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How high do birds fly? A review of current datasets and an appraisal of current methodologies for collecting flight height data: Literature review

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Birds Science People

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How high do birds fly? A review of current datasets and an appraisal of current methodologies for collecting flight height data: Literature review

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EXECUTIVE SUMMARY [top]

1. The consideration of flight heights is a key factor determining how seabirds interact with offshore wind farms. Of particular interest is the need to accurately predict flight heights, in order to feed into predictive Collision Risk Models (CRM). Data within CRM have traditionally relied quite heavily on boat surveys collected by observers, but now routinely, different methods are being used to estimate flight heights of birds.

2. To date, the relative suitability of methods for the collection of flight heights has not been rigorously appraised. For marine birds, this has primarily included visual methods from boat-based surveys, but more recently remote monitoring techniques such as high definition aerial imagery (images, video and spectrographic techniques) have been used. Alternative methods have also included bird-borne telemetry, radar, laser rangefinders, thermal imagery and acoustic methods, but their suitability to obtain reliable flight height distributions for potential use within CRM has not yet been assessed. This report details and compares each method for estimating flight heights, evaluating the relative merits and disadvantages of each method.

3. We conducted a literature review and assessed each method based on their (1) general use in deriving flight height distributions of bird species, (2) the testing, calibration and validation of these methods that have been carried out, and (3) the relative advantages and disadvantages of each. We then collated available flight height information as a first step in comparing results from different survey platforms for different species.

4. Boat-based surveys using observers have visually assessed the flight heights of individual birds at sea, with observers placing observations into flight height bands. These methods have been widely used to give flight height distributions. However, they can only be used in the day in good weather conditions and have a degree of imprecision, as they do not ascribe a specific flight height to each observation. Issues of disturbance/attraction are also present, with some species being sensitive to presence of the survey vessel and others attracted to it. A further concern lies in the safety implications of sending surveyors to sea, especially for offshore sites.

5. More recently, aerial high definition methods have been used to estimate flight altitudes of birds from visual stills and video methods. Such methods provide a permanent record that can be revisited, re-analysed and quality assured, as well as avoid disturbance issues if the aircraft is flown at a suitable altitude (above 460m). Survey conditions must be suitable to allow identification (avoiding high winds or very rough sea state) and good visibility (avoiding foggy conditions) and is generally restricted to daytime operations.

6. Spectrometry methods are under development which uses two high resolution cameras to create a three-dimensional image from which flight height can be accurate determined, and these methods can be used throughout day and night. Further testing and validation of these methods is ongoing and is the subject of trials in the UK and overseas.

7. Telemetry methods include altimeter and geographical positioning system (GPS) derived altitude data and although relatively few studies have investigated their use, they have recently been used to estimate bird flight heights. Studies using altimeters have reported small errors on estimates. Initially, altimeters were too heavy for some species and could not be deployed simultaneously alongside other sensors recording latitude and longitude to obtain geo-referenced three-dimensional information. However, this issue is now being overcome through advancements in technology. In contrast, GPS flight altitudes have higher error surrounding

measurements, e.g. 15-20 m and accuracy bias, but modelling approaches can be used to obtain flight height distributions, and 3-D behaviour can be investigated in great detail.

8. Telemetry may cover the full range of habitats used by birds, allowing more in depth analysis of flight height distributions. Telemetry can also produce flight height distributions for particular protected sites. Telemetry must be assessed for potential impacts to individual birds on which devices are mounted, and has considerably lower sample sizes than radar or other techniques. They are often deployed on particular life stages (e.g. breeding birds, rather than immatures/non-breeders, as they return to colony frequently), and for some species data collection may be restricted to the breeding season only (i.e. when using GPS and GPS+altimeter methods). Typically, harness methods are required for study during the non-breeding season, which may not be suitable for smaller species. The impact of a telemetric device and attachment method on an individual's behaviour needs evaluation in any study carried out. The population-level representativeness of the telemetry data collected using a relatively small sample of birds also requires consideration.

9. Radar and other methods (laser rangefinders, infrared imagery, and sound) have been widely used to estimate flight heights and can have a high level of accuracy. Radar can give a greater temporal coverage being used in all weather conditions and times of the day/year. Radar can be more restricted in spatial coverage, although it may still be sufficient to understand questions posed by offshore wind farm impact assessments (e.g. at a specific wind farm). Radar sometimes cannot identify very low altitudes due to clutter. There is also a significant problem with species-level identification or even identifying groups from single individuals if radar techniques are used in isolation. As such, it may be necessary to use radar in combination with an additional method.

10. Validation comparisons of the flight heights obtained from radar and laser rangefinders have been carried out, finding good agreement in many instances. Furthermore, altimeters have been compared to altimeters on planes to calibrate instruments. Boat-based visual flight height distributions have been compared to GPS flight height distributions of Lesser Black-backed Gulls finding good agreement during the daytime. However, laser rangefinders have also recorded higher proportion of lower altitude measurements than radar in other studies; for example due to difficulties in selecting and recording more precise estimates for bird further away. Moreover, visual methods are restricted towards daytime use (or night-time for ceilometers and moon-watching methods) and given species have been found to differ in flight behaviour in day and night, which may bias the overall flight height distribution.

11. The use of telemetry and radar in combination may offer advantages over traditional visual methods, including wider spatial (and vertical) coverage. Telemetry in particular has the potential to deliver data on individuals' behaviour, but to our knowledge no studies have yet compared data collected alongside different telemetry sensors nor to other methods such as radar. Radar cannot identify individuals to species level, requiring more targeted validation from other methods, such as visual observations.

12. Other methods reviewed included laser rangefinders, inclinometers, acoustic methods, thermal imagery, moon-watching and ceilometers and ornithodolites. These methods were considered useful but generally have certain restrictions that limit their use to a more supplementary role or are not suitable for use in the marine environment. These limitations include restrictions to lower altitudes, day or night biases in measurement period, and smaller spatial scale coverage. Laser rangefinders, inclinometers and ornithodolites in particular work best with a stable platform to reliably lock on to and register flight altitudes of targets, making them less suitable for use on unstable platforms in the marine environment.

13. The site-specific practicalities of different technologies are ultimately likely to determine the method used for a given study. Therefore, no single method is recommended for all situations. However, the most feasible methods reviewed here to provide reliable estimation of bird flight altitudes offshore are: high definition digital imagery surveys (such as aerial surveys), telemetry methods (altimeter and/or GPS) and X-band radar. A combination of these methods (deployed across multiple seasons, sites and species) is likely to give the most accurate and widely applicable information on seabird flight heights. This could also be supported by other methods such as visual, laser rangefinders and infra-red thermal methods, where applicable for validation/ground-truthing.

