievergelt et al. (2015) and A. F. Zuur et al. (2009, 2010), among others. In particular, the conditions of independence (such as the strength of the temporal autocorrelation), the existence and influence of outliers, the normal distribution of the "random intecept" and tested/checked for over- or under-dispersion. No clear violations of these conditions were detected.

Estimation of the total rate using the delta method

Two variants of the delta method were used to multiply two proportion-based estimates, in this case the detection rate and the recognition rate, in order to derive an overall rate and a corresponding confidence interval. In both cases, the calculation was based on the assumption that the two estimators are independent of each other (which is presumably not the case with this degree of precision, see Section 1).

The classic variant of the delta method is based on linear error propagation using the first derivative of a function. For the product of two expected values, this means that the variance of the product can be described by the sum of the variances of both terms weighted by the respective other expected value . The associated standard error was calculated from the given confidence intervals were derived, assuming symmetrical intervals and normally distributed errors. A 95 percent confidence interval for the overall rate was then calculated on the basis of the estimated standard error. A normal distribution of the errors cannot be assumed in the present case due to the binomial data; nevertheless, we applied this method on the assumption that this error is not very strong and since this variant is known to be particularly well established and robust in the delta method.

The second variant of the delta method was based on the distribution structure of proportions by modeling the uncertainties not as normally distributed, but as beta-distributed random variables (distribution between 0 and 1). For this purpose, a beta distribution was parameterized for each of the two rate values, the shape parameters of which were calculated on the basis of the estimated rates and the approximated effective sample size. The latter was obtained by back-calculation from the standard error under the assumption of a binomial basic distribution. As part of a Monte Carlo simulation, 10,000 random values were drawn from each of the two beta distributions and then multiplied in pairs. The mean value and the 2.5, 50 and 97.5 percentiles were determined from the resulting distribution of the products in order to derive the mean value and confidence interval of the overall rate. In contrast to the classic delta method, this method therefore takes into account the asymmetrical nature of proportion distributions and the reduced effective information density/sample size due to the model structure (in particular the temporal autocorrelation)

Both variants were used in parallel to reveal possible distortions due to distributional assumptions and to check the robustness of the overall estimate.

4. RESULTS

Capture rate

The results for the detection rate are shown in Figure 1. Using the GLMM_AC method, a detection rate of 95% [92% - 97%] is measured; using simple averaging, a rate of 96% [95% - 97%] is measured. The requirements of the KNE checklist (rates of at least 75 % - in individual cases over 90 %) are therefore met to a high degree.

