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Counting shorebirds using high-resolution aerial imaging: a pilot study in the Schleswig-Holstein Wadden Sea, Germany

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Knowledge of migratory shorebird population changes and site use is important to develop sound conservation measures. In the Dutch-German-Danish Wadden Sea, a key intertidal staging site for migrating shorebirds within the East Atlantic Flyway (Meltofte *et al.* 1994, van de Kam *et al.* 2004, van Roomen *et al.* 2025), monitoring abundance and distribution of migratory shorebirds is a long-standing tradition (Meltofte *et al.* 1994, Blew *et al.* 2016, Kleefstra *et al.* 2022a, 2025). Numbers are monitored by a network of professionals and volunteers within the Trilateral Monitoring Assessment Program (TMAP) at up to 600 counting units (Kleefstra *et al.* 2022a, b, 2025). In the Schleswig-Holstein Wadden Sea, Germany, ground-based counts of high-tide roosts have been used at around 60 spring tide counting sites once or twice a month. However, some high tide roosts of potential importance might not be (regularly) counted as they are located on remote and difficult to access sandbanks, and not all of them are part of the regular counting scheme. Consequently, in Schleswig-Holstein, significant proportions of migratory shorebirds may not be recorded during such standard ground-based counts.

Aerial surveys offer an alternative method to ground-based counts. Although aerial surveys are currently conducted in the German Wadden Sea when counting e.g. Harbour Seal *Phoca vitulina*, Common Eider *Somateria mollissima* and Shelduck *Tadorna tadorna*, migratory shorebirds have rarely been counted from the air. There have only been three observer-based airplane surveys which have covered some of the German Wadden Sea – in 2007, 2012 and 2014 (Scheiffarth & Becker 2008, Frank 2014, Kempf *et al.* 2015). Even though these surveys detected large numbers of roosting shorebirds in remote locations not usually accessed on foot during high tide counts, aerial surveys have not become a standard method and remote locations like these have not been monitored on a regular basis, if at all.

Observer-based aerial surveys usually require the aircraft to fly at low speed and low altitude, ranging from ~60 m (200 ft) to ~150 m (500 ft; Laursen *et al.* 2008, Scheiffarth & Becker 2008, Kempf *et al.* 2015). Typically, birds are identified and counted directly, and/or photographs of flocks are taken for subsequent cross-validation and analysis. However, due to the relatively low flight altitude, such observer flights carry the risk of disturbing and flushing resting birds (Laursen *et al.* 2008). Low flight heights also create safety risks for pilots and observers. For this reason, since 2012, the Standardised European Rules of the Air define the lowest safe altitude as 150 m (500 ft; SERA5005(f)(2); Regulation (EU) No 923/2012).

Alternatively, digital aerial imaging surveys, where high resolution camera systems are integrated in an aircraft, have proven to be efficient and precise when surveying seabirds and waterbirds, even in direct comparison with flights using observers (Žydelis *et al.* 2019). The camera systems collect videos which are later analysed frame by frame. As the aircraft can fly faster and at higher altitudes (> 500 m or 1,800 ft), these digital imaging surveys are able to cover a larger area at one time, with potentially less disturbance than observer surveys. We tested the suitability of digital imaging survey flights as a method to assess numbers and site use of migratory shorebirds in the Schleswig-Holstein Wadden Sea, Germany.

On 15 May 2015, we used digital aerial imaging to survey 14 uninhabited barrier sandbanks and the shores of the uninhabited island Trischen (Fig. 1). The survey flight lasted 2 hrs 47 mins and started at 10:36 hrs (all times are Central European Standard Time) in the southernmost area (Gelbsand) and finished at 13:23 hrs in the northernmost area (Kormoraninsel). High tide in Büsum was at 11:03 hrs and at 12:08 hrs in Husum. The high tide during the survey was at a height similar to mean high tide.

The digital survey was carried out with a two-engine high-wing Partenavia-P68 Observer plane, equipped with a customized 4-camera system from HiDef Aerial Surveying Limited UK (for a more detailed account of the HiDef methodology see also Weiss *et al.* 2016, Žydelis *et al.* 2019). The system consists of high-resolution digital cameras, recording with 2 cm/pixel ground resolution, mounted below the aircraft to record the ground in parallel strips. For the purpose of capturing all sites and flocks completely, the field of view of adjacent cameras overlapped by ~10 m, resulting in a transect width of ~520 m. The distance between transects was 400 m to again allow for overlapping footage, so as not to miss roosting birds. To avoid sun reflections that might hinder species identification (glare), the camera system was mounted at a 30° angle and directed to either scan forward or backward. GPS positions of the aircraft were recorded at 1-second-intervals. Flight altitude was 549 m (1,800 ft) with a flight speed of 222 km/h.