1. INTRODUCTION [top]

1.1 Background

Strategic Environmental Assessments (SEAs) and Environmental Impact Assessments (EIAs) for offshore renewable development have identified a need to evaluate potential interactions between offshore renewables and marine wildlife as a matter of priority so that appropriate mitigation can be investigated and where needed, applied. Offshore wind farms have the potential to affect seabirds through: (i) displacement and disturbance associated with developments, (ii) barrier effects to migrating birds and birds commuting between breeding sites and feeding areas, (iii) collision mortality, and (iv) indirect effects due to changes in habitat or prey availability. Each of these aspects needs consideration within impact assessments. However, predicting and quantifying these sensitivities is challenging and requires further research to reduce uncertainties in the methods used.

The consideration of flight heights is a key factor determining collision risk of seabirds with offshore wind farms (Garthe & Hüppop 2004; Desholm and Kahlert 2005; Johnston *et al*. 2014a; Furness *et al*. 2013). The use of species-specific flight height information is important since species differ greatly in their sensitivity to collision risk (see recent reviews by Garthe & Hüppop 2004; Furness *et al*. 2013). For instance, species such as gulls (including kittiwake) and skuas are considered more at risk of collision than other species due to flight heights estimated within the rotor sweep zone of wind turbines (Furness *et al*. 2013).

Seabird collision rates with offshore wind turbines are estimated using a collision risk model (CRM) which requires estimates of seabird flight heights. An early version of a CRM commonly used in the UK (*i.e.* the "basic" Band model; Band 2000) simply required an estimate of the proportion of all birds present which are flying within a height band corresponding to the lower and upper limits of the rotating blades. This modelling approach, coupled with the limited precision with which observers can record bird flight heights in the field, resulted in most field studies simply recording each bird as flying within a flight height band, *e.g.* 10-20 m or 20-30 m. However, a more recent version of this CRM (*i.e.* the "extended" Band model) allows for bird flight heights expressed in the form of a continuous frequency distribution to be used to generate more refined estimates of collision mortality by accounting for the variation in bird density and probability of collision with height across the risk area. This approach requires density distributions, which can be produced in a number of ways. Previously, distributions of bird density in relation to height above the sea surface have been generated using complex statistical approaches from flight height data originally collected in coarse bands (*e.g.* Johnston *et al*. 2014a).

Within offshore wind farm impact assessments, flight height information has come from different sources but has predominantly been from at-sea surveys or aerial methods conducted as part of baseline surveys for impact assessments (Cook *et al*. 2012; Johnston *et al*. 2014a). Flight heights are now routinely being estimated from high definition aerial surveys (Thaxter & Burton 2009). Flight height data can also be collected from the coast through visual "sea-watches", as used previously for coastal birds (e.g. Krüger & Garthe 2001), although such methods typically cannot be used for offshore assessments and suffer from a degree of subjectivity. The use of visual land-based or at-sea survey methods, however, are not the only means of estimating flight heights of species. A variety of other methods and technologies can also be used to give estimates of flight heights for different species, yet their relative importance alongside more traditional methods of boat surveys and more recent high definition imagery methods has not been appropriately appraised. These alternative methods include: bird-borne telemetry devices such as altimeters recording pressure and GPS devices recording relative altitude. The advance of tracking and telemetry technologies is now

permitting insights into flight behaviour, including altitude, resulting in a growing number of studies that could be used to estimate flight height distributions (Weimerskirch *et al*. 2005; Corman & Garthe 2014, Ross-Smith *et al*. in prep). Radar methods have been used for many years to estimate flight heights of birds (e.g. Eastwood 1967; Alerstam 1990; Cooper *et al*., 1991; Klaassen & Biebach 2000), including for offshore wind farm assessments (e.g. Krijgsveld *et al*. 2011). Other methods include the use of laser rangefinders and inclinometers, infra-red imagery, high resolution spectroscopic video, acoustic methods, and ornithodolites.

Implicit in all collision risk modelling undertaken is the assumption that the flight heights of birds are recorded accurately – whether that be attribution of each individual to the "correct" flight height band (such that the % within the risk height band is accurate) or assigning the correct absolute flight height to each bird to ensure that a realistic continuous flight height distribution is generated. While the significance of site-specific errors may be reduced when data sets are pooled, any systematic bias in flight height estimates (*e.g.* observers tending to underestimate flight heights) will persist whether or not pooled data sets are utilised. Recent work by Furness *et al*. (2013), Cook *et al*. (2014) and Masden (2015) has also indicated that flight height estimates are a key factor influencing predicted collision mortality. Yet the validation of flight height measurements or estimates derived by any field method is extremely limited. This results in considerable uncertainty over the reliability of estimated collision rates and may result in inaccurate assessment methods being applied. Improved data on flight heights of different species is therefore needed (Furness *et al*. 2013; Masden *et al*. 2015). The need for these data to be verified, for robust data to be collected and for the uncertainty around the data to be quantified is of prime importance (Masden 2015). These data, while of primary importance for offshore wind farms, would also have relevance in other sectors such as the aviation industry, and to others with research interests in flight behaviour of different species.

1.2 Project Aims and objectives

This study has the following aims:

1. Collate, review and synthesise flight height data collected from boat based and digital aerial surveys (and other methods where possible).

2. Carry out an appraisal of the advantages and disadvantages of current methodologies for collecting flight height data.

We assessed and compared visual estimation of flight altitudes from boat-based surveys with those estimates from digital aerial surveys. We reviewed the use of further methods for estimating flight heights of birds including, bird-borne telemetry, radar and other approaches. We appraised the applicability of all methods for estimating flight height distributions of species, and assessed the advantages and disadvantages of each for practical and analytical use in estimating flight heights of birds. In particular, we give due consideration to the validation of these methods that studies have carried out. Where possible, we also consider additional factors that could influence flight heights and draw on examples where such factors have been investigated. This will enable a better understanding of site-specific and temporal variation in flight behaviour.

2. METHODS [top]

2.1 Literature review

We conducted a thorough literature review using popular search tools such as Web of Science and Google Scholar, and general web-browsing. We used key-words representing the main subject matter such as “flight”, “height”, “altitude”, “survey”, “distribution”, as well as targeted species taxa groupings “bird”, “seabird”, and other taxa such as “bat”, “insect”, and known methodologies investigated as part of this review such as “GPS”, “satellite”, “PTT”, “tagging”, “altimeter”, “radar”, “laser rangefinder”, “thermal imagery” and “acoustic monitoring”. We paid particular attention to previous reviews of methods (e.g. Kunz *et al*. 2007; Desholm *et al*. 2006), and followed literature trails where other methods were subsequently discovered.

Once studies were compiled, they were sorted and organised into relevance and methodologies used. Each study was clearly investigated for the production of species-specific flight height estimates, the limitations stated for their approach, the calibration/testing of the approach that can be useful to understand the potential source of error surrounding estimates, and the validation of the method (e.g. alongside other methods) that had been carried out – frequently these latter two aspects were interconnected and so are grouped together in the following results.