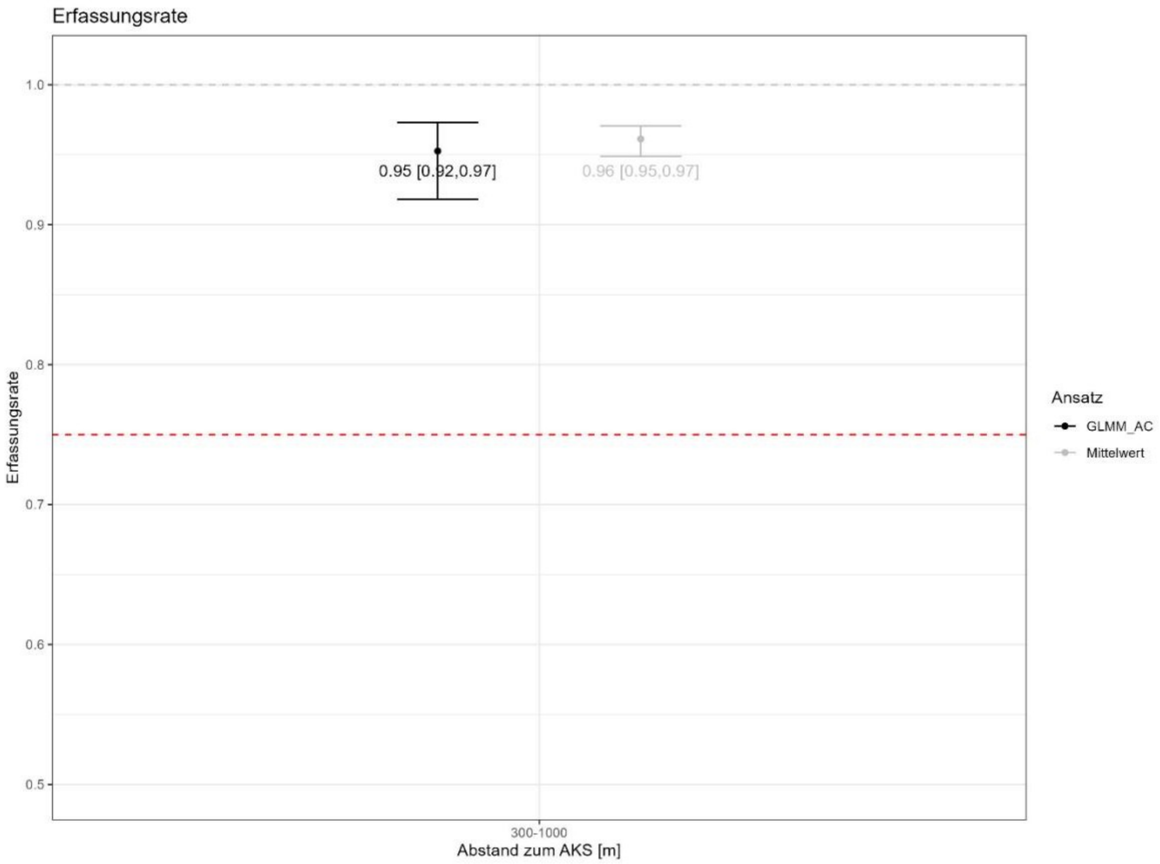

Figure 1: The results of the detection rate and 95% confidence intervals based on the GLMM_AC method (black dots/error bars/numbers) and simple averaging (black dots/error bars/numbers). Red dashed line indicates the minimum criterion of the KNE checklist with regard to the mean value (75%).

Recognition rate

The results for the detection rate are shown in Figure 2. A recognition rate of 86 % [82 % - 89 %] is measured using the GLMM_AC method, a very similar rate of 87 % [82 % - 91 %] using the bootstrapped track-mean method and a rate of 94 % [94 % - 95 %] using simple averaging. With regard to the latter rate, this is an example of how an overestimation of the rate and an extreme underestimation of the confidence intervals can be observed with strongly time-autocorrelated data.

The requirements of the KNE checklist (rates of at least 75% - ideally 90%) are therefore also met here.