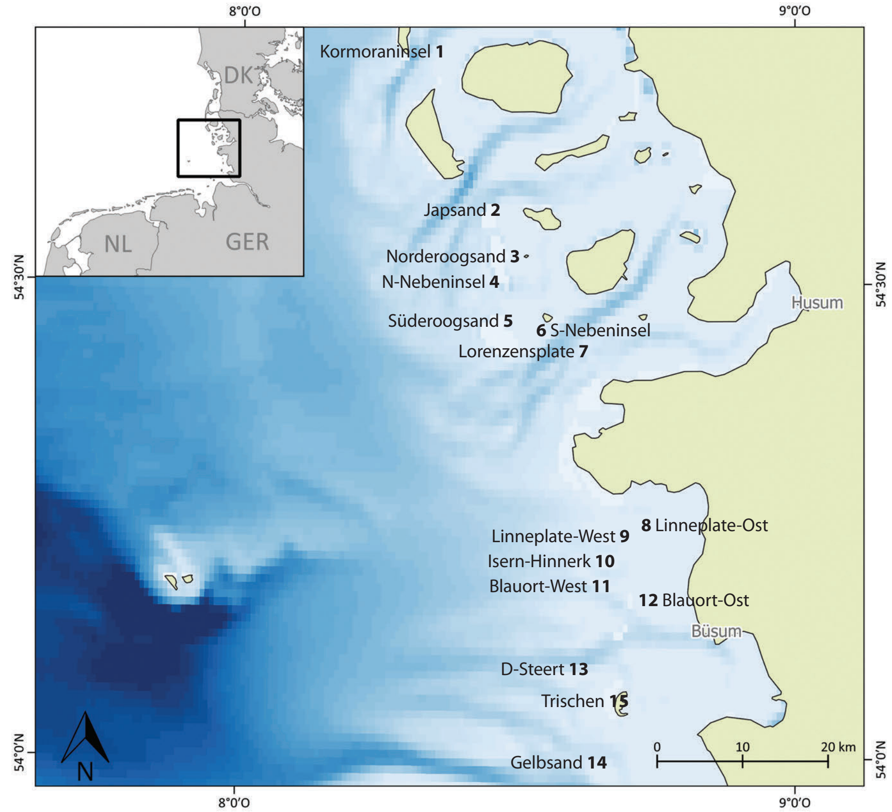

Fig. 1. Study area in the Schleswig-Holstein Wadden Sea, Germany, with the estuary of the river Elbe (the river mouth being cut off at the southern end of the large map but visible in the inset) as the southern border and the southern tip of the island of Sylt (close to the Danish border) as the northern border. Basemap of landmass outline: © EuroGeographics (2020). Basemap of bathymetry: GECBO Compilation Group (2014).

Trained staff screened the video material frame by frame for roosting flocks using StreamPix 6 digital video recorder software (Norpix Inc., Montreal, Canada). All images containing birds were marked, and their location was visualised in GIS, using the GPS information recorded by the plane. This procedure allowed us to identify flocks stretching over several images of neighbouring cameras within and across transects. In such cases, all images showing (parts of) a given flock were digitally assembled. This eliminated any overlap, resulting in one stitched image per roosting flock, thereby avoiding double counts. In a second step, single and stitched images of roosting birds were passed on to ornithologists, who identified birds individually to species level by their size, plumage colours, and morphology, which was possible for about three-quarters of shorebirds (details below).

Grey Plover *Pluvials squatarola* could be clearly identified by their distinct white neck and head breeding plumage patterns (Fig. 2). Red Knot *Calidris canutus* and Bar-tailed Godwit *Limosa lapponica* were readily identified by their reddish breeding plumage and were distinguished according to their different body size, especially when compared to Grey Plover. Smaller shorebird species such as e.g. Dunlin *Calidris alpina* or Sanderling *C. alba* were more difficult to distinguish. Birds that could not be assigned to a species were collated in species groups, such as small or large shorebirds whenever possible. We defined small shorebird species as comprising species like Dunlin, Sanderling, Common Ringed Plover *Charadrius hiaticula*, Red Knot and other shorebirds of similar size, while we defined large shorebirds as including Eurasian Curlew *Numenius arquata*, Bar-tailed Godwit, Eurasian Whimbrel *Numenius phaeopus* and similar sized species. While identifying the birds, they were also individually counted using the software ImageJ (Rasband, W.S., ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA, https://imagej.net/ij/, 1997-2018; Fig. 3).