We present results organised by each methodology, with a brief description/history of the method, examples of use in estimating flight heights, testing/calibration/validation, and advantages and disadvantages of each method. Each method was subsequently summarised in a final table to enable each to be tallied against one another.

This review brings together information from the wider bird taxa, including seabirds, for each method used to estimate flight heights. Throughout, however, we highlight the relative suitability of the various methodologies to the offshore environment and to study of seabirds to assess collision risk.

2.2 Collating flight height data

We collated information on flight heights of marine bird species that are of importance when considering collision risk within impact assessments. This enabled a simple comparison to be made across different survey platforms for different species. Some other studies focused on nocturnal migrants and waders, however for simplicity of approach we focused on marine birds only. Different studies summarised flight height information in different ways (e.g. as means, boxplots, full flight height curves or percentages at collision risk height). Units of measurement also varied between birds, time spent, or number of GPS fixes. Therefore, it was not possible to conduct a formal statistical comparison across different methods. Some additional studies also presented flight height information for the same marine bird species, but were omitted as it was not possible to obtain a complete distribution or proportion of the distribution at potential risk height of collision.

We used a traffic light system similar to that presented in Krijgsveld *et al*. (2011) that highlighted the extent of general risk posed by offshore wind farms. We assessed distributions in relation to the rotor sweep zone (RSZ), defined as the lower turbine sweep limit (20-30 m, LSL) to the maximum turbine sweep (120-150 m, USL). We delineated three categories based on the proportion of time, birds or fixes at particular heights (depending on how the data had been presented), and/or the proportion of overlap of these distributions within the study-specific RSZ. These categories were classes as follows: (1) low risk (green), <10% time/birds/fixes more than LSL and/or <10% overlap with the RSZ, (2) medium risk [yellow] 10-30% time/birds/fixes more than LSL and/or 10-30% overlap

with the RSZ and, (3) high risk [red] >30% time/birds/fixes more than LSL and/or >30% overlap with RSZ. The range of LSL-USL depended on the specific studies and turbine specifications used. For the marine bird species presented, the distributions rarely exceeded the USL therefore categorisation was based on the crossing of the LSL threshold only.

Where possible, distinction was retained for more detailed influences on distributions such as time of year migration or local breeding movements (e.g. Klaassen *et al*. 2011) and day (Ross-Smith *et al*. in prep). The period of the remaining studies presented was primarily during the breeding season, unless otherwise stated, with the diurnal timing of observation related to the method used. For simplicity, no further breakdown for example related to weather patterns is presented.

3. RESULTS [top]

3.1 Visual Surveys and Boat-based Transect Surveys [top]

3.1.1 Examples of use

As part of the EIA for offshore wind farms, data on the abundance, distribution and flight height of birds have traditionally been collected from boat-based transect surveys (hereafter "boat-based surveys") carried out following the guidelines set out in Camphuysen *et al.* (2004). Under this methodology, the flight heights of all birds within 300m of the survey vessel are estimated by trained observers at five minute intervals. Each flying bird is assigned to a particular height band, which are typically set with reference to the height of fixed objects, for example the height of the ships mast. As a consequence, the height bands which are used tend to differ between sites (Johnston *et al.* 2014a). However, standardised methodology has previously suggested categories of 0-2 m, 2-10 m, 10-25 m, 25-50 m, 50-100 m, 100-200 m, and > 200m (Camphuysen *et al.* 2004).

These methods have been widely used in the offshore environment. Johnston *et al.* (2014a) identified data for 25 bird species which had been collected from 32 proposed offshore wind farm sites in five countries in Northern Europe (UK, Belgium, Netherlands, Germany and Denmark). Similar datasets have been collected elsewhere, including from Pacific and Atlantic coasts of the US (Ainley *et al.* 2004, Sadoti *et al.* 2005). The data collected from Northern Europe have subsequently be combined, using a statistical framework, in order to produce a series of generic flight height distributions for individual species, which can be used to estimate the proportion of birds likely to be flying at any given altitude (Johnston *et al.* 2014a).

Visual estimations of flight heights have also been made from fixed platforms at sea from constructed offshore wind farms. For example Krijgsveld *et al*. (2011) studied the flight behaviour of species at the Egmond aan Zee wind farm using 360° "panorama scans" (Poot *et al.* 2000) alongside radar. Panorama scans of the air and sea were carried out each hour, using a high-quality pair of 10*42 binoculars fixed on a tripod counting all birds within sight (up to 3 km, beyond which a reduction in detectability was recorded) of the observation platform. Within these scans, flight altitude was also recorded into four classes and two full 360° sweeps (low, 1/2°) and (high, 1/8°) were carried out to capture low and high flying birds. Distance classes varied in distance from observers and whether scans were low or high. Although birds were recorded up to 500 m altitude using this method, this was at a distance of 5 km from the observer; a 3 km horizontal distance resulted in a maximum altitude of 300 m (Krijgsveld *et al*. 2011). Panorama scans allowed flight heights to be assessed at the species level in relation to the vertical rotor sweep zone (RSZ) of the wind farm and flight heights both inside and outside the wind farm; for example, 50% and 30% of sandwich terns recorded were at the RSZ inside and outside the wind farm, respectively. In contrast more than 50% of Lesser Black-backed Gulls were at rotor height both inside and outside the wind farm (Krijgsveld *et al*. 2011).

3.1.2 Calibration, Testing and Validation

During boat surveys, observers typically calibrate their estimates of flight height with reference to the height of fixed objects, for example the ships mast. Comparison of data collected during pre and post construction surveys of offshore wind farms reveals differences in the estimates of the number of birds flying in each height band (Cook *et al.* 2014). However, it is unclear whether these differences relate to a behavioural response of the birds to the turbines, or the presence of fixed objects, of known height, providing an additional reference point with which to assess the flight height of each bird.

Johnston *et al.* (2014a) attempted to assess the transferability of flight height estimates between sites. They compared data collected from novel sites to generic flight height distributions in order to determine how well these distributions could predict the risk posed by turbines to birds in flight. These analyses revealed significant species-specific differences. For example, the generic distributions correctly predicted the proportion of Herring Gulls in height bands at novel sites on 39% of occasions, and correctly predicted the proportion of northern fulmar in height bands at novel sites on 88% of occasions. It is unclear the extent to which these differences relate to observer effects and to what extent they relate to site-specific effects including potential seasonal and behavioural differences.

Recent trials have attempted to assess the accuracy with which observers are correctly able to estimate flight height using drones at known heights (RSPB unpublished report). These trials suggest that observers incorrectly assign birds to the correct height band between 50 and 70% of the time. Initial results suggest a tendency to overestimate the height of birds in flight. However, it should be stressed that these are preliminary results and, as such, should be treated with caution.