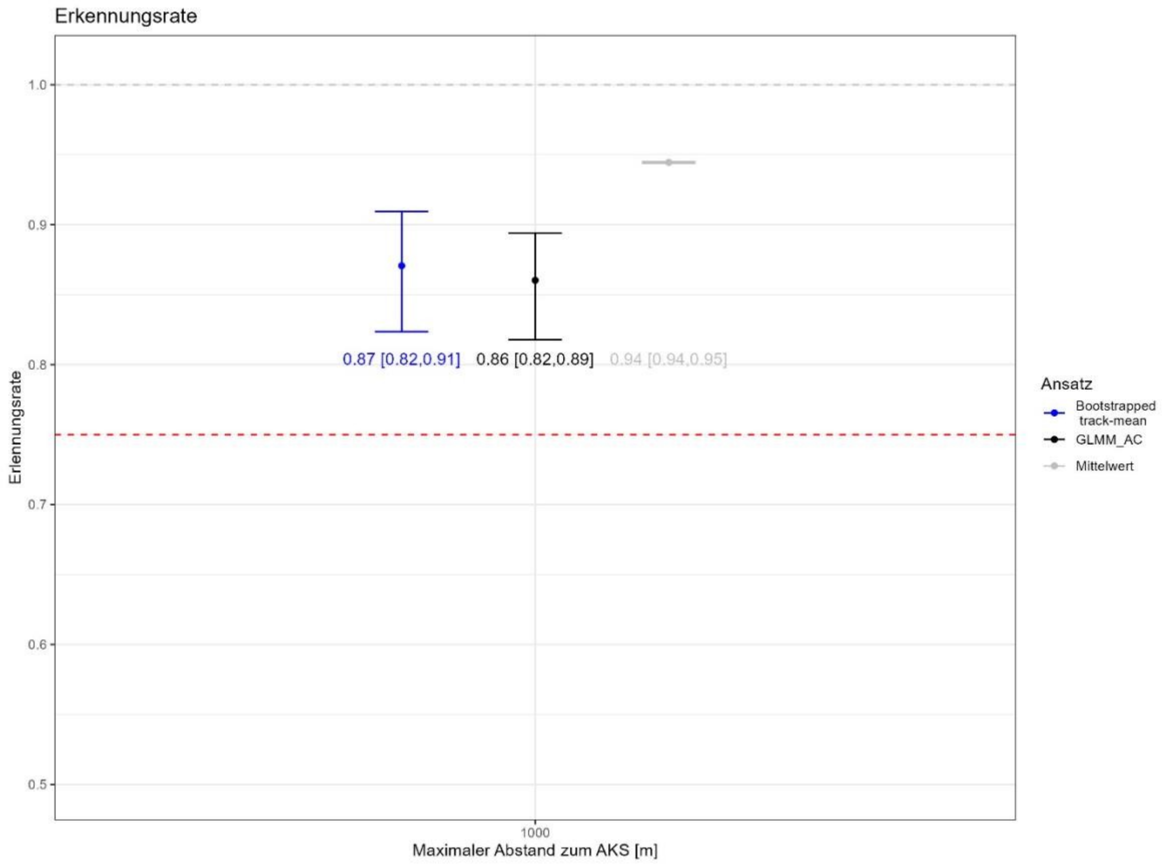

Figure 2: The results of the detection rate along with 95% confidence intervals based on the GLMM_AC method (black dots/error bars/numbers), the bootstrapped track-mean method (blue dots/error bars/numbers) and simple averaging (black dots/error bars/numbers). The red dashed line indicates the minimum criterion of the KNE checklist with regard to the mean value (75 %).

Total rate

The results for the overall rate (using two different delta methods) are shown in Figure 3 and Figure 4. The total of 4 results provide very similar mean values of the overall rate of 82-83% and lower limits of the 95% confidence intervals of 77-78%) - which speaks for the robustness of these estimates.

Note on interpretation: The application of the delta method assumes that the two rates are independent of each other - an assumption that is probably not fulfilled in practice. This can potentially distort the results. However, as the lower limits estimated in this way are well above the required 70 %, it is very likely that the actual (unbiased) value is also above this threshold.

In addition, it has already been shown for the red kite that the AVES system, even taking into account the presumed correlation between detection and recognition rate mentioned above, shows an overall rate with a lower bound of the confidence interval (CI) of 75 % - based on a detection rate with a CI of 92 % and a recognition rate with a CI of 79 % (cf. 380-580 m distance to the AKS in Gross et al., 2024; Mercker, 2023). In the present case of the white-tailed eagle, the UGKs of both partial rates are at least at a comparable level (detection rate) or even higher (recognition rate) - as shown in the previous chapters. It is therefore highly likely that the CI of the resulting overall rate is also above 75 %, which fits very well with the 77-78 % calculated above.

Based on these results, we assume that the criteria of the LfU-AKS test framework are met to a greater extent for the AVES system and the white-tailed eagle.