We detected a total of 215,234 birds (including cormorants, gulls, terns, ducks and geese), of which 14 individuals could not be assigned to any species group (<0.01%). We counted 190,422 shorebirds, of which we identified 144,720 individuals (76%) to species level. The other 45,701 shorebirds (24%) we could allocate to a higher-level classification: small (43,345 individuals) and large (1,126 individuals) shorebirds, respectively. Among those identified to species level, Red Knot made up the most of all identified shorebirds (119,014), followed by Bar-tailed Godwit (13,761), Grey Plover (9,672), and Eurasian Oystercatcher *Haematopus ostralegus* (1,187: Table 1). The highest shorebird numbers were counted in the northern part of the study area (Nordfriesland, sites 1–7: Fig. 1), while the barrier sandbanks in the southern part (Dithmarschen, sites 8–15: Fig. 1) had lower numbers (Table 1).

Table 1. Individual shorebirds counted per species/species group and site during a digital aerial imaging survey on 15 May 2015 in the Schleswig-Holstein Wadden Sea. Sites 1–7 are located in Nordfriesland and Sites 8–15 in Dithmarschen. For details of which species are classified as small and large shorebirds, see the text; for locations of the various sites and site numbers see Fig. 1.

Species	Totals	Kormoraninsel	Japsand	Noderoogsand	Norderoogsand Nebeninsel	Süderoogsand	Süderoogsand Nebeninsel	Lorenzenplate	Linnenplate Ost	Linnenplate West	Isern Hinnerk	Blauort West	Blauort Ost	D-Steert	Trischen
Shorebirds identified															
Oystercatcher	1,187		7	205	1	12								4	884
Grey Plover	9,672		892	418		6,936			313			36	1,070	7	
Eurasian curlew	531			62		22			28						407
Bar-tailed godwit	13,761			127		13,634									
Red knot	119,014		11,349	8,167		95,081			3,513			904			
Dunlin	437			437											
Redshank	2														2
Shorebirds unidentified															
Large shorebirds	1,126		2	4		914							203	3	
Small shorebirds	43,345	237	3,732	689	174	19,800	444				521	417	16,234	5	1,092
Other shorebirds	1,347		304	7		369			651						16
Grand Total	190,422	237	16,286	10,116	175	136,768	444	-	4,505	-	521	1,357	17,507	19	2,401

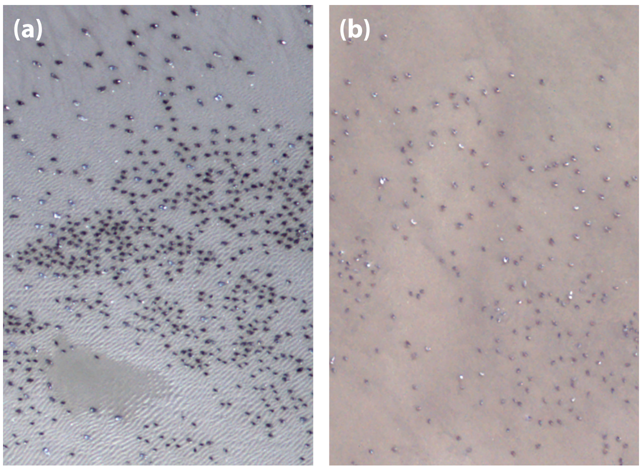

Fig. 2. Aerial photographs of flocks of shorebirds. **(a)** Eurasian Oystercatchers at the top of the picture, Red Knots in the central part and small shorebirds (not identified to species) in the lower part, dotted with single Grey Plovers throughout, on Süderoogsand, 15 May 2015. **(b)** Bar-tailed Godwits (upper part) and Red Knots (lower part), with single Grey Plovers, on Süderoogsand, 15 May 2015. The lighter colour with a white neck and head makes Grey Plovers stand out. Red Knots are distinguishable by their smaller size (compared to Bar-tailed Godwits) and their reddish plumage.

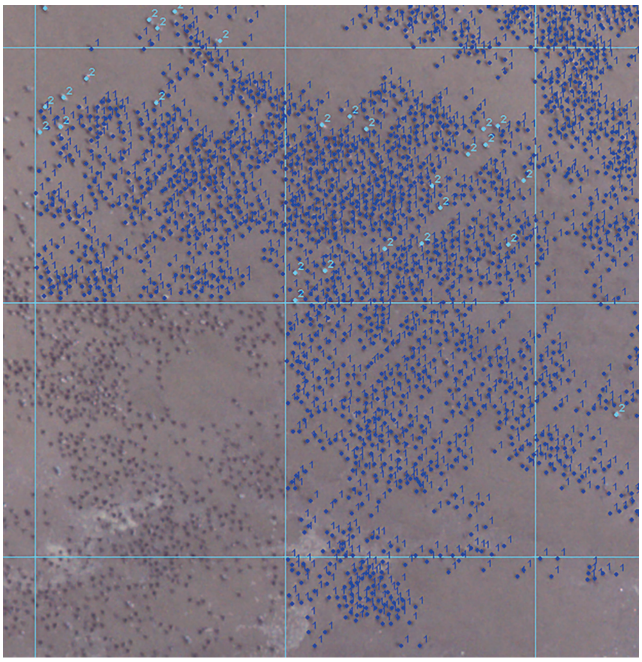

Fig. 3. Section of a processed image when counting individuals of a flock: Red Knots marked with '1' in dark blue, and Grey Plovers marked with '2' in light blue, on Süderoogsand, 15 May 2015.