Panorama scans in Krijgsveld *et al*. (2011) were also validated by a second observer to check for bias in records. The technique has been previously calibrated using different observers and in comparison to the target tracking radar of the Netherlands Royal Air Force (Poot *et al*. 2000), finding that panorama scans are a reliable way of estimating flux and lower flight altitudes (Poot *et al*. 2000); with an increasing distance from the observer, increasing error in measurements resulted. Using three different height estimation classes (0-25 m, 25-100 m and 100+ m) Poot *et al*. (2000) found that birds flying higher than 100 m were systematically underestimated in comparison to radar (Figure 3.4 in Poot *et al*. 2000) and potential species differences in altitude biases existed e.g. between light-coloured gulls being harder to observe than darker coloured seaducks (Figure 3.6 in Poot *et al*. 2000). Within Krijgsveld *et al*. (2011) this method served as a backup and calibration to radar methods whilst providing additional species-level detail than radar alone.

3.1.3 Advantages and Disadvantages

Methods used to estimate flight heights during boat-based surveys follow well-established protocols and data can be collected as part of others surveys (such as habitat, benthic and geophysical surveys), helping to make them more cost-effective. By using trained observers and limiting data to that collected within 300 m of the survey vessel, the proportion of birds correctly identified to species level is close to 100%, in line with the rates currently being achieved by digital video surveys. Another potential advantage of boat-based transect surveys relates to the issue of availability bias. For some pursuit-diving species (e.g. auks) availability bias can be a problem with digital aerial, as well as some other survey methods. In boat-based surveys, because of the long survey duration, it is thought this would typically allow birds to 'pop back up into survey' following dive periods. This requires further analysis and standardisation of approach, but for a certain number of species, boat-based surveys may avoid the need to account numerically for availability bias, because the birds become available during the length of the survey transect passage. Equally, however, the longer survey duration means that boat-based transect surveys may be subject to double-counting issues; although methodologies are meant to take account of this to some degree for example through line spacing being a minimum of 2 km (Camphuysen *et al*. 2004).

There are other disadvantages to this approach. For example, as birds are assigned to a series of flight height bands, rather than being given individual flight height estimates, this has implications for how collision risk is assessed. It means that assessment of the impact of changing the size or height of turbines is constrained by pre-construction decisions on the flight height bands used during

boat surveys. However, this difficulty can be overcome by combining data across sites to give continuous distributions, as in Johnston *et al.* (2014a). In addition, birds are likely to adjust their flight behaviour in response to weather conditions and time of day (Garthe & Hüppop 2004, Blew *et al.* 2008, Krijgsveld *et al.* 2011). However, practicalities associated with health and safety and detectability limit data collection to periods of daylight, moderate winds and good visibility (Camphuysen *et al.* 2004, Hyrenbach *et al*. 2007). This means that it is not possible to collect flight height data during periods in which birds may be most at risk of collision. Finally, there is likely to be a strong observer effect as many species are either attracted to, or displaced by the survey vessel or attracted to fishing vessels (Spear *et al.* 2004, Hyrenbach *et al.* 2007, Schwemmer *et al.* 2011). This risks biasing estimates of flight height as a result of detecting birds as they are taking off from the surface of the water as a result of being flushed by the survey vessel, or being attracted to fly at lower altitudes by the presence of the vessels.

3.2 Digital Imagery Survey Methods [top]

3.2.1 Examples of use

In response to methodological and analytical advances (Thaxter & Burton 2009, Buckland *et al.* 2012, Johnston *et al.* 2014a), the use of digital aerial surveys to collect data on seabird abundance and distribution has increased in recent years. Data can be collected using either still photography or high definition video imagery. These data can then be used to estimate the heights of flying birds either by basic trigonometry based on the size of the bird in the image and the known height of the plane or, in the case of video, comparing the speed at which the bird passes the plane to the speed of the sea surface. These approaches are increasingly being used to estimate the heights of flying birds in relation to offshore wind farms.

In addition to digital stills and video imagery, recent technological advances have been made allowing the use of spectrographic imagery. This is not an aerial technique, but instead is a system mounted on a fixed platform (e.g. turbine) which functions remotely. Recently, a Collision Avoidance Monitoring System (CAMS) has been deployed at the Sheringham Shoal Offshore wind farm[1] (Mellor & Hawkins 2013). This system uses a pair of 16 megapixel cameras with fisheye lenses enabling a wide field of view, with a resolution of 1 cm up to 100 m range, thereafter decreasing in accuracy up to 500 m maximum range (Mellor & Hawkins 2013). The two cameras are offset creating a three dimensional view around the wind turbines and surrounding area (Mellor & Hawkins 2013). The system collects data remotely, transmitting information to the user every five minutes. Using software algorithms, the degree of randomness can be can be assessed and projections of avoidance behaviour from the turbines can be made (Mellor & Hawkins 2013). As the technique is three-dimensional, this technology can also estimate flight heights of individual birds tracked within the distance ranges specified above.

3.2.2 Calibration, Testing and Validation

At present, flight height estimates derived from digital aerial survey are presented with an estimate of the error surrounding them. Although validation exercises have not yet been carried out, the accuracy of flight heights derived from digital aerial survey is currently being tested. In addition as part of this project, data will be analysed in order to obtain continuous distributions which can be qualitatively compared to those derived from boat-based surveys. For spectrographic techniques, given the recent development of this approach, further validation and testing of the system is still

[1] http://www.hidefsurveying.co.uk/latest-news.html [last accessed 02/07/2015]

needed, including validation alongside other systems. Currently, as with some other HD systems, post-processing of the CAMS system involves manual decisions to be taken by observers on whether or not the object is a bird and if a species ID can be assigned. However, further tests following the recent trial will examine automation of these procedures. For aerial high definition imagery methods, decisions on species ID may be automated to detect targets, or even species for example using object- or pixel-based recognition algorithms (e.g. Groom *et al*. 2007). However, most surveys currently require human identification of species. The quality assurance procedures that are in place verify and check images thoroughly until at least 90% agreement is reached between reviewers (Thaxter & Burton 2009).

3.2.3 Advantages and Disadvantages

Initial concerns over the ability to correctly identify birds to species level from digital aerial survey have been allayed as technological advances mean that the majority of images are now identified for instance now reaching over 95% identification (Webb & Hawkins 2013, Busch & Rehfisch 2015). In addition to being more cost-effective than other approaches, for example boat-based surveys, digital aerial surveys have the advantage that the images collected can be stored and the data re-analysed at a later data in response to technological and methodological advances (Buckland *et al.* 2012). Storing the images also offers valuable quality assurance in that they, potentially, make it possible for flight height estimates to be re-analysed and independently verified. However, one of the key advantages of digital aerial surveys is that when flown at suitable heights (i.e. over 500m) the risk of disturbance to birds is reduced, therefore reducing the risk of attraction and displacement associated with boat based surveys (Buckland *et al.* 2012).