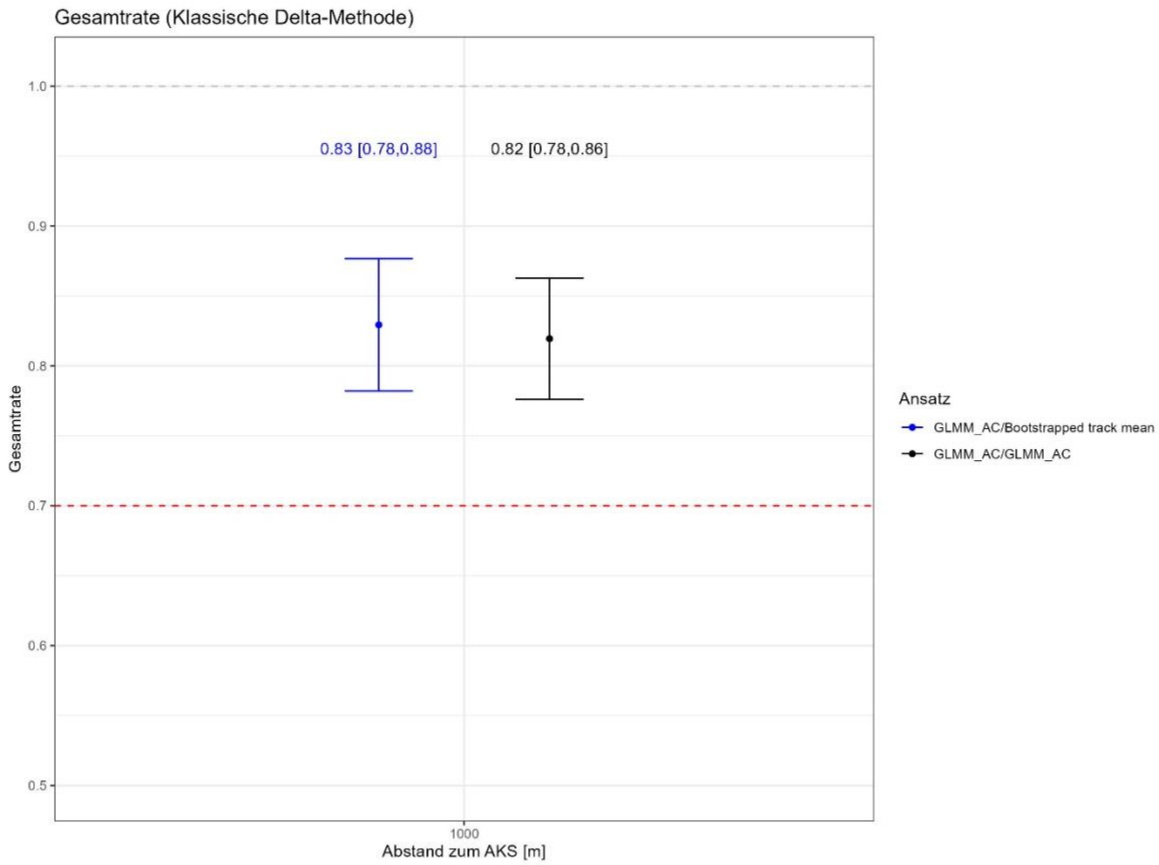

Figure 3: The results for the overall rate (classic delta method) together with 95% confidence intervals based on the GLMM_AC method (detection rate) in combination with the bootstrapped track-mean method (blue dots/error bars/numbers) or again the GLMM_AC method (black dots/error bars/numbers) with regard to the detection rate). Red dashed line indicates the minimum criterion of the KNE checklist for the lower limit of the confidence interval (70 %).

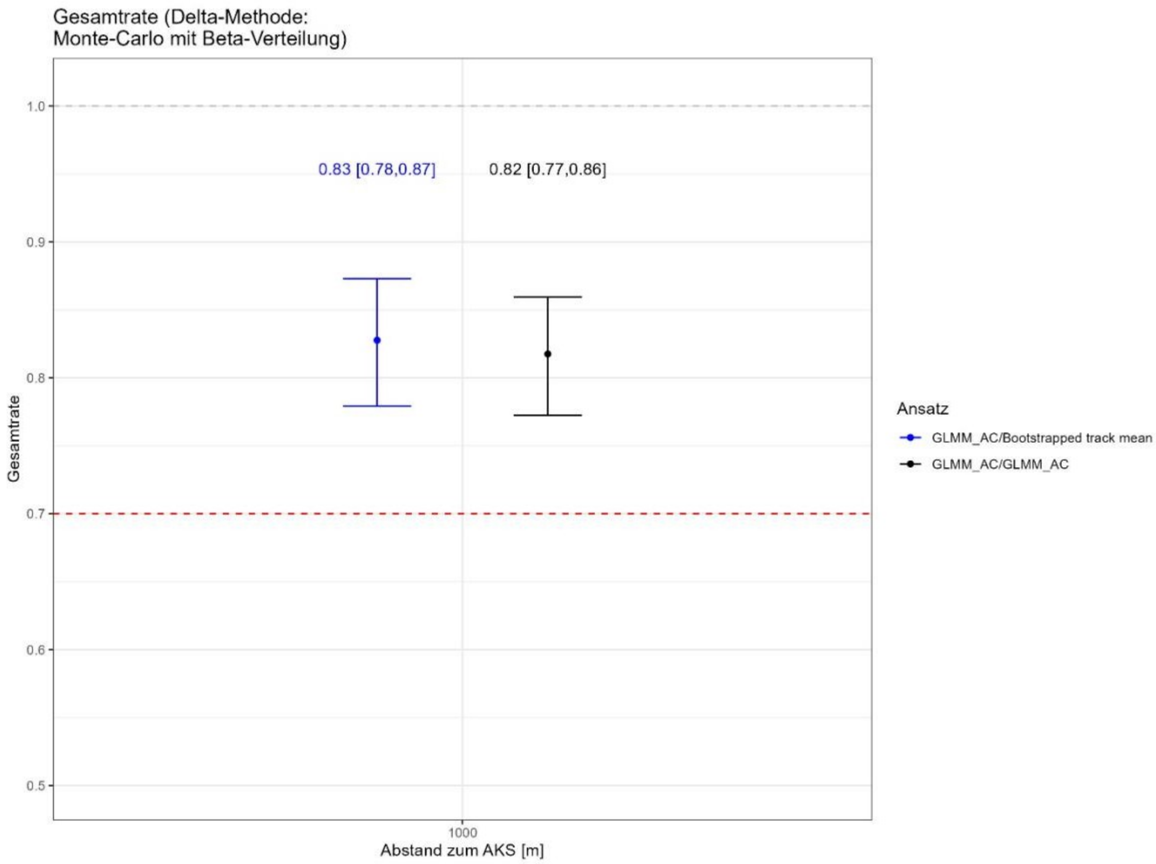

Figure 4: The results for the overall rate (delta method in combination with Monte Carlo simulations and the beta distribution) together with 95% confidence intervals based on the GLMM_AC method (detection rate) in combination with the bootstrapped track-mean method (blue dots/error bars/numbers) or again the GLMM_AC method (black dots/error bars/numbers) with regard to the detection rate). Red dashed line indicates the minimum criterion of the KNE checklist for the lower limit of the confidence interval (70 %).

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