In this digital aerial survey pilot study, we were able to identify a large proportion of detected shorebirds to species level. We identified higher proportions than other, observer-based aerial surveys carried out in the German Wadden Sea (Scheiffarth & Becker 2008, Frank 2014) apart from Kempf *et al.* (2015), who were able to identify all detected birds in 3 out of 4 survey occasions in spring 2012. Their approach of making additional and closer passes after gaining an overview of present flocks may have facilitated high identification rates.

There is a trade-off between resolution and area covered in digital aerial surveys: higher resolution reduces the strip width of the footage and thus the area covered in a given time. Higher resolution therefore also increases flight time and costs of surveys. Our ground resolution of 2 cm appears to be sufficient to allow – we believe – a high rate of species identification. While for smaller species a higher resolution might be preferable, we still expect that the identification of small waders in mixed flocks would remain a difficult task. For seabird surveys, a resolution of about 2 cm has been established as a good compromise (Žydelis *et al.* 2019, Webb & Nehls 2019), allowing a very high rate of species identification while ensuring a wide strip width. Here we show that this resolution also works for shorebirds. However, our survey took place in May when most shorebirds were in their relatively distinct breeding plumages. To assess the performance of our method more thoroughly we certainly need trial studies outside the (pre)breeding season when shorebirds have their typical greyish-white non-breeding plumages. Simultaneous surveys from air and ground could be used to verify species compositions detected on aerial imagery in a future project.

While our survey confirmed the presence of large flocks of roosting shorebirds at sandbanks that are also traditionally counted from the ground, we did not detect large numbers of birds on remote locations not covered by the standard ground counts (sites 8–11, 13–14 in Fig. 1). This latter observation contrasted with four observer-based aerial surveys carried out by Kempf *et al.* (2015) in May 2012, who found large numbers of individuals roosting on these remote sandbanks in Dithmarschen; up to around 24,000 in a single location. However, Kempf *et al.* (2015) also showed that shorebird numbers roosting on remote sandbanks vary strongly between surveys. Hence, even though we could not confirm large numbers of roosting birds in this area with our single survey, we suggest that these remote locations may provide important undisturbed roosting sites. We base this hypothesis on a number of indications: (1) the observations from Kempf *et al.* (2015); (2) very few short trips by boat in the vicinity of the sandbanks, where shorebirds were observed to move to these areas with the incoming tide (JL pers. obs.); (3) from tracking studies of e.g. Red Knots, using these potential roosts (J.A. van Gils, JL unpubl. data) and (4) from publicly available tracks on Movebank (https://www.movebank.org) for e.g. Grey Plover (e.g. Exo *et al.* 2019). However, evidence is inconsistent due to scarce data, mostly anecdotal observations and the shorebirds' highly dynamic site use in the Wadden Sea. Our digital aerial survey merely represents a snapshot count, underlining the need to repeat such surveys, so that we can compare a number of sampling events, as potentially substantial numbers of shorebirds are missed during the regular ground-based counts.

Shorebirds not only roost on remote sandbanks far away from shore but also along the shorelines. There, ground-based counts might face the risk of missing substantial numbers of roosting birds because of 'blind zones' behind an elevated foreland or saltmarsh (Castenschiold *et al.* 2023). These areas are also important candidates to be included in future piloted digital aerial imaging surveys.

Each year, migratory shorebirds of the East Atlantic Flyway concentrate in the Wadden Sea during migration and winter. Shorebird numbers, population trajectories and site use have been monitored predominantly from the ground for decades. Aerial surveys provide the means to also cover remote and inaccessible locations on a regular basis. Digital aerial imaging surveys allow this to work in a scalable way as the high altitude and high speed at which the planes operate allow coverage of large areas in a relatively short period of time. For example, all the main Schleswig-Holstein Wadden Sea roosts can be covered during one single high-tide period. Our method can thus complement existing data series, add knowledge on site use of potentially important remote locations, and enhance the understanding of results gained from ground-based counts and overall population censuses. Recent technological advances have made unmanned aerial vehicles (UAVs or 'drones'), with longer operating distances, available for civil use, hence allowing digital surveys to be conducted in a more environmentally friendly manner by reducing fuel consumption significantly. Also, using artificial intelligence (AI) for the automated processing of digital aerial images is moving forward at great pace (Schmoll *et al.* 2025), promising faster and more cost-effective analyses compared to manual processing.

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