Less clement conditions can affect both boat and aerial surveys, Boat surveys are not advised to survey when sea conditions beyond sea state 5 (Camphuysen *et al*. 2004). Wind may also be restrictive for aerial methods as it is necessary to ensure that the plane remains relatively stable when collecting data. However, although the use of spectrographic techniques is a new and emerging field, the method can operate above Beaufort scale 4. There are still considerable limitations for aerial methods in that sometimes boat surveys can survey in low cloud whereas aerial high definition may not be able to. Good visibility is required, meaning it is not possible to collect data at night or in foggy conditions. In addition, sun glare may pose an issue for still cameras mounted vertically as a result of light reflecting off the sea surface and the fact they cannot divert away from the glare, although this isn't of concern for oblique video systems. For example, rotating camera rigs now allow for the avoidance of glare and no loss of data because of that effect; furthermore, the sideways profiles of birds are also obtained permitting greater identification of plumage features (K. Hawkins Pers. Com.). Aerial digital survey methods have traditionally been restricted to daytime periods. However, some cameras have near-infra-red capability, including the CAMS system above, which removes any observation bias and permits 24-hour monitoring – see also section 3.8. Digital video also allows operators to play and rewind footage allowing contrasts between the sea and target objects to be clearly defined.

3.3 Bird-borne telemetry [top]

Two dimensional movements are now routinely studied for many species using bird-borne devices. These telemetry methods include archival geolocation (Guilford *et al*. 2009), archival GPS (requiring data recovery of the tag and two captures of the same bird), GPS local remote transmission, such as through a network of relays at the breeding colony (Bouten *et al*. 2013), and wider transmission, Argos GPS/satellite (Klaassen *et al*. 2011) and GPS/GSM (Russell *et al*. 2014). Three-dimensional movements can also be studied using accelerometers, very useful in refining our understanding of behaviour of animals (Shamoun-Baranes *et al*. 2012). Accelerometers have been used to study above

water movements for many other species such as gannets (Ropert-Coudert *et al*. 2004) and gulls (Shamoun-Baranes *et al*. 2012). However, to understand positional three-dimensional movements, additional methods and sensors are required. These combine the two-dimensional plane of traditional telemetry with sensors that can estimate the altitude of birds directly for each positional location. This can be achieved by using: (1) altimeters alongside positional telemetry or, and (2) positional telemetry directly using GPS and satellites where altitude is also recorded directly.

3.3.1 Altimeters (pressure sensors) [top]

3.3.1.1 Examples of use

Altimeters can be used to record flight heights of birds and underwater diving events through changes in pressure (Weimerskirch *et al*. 2005, Garthe *et al*. 2013) – the latter being similar to time-depth recorders that are routinely used to monitor underwater diving behaviour of seabirds. The first studies of flight heights using altimeters were conducted relatively recently. Weimerskirch *et al*. (2005) used 30 g (Suunto X6 altimeters, Suunto Oy, Vantaa, Finland) altimeters to study the flight heights of red-footed boobies, recording altitude every 10 seconds (10 foraging trips, eight individuals). Altimeters were attached to the central tail feathers (Weimerskirch *et al*. 2005) and were used alongside other telemetry devices such as GPS, satellite device and accelerometers attached to separate birds. Weimerskirch *et al*. (2005) noted that the flight height distribution of red-footed boobies included birds generally moving close to the sea surface over a range of heights typically between 1-40 m (derived from Fig 9 in that study) but birds regularly climbed to 20-50 m during travelling phases (thought to be influenced by wind and prey-search behaviour), and climbed to very high heights, up to 500 m before descending rapidly back to the colony (Weimerskirch *et al*. 2005). Previous study using the same type of altimeters attached to the back or tail feathers to adult frigatebirds (Suunto X6, 32-35 g sampling every 60 s) revealed that they flew to heights up to 2,500 m (Weimerskirch *et al*. 2003), with a maximum of 2,867 m (Weimerskirch *et al*. 2004). When foraging, frigatebirds remained on average 180 m above sea level continuously climbing and descending, but rarely coming close to the sea surface (Weimerskirch *et al*. 2004).

The height of plunge diving has been studied in northern gannets using altimeters attached to the top of central tail feathers of seven birds (Garthe *et al*. 2013). These were 15 g (65 mm length, 16 mm diameter) devices from Earth & OCEAN Technologies, Kiel, Germany and consisted of a pressure and temperature sensor (-7 m to +2000 m range, 1 s sampling interval). Garthe *et al*. (2013) observed that plunge-dives by gannets were initiated at 11-60 m (range 3-105 m), and gannets flew at 28.9-45.6 m before dives, with an overall flight height mean of 37.1±2.8 m (per individual, n = 7).

Pennycuick *et al*. (1999) used altimeters within Argos platform terminal transmitters (PTTs – PTT100, Microwave Telemetry Inc.) attached to seven Whooper Swans to determine migration flight heights. Although error in these measurements was higher than other altimeter studies report (see below), the maximum altitude reached by any bird was 1,856 m over the sea on route to the British Isles from Iceland. Spring routes back to Iceland were all less than 500 m.

Shannon *et al*. (2002a and 2002b) gathered information on American white pelican flight altitude data through visual observations and satellite radio telemetry transmitters containing an altimeter (total weight of transmitter+radio+harness, 121 g) attached to the back of ten pelicans using a leather harness. Each transmitter was equipped with an altimeter sensor (Motorola MPX4115AS temperature compensated and calibrated piezoresistive absolute pressure transducer), recording every 60 s. Heights of pelicans were recorded at 4,240 m (3040 m AGL).

In addition to bird-borne devices used to estimate flight altitude, the altimeters of planes have also been used to directly record the height of flocks of birds, here termed "plane-based altimetry". For example, Shamoun-Baranes *et al*. (2003) used radar to detect flocks of birds after which a light aircraft took off and pinpointed the recorded flock estimating the flight altitude above sea level with the on-board altimeter.

More recently, the flight altitudes of gannets are being studied from Bass Rock in SE Scotland[2]. This is ongoing work and will provide further information on the flight heights of this species and inform further on the use of altimeters. At the time of writing, specific outputs are not yet available however, it is anticipated these results will be key in relation to offshore wind farms with revised collision risk estimates being informed by altimeter-derived altitude.

3.3.1.2 Calibration, testing and validation

Weimerskirch *et al*. (2003, 2004. 2005) corrected for shift in atmospheric pressure by using recordings from an altimeter at a fixed location in the breeding colony. The resolution of altimeters used by Weimerskirch *et al*. (2003) is stated as 3.3 m. Garthe *et al*. (2013) calibrated altimeters by correcting for changes in air pressure incorporating hourly measurements from a nearby weather station, and simply subtracting or adding air pressure measurements to/from the altimeter sensor to standardise air pressure in the atmosphere. Pressure calibration was also frequently carried out using periods when birds were swimming (1 hPa equates to a difference of ca. 8.4 m altitude in air). Garthe *et al*. (2013) state that the resolution of altimeters in air was 2 m with an accuracy of 8.4 m (i.e. 1 hPa). Pennycuick *et al*. (1999) indicate that measurement error was likely no more than ±50m above sea level, but provided no apparent validation of their above sea level measurements. This is an early study investigating altimeter barometric pressure from Argos measurements, and the error is much greater than some other more recent studies (e.g. Weimerskirch *et al*. 2005). To our knowledge with appropriate calibration of pressure and location/time-specific pressure, the error of height derived from altimeters has therefore improved over time. Shannon *et al*. (2002b), when using satellite transmitters and altimeters, carried out a thorough independent evaluation of altitude sensor performance by placing altimeters to be deployed on birds in an unpressurised cabin of a Cessna 210 aircraft that was then flown to a range of altitudes (n = 6, 1,500-3,050 m). At each height, the height from the altimeters was recorded. Shannon *et al*. (2002b) reported that the difference between the bird altimeter altitude and the plane altimeter altitude increased with altitude, but this was linear and attributed to calibration differences in the two instruments. These biases were subsequently removed leaving standard deviations of the tested control flight heights as 12-18 m primarily attributed to slight deviations in the aircraft as it flew. Note however, Shannon *et al*. (2002b) the altimeter was taken as the "true" height, therefore ideally further validation is required and more information is needed as to the accuracy of aircraft altimeters themselves.

3.3.1.3 Advantages and disadvantages

Altimeters offer a direct approach for studying flight heights of individual species. For diving species, periods of travelling can be separated from diving by categorising trips into periods of continuous flight after leaving the colony area, and periods of diving activity (Garthe *et al*. 2013). Such information is very useful in distinguishing periods of trips and behaviours at sea for some species. The precision of altimeters has been estimated in some cases as small as 2-3 m, and accurate to 8 m, although in some cases errors appear to be slightly greater (Pennycuick *et al*. 1999). Such values could be considered smaller than some GPS-derived errors of altitude (see below).

[2] http://www.fbs.leeds.ac.uk/staff/profile.php?tag=Hamer_K

The review of flight height information is applicable to a wide range of different industries and sectors (such as aviation) and including offshore wind farms, the main focus of this report. A key emerging goal is to understand the interaction of species with offshore wind farms in more detail within three-dimensional space. For some larger species such as pelicans and swans (e.g. Pennycuick *et al*. 1999; Shannon *et al*. 2002a, b) altitudes and position can be measured simultaneously on the same bird, for instance packaging altimeter channels alongside PTTs. However, for the majority of species this has not previously been possible due to the combined mass of instruments being too great for species to carry. Many altimeters used on species such as frigatebirds (Weimerskirch *et al*. 2004, 2010) and northern gannets (Garthe *et al*. 2013) have been limited to single deployments of one device on one bird rather than dual deployments of altimeters in conjunction with other positional telemetry instruments. Such dual deployments may be possible for many species, including UK species, up to the weight increment limit, but effects would always need careful assessment within any study conducted.

The weight and restrictions of tags can be considered a disadvantage compared to other methods such as radar, in particular if a species of research interest but where technology cannot currently offer solutions to study. Among other aspects, an important consideration is the weight of the device to be used on species. The section below for the advantages and disadvantages of GPS tags (section 3.3.2.3) also considers the weight of current devices. Note, it is not the purpose of this report to proscribe specific tags for specific species. The specific tag choice will also depend on many factors for instance related to the attachment solutions for the species and the goals of research for the study. However, it is useful to highlight the current weight thresholds for altimeter technology to place the current technology in context of applicability to seabirds considered of concern for collision risk assessment.

For instance, the altimeter used by Garthe *et al*. (2013) was 15 g (earth & OCEAN Technologies, Kiel, Germany), making it theoretically applicable to species more than 500 g, based on a minimum of 3% body mass increase deemed acceptable. In terms of key species of collision risk identified in Furness *et al*. (2013), taking species in the top 15 of that list and using information on species body mass in Robinson (2005), species that would not be studied with a 15 g tag (plus attachment materials) would include: Common Gull, Kittiwake, Arctic Skua, Black-headed Gull, Sandwich Tern, Common Tern and Little Tern. Note, however, this would also depend on factors such as attachment method used and ability to initially capture birds, species-sensitivity, plus specific tag shapes and attachment points, which may also rule out specific tag uses regardless of weight suitability.

Further advances in miniaturisation and bespoke solutions to wildlife tracking will no doubt allow smaller and lighter altimeter designs as well as incorporation of altimeters as additional sensors alongside GPS sensors within the same telemetry devices. Some companies have begun to develop lighter altimeters already, for example being as little as *ca*. 5 g (PathTrack Pers. Comm.), although such a weight is considered a very rough approximation until it has been manufactured. Potentially this could allow additional species as light as *ca*. 165 g to be studied, and from the list above, would exclude Little Tern (56 g) and Common Tern (130 g), but with the same caveats listed above. The final weight of a “combined” devices (i.e. with battery, GPS and altimeter sensor) is at the time of writing is more uncertain. However, a GPS device with an additional altimeter may be possible to manufacture at a weight of 17 g (PathTrack Pers. Comm.), although this is only an estimate at the present time. Hence, this would allow the same top-15 species in Furness *et al*. (2013) to be studied excluding the seven species mentioned initially that are too light above. This tag allows a year-long data collection protocol (solar panel plus larger battery), therefore lighter tags may be possible if research goals require shorter duration study.

3.3.2 GPS and satellite telemetry [top]

Altitude is also recorded from positional telemetry directly. GPS altitude is estimated via trilateration and calculated in relation to a mathematical model representation of the earth, which may be greater or less than this model at certain points. Further digital elevation models are then applied to estimate height relative to ground/sea level (Ens *et al*. 2008). Consequently, it has been reported that measurement error may be up to 20 m for GPS-derived altitude (Ens *et al*. 2008; Thaxter *et al*. 2011). This error was obtained from ground-truthing the altimeter readings at fixed height locations. However, the precision of GPS-altitude may be influenced by additional factors. In particular, error of position, speed and altitude all increase with a coarser measurement interval (Bouten *et al*. 2013). Bouten *et al*. (2013) trialled high performance GPS devices and evaluated their performance on White Storks and Honey Buzzards. That study found altitude measurements from stationary GPS devices on a 6 s rate had a 95% confidence interval of 0.25-3.75 m, corresponding similarly for a white stork at its nest CI = 0.38-7.61 m, whereas 60 s rates for the stationary device were larger (95% CIs, 0.23-9.76 m) and 600 s the longest (95% CIs, 2.13-102.0 m) – a stationary honey buzzard at its nest on a 600 s rate had a CI = 0.76-45.24 m (Bouten *et al*. 2013). For these devices, an increasing measurement interval greater than 15s leads to the receiver of the device turned off between sequential measurements thus reducing the time to fix and number of satellites available (Bouten *et al*. 2013).

3.3.2.1 Examples of use

De Monte *et al*. (2012) extended the previous studies using altimeters on frigatebirds (Weimerskirch *et al*. 2003, 2004) by investigating flight heights using GPS devices only (Technosmart, Rome, Italy, 25-30 g). This study revealed local three-dimensional latitude, longitude and altitude by using the GPS-derived altitude data. Reassuringly, similar flight heights were recorded from GPS-derived altitude compared to the previous altimeter data collected at this colony. In studying the migration behaviour of lesser black-backed gulls, Klaassen *et al*. (2011) used 30 g Argos GPS/PTTs attached to eight birds to record positional information and altitude above mean sea level (typically 8-10 fixes per day). When "travelling" during migration phases, gulls rarely flew higher than 250 m above the ground (max 1,744 m), with negative values also recorded due to errors in the ground elevation model applied (minimum category plotted, -250 m to 0 m, Klaassen *et al*. 2011).

More recently, the flight heights of lesser black-backed gulls (Corman & Garthe 2014) have been examined using GPS altitude data. Corman & Garthe (2014) modelled flight heights during the breeding season (Corman & Garthe 2014) finding that 89% of fixes were below 20 m, not overlapping with rotor sweep zones of wind turbines, and flying lower over sea than land and lower at night. Similarly 24 lesser black-backed gulls were tracked in SE England and 24 great skuas were tracked from colonies in Shetland and Orkney. GPS altitude data was then analysed using state-space Bayesian modelling techniques (Ross-Smith *et al*. in prep). Ross-Smith *et al*. found that lesser black-backed gulls flew higher over land than sea and lower after dark than during the day – typically flight altitudes were *ca.* 10 m in marine areas, and 35% and 20% of observations overlapped with rotor sweep zones of offshore wind turbines, for day and night respectively. For great skuas, birds flew even closer to the sea in marine areas (Ross-Smith *et al*. in prep). Furthermore, Ross-Smith *et al*. (in prep) compared distributions of GPS altitude of lesser black-backed gulls with that of Johnston *et al*. (2014a) containing flight height curves derived from boat surveys. Johnston *et al*. (2014a) found that 28% of lesser black-backed gulls and 6% great skuas flew at risk height (20-120 m rotor sweep zone), which Ross-Smith *et al*. (in prep) reported as being similar to GPS flight height distributions during the day (31% for lesser black-backed gulls, and 4% for great skuas), equivalent to the survey period for boat-based data. However at night, Ross-Smith *et al*. (in prep) reported smaller estimated proportions at risk height for gulls (18%) and slightly higher proportions for great skuas (8%) than

Johnston *et al*. (2014a). Additionally, birds may also have different flight heights due to different ages, different times of the year (e.g. breeding, non-breeding) or different activity patterns (e.g. foraging, commuting, and searching). Recent study on northern gannets is currently investigating differences in flight altitude between commuting and foraging. Further study into these aspects would be highly recommended to further inform collision risk potential for species.

Bishop *et al*. (2015) used GPS-PTT devices (PTT-100) to study the physiological and biomechanical requirements of flight of bar-headed geese in relation to high altitude, finding that one bird flew at 7,300 m. This was also noted previously in Hawkes *et al*. (2012) where birds reached 7,290 m and 6,540 m above sea level on southbound and northbound migrations across the Himalayas, but typically the flight height distribution was normal with peaks at ca. 5,000 m (Hawkes *et al*. 2012). Hawkes *et al*. (2012) also state that the use of GPS-PTTs enabled quantitative measurement of flight heights (using derived GPS altitude data), as previous studies such as those using PTTs (Koppen *et al*. 2010) did not measure altitude directly. Hawkes *et al*. (2012) used a simple distribution barplot of GPS altitude measurements that were available from 97% of fixes. Finally, among birds of prey, Horton *et al*. (2014) studied the movements of juvenile Ospreys using GPS-PTTs and reported the flight height of ten osprey tracks was 264±224m; however, no further information is given as to the reasons behind the wide variability in the mean estimate due to variability or inaccuracy.

3.3.2.2 Calibration, testing and validation

De Monte *et al*. (2012) were able to use previous altimeter data from altimeters deployed on the same species and colony (Weimerskirch *et al*. 2004) to identify behaviour to be assigned to GPS-derived altitude of frigatebirds. The range of altitude measurements from de Monte *et al*. (2012) tally with that of the previous altimeter studies, e.g. birds climbing up to over 500 m and also remaining low at less than 15 m, but a strict direct validation to altimeter data was not provided. Ens *et al*. (2008) carried out tests of GPS-PTT transmitters, the same type as used by Klaassen *et al*. (2011), by placing them in fixed positions for a certain amount of time. This trial indicated that the vertical error was as specified by the manufacturer or perhaps even better, being ±22 m for altitude, with a tendency for greater error in altitude measurements with increasing altitude. Similar to Ens *et al*. (2008), Thaxter *et al*. (2011) conducted tests of the error in altitude measurements of GPS devices by placing a tag in fixed locations at known height locations above mean sea level. Thaxter *et al*. (2011) found that for the site used to study lesser black-backed gulls in southeast England, an accuracy bias of ca 6 m below mean sea level was present in the data and although only two birds were presented as examples, a similar precision error compared with Ens *et al*. (2008) of up to 15 m was recorded (Thaxter *et al*. 2011). Corman & Garthe (2014) used a test calibration height of 11 m, finding that errors ranged up to ±20 m (2% observations), but were most frequently ±10 m (32% observations). In most studies, no independent validation of the GPS altitude data has been made, for example, comparing to other methods. Horton *et al*. (2014) reported that the altitude of a juvenile Osprey, as shown from GPS-PTT telemetry, was consistent with the velocities and altitudes expected for a large vessel with which this bird interacted, providing some level of additional validation.

3.3.2.3 Advantages and disadvantages

The precision of GPS-derived altitude may be considered generally lower than altimeters, however such error is dependent on numerous factors and with faster sampling measurement, lower errors are recorded (Bouten *et al*. 2013). Other than de Monte *et al*. (2012) – see above – to our knowledge, there has been no further validation of GPS-based flight altitude of birds alongside other methods such as radar or altimetry methods; although note much focus has been placed on the potential error and accuracy of such measurements. As noted above, errors in measurements of GPS

devices are linked to sampling interval and number of satellites available, but may also occur due to the their position in the sky ("pdop" value). Similar to altimeters, other variables such as tidal state, temperature, humidity and pressure may also influence GPS devices (Thaxter *et al*. 2011), but since altimeters rely on pressure for height estimation, these additional ambient factors are more likely to affect altimeters to a greater extent than GPS.

Attaching devices (altimeter or GPS) to animals may affect their behaviour, physiology, reproduction and survival (Murray & Fuller 2000, Walker *et al*. 2012). These effects could be through additional weight added and/or the attachment method used. To minimise impacts, a general threshold of 3% body mass is used. However, studies must always make sure that data gathered is representative of normal behaviour of the species, for example through careful monitoring of a control sample of individuals, and direct assessment of behavioural/physiological impacts (Thaxter *et al*. submitted). With the exception of potential observer bias to individuals observed, e.g. through laser rangefinders on boats and boats disturbing birds, all other methods reviewed here can be regarded as remote gathering of information in absence of potential impacts that telemetry methods face. More resources are therefore needed for tagging studies (for example in comparison to radar) to meet this important research requirement.

The weight and restrictions of tags can be considered a disadvantage compared to other methods such as radar, in particular if a species is of research interest but where technology cannot currently offer solutions to study. Among other aspects, an important consideration is the weight of the device to be used on species. The section above for the advantages and disadvantages of altimeters (section 3.3.1.3) also considered the weight of current devices. Note, it is not the purpose of this report to proscribe specific tags for specific species. The specific tag will also depend on many factors related to the attachment solutions for the species and the goals of research for the study. However, it is useful to highlight the current weight thresholds for GPS technology to place the current technology in context of applicability to seabirds considered of concern for collision risk assessment.

Currently, GPS devices are available as light as 1 g, for example[3], which would potentially allow all species in the top 15 of those most sensitive to collision in Furness *et al*. (2013) considered above, to be studied using GPS technology. However, the duration of tracking period required, number of fixes desired and quality of the device for altimeter data needs further consideration. To date, although GPS devices all collect altitude information, the quality of information from different GPS devices or systems is perhaps less well known. However, some differences exist in current military and civilian grade GPS systems in the USA, the former having access to ionospheric delay corrections that permit less radio degradation and subsequently better accuracy[4]. Similarly corrections for these signal delays can reduce error gave improvements in both horizontal and vertical errors approaching that seen under dual-system frequencies (Allain & Mitchell 2008). Additionally, studies that require long-term focus (i.e. throughout the year) and high resolution sampling frequency (i.e. more fixes per day) are typically heavier to accommodate the battery and solar panels from which the tag recharges and collects the required data. Long-life devices used to date on Lesser Black-backed Gulls (University of Amsterdam, Bouten *et al*. 2013) have weighed up to 21 g (plus attachment materials) (Thaxter *et al*. 2015), which would require a species to weigh at least 700 g. A generic 21 g tag weight would exclude study on: Common Gull, Kittiwake, Arctic Skua, Black-headed Gull, Sandwich Tern, Common Tern and Little Tern. Note again, there are a wide variety of tag types on the market currently with many lighter devices, dependent on the study requirements of battery size.

[3] http://www.lotek.com/introducing-pinpoint-gps.htm [last accessed 11/052015]
[4] http://www.gps.gov/systems/gps/performance/accuracy/ [last accessed 02/07/2015]

A key current advantage of GPS methods to estimate flight heights is that no additional devices are required on the same bird other than the simple GPS device. More importantly, detailed three-dimensional data can be gathered where the altitude measurements are locally geo-referenced to latitude and longitude of the bird. This can enable powerful datasets to be assembled to answer more specific questions such as potential avoidance of species in three-dimensional space. However, note above in the "altimeter section", the continuing development and improvement of altimeters may enable a wider range of species to be tracked with lighter devices.

Tagging studies have an assumption that the birds selected for tagging are representative of the population. They are also dependent on the number that can be captured and tagged, for example related to capture practicalities, cost of devices or licensing constraints that may limit the number of birds that are allowed to be marked. The specific nests targeted may be those that can be readily accessed, thus an assumption is made that those birds are representative of suitable quality individuals using suitable quality habitat, reflecting the general population. A disadvantage of telemetry methods is that the sample sizes are often far smaller – for example, telemetry study may track 20 birds from a population but aerial surveys may record many thousands, raising raises questions on population-level representativeness of the data. Methods are available for tagging studies to assess adequacy of sample sizes, by considering horizontal spatial area usage of the birds tracked in relation to that predicted for the population (Soanes *et al*. 2013). Relatively few studies have qualified their data in this way, which should remain a priority for future tracking studies. However, no telemetry studies have yet considered whether enough birds have been tracked to allow appropriate characterisation of vertical spatial area usage.

Typically most seabird telemetry studies have focused on the breeding season. For all telemetry methods (e.g. altimeters and GPS) careful assessment of the correct device, attachment method, assessment of device and attachment effects and sample sizes to answer the questions posed are required before study commences. For short-term study during the breeding season, a device may be attached temporarily to feathers (e.g. Hamer *et al*. 2009). A current disadvantage of GPS (and altimeter) methods is the potential restriction to breeding season periods for many species. To use GPS devices outside breeding, such as migration and non-breeding, devices must remain in place through periods of feather moult and potential body size changes, hence requiring alternative attachment methods such as a harness (e.g. Klaassen *et al*. 2011; Thaxter *et al*. 2015). These may not be applicable for some species, such as those diving species. Assuming a very light 1 g tag + feather attachment in theory it is possible to study the majority of species of key concern for collision risk during the breeding season (see above). By contrast, currently, very few UK species have been studied with GPS outside the breeding season – being Lesser Black-backed Gull, Herring Gull, and Great Skua (Ens *et al*. 2008, Thaxter *et al*. 2011, Klaassen *et al*. 2011), and for some individual Northern Gannets whose tags lasted outside the breeding season (e.g. Langston *et al*. 2013). However, note it is beyond the scope here to make recommendations of specific studies on particular species.

Radar methods can cover all the individuals of a particular species moving through a surveyed area. However, GPS can also identify behaviour (and flight heights) of individual birds of a species. Telemetry methods have an advantage in that they can determine the origin of birds i.e. from a protected site allowing potential impacts of effects of offshore wind farms to be better understood – often the reason for conducting the work in the first place is due to concerns over potential use of an area by birds from a protected site. For example, Thaxter *et al*. (2015) have shown, for lesser black-backed gulls in southeast England, connectivity between a Special Protection Area (SPA) and areas of proposed, consented and constructed offshore wind farms, and variation between individual birds during the breeding season. Often a specific area is studied using radar methods, for

example tracks of birds in relation to an offshore wind farm. The wider coverage of GPS telemetry allows for a more powerful investigation of flight heights across different habitats (Ross-Smith *et al*. in prep). Flight heights of individual birds can also be assessed for birds from a protected site across the year (Klaassen *et al*. 2011). However, studies that focus on individual species often require dedicated focus, for example studying single species. Therefore, more intensive survey methods may not lend themselves well for studying a wider suite of species.

Most studies of seabirds using bird-borne devices have been conducted from breeding colonies. However, for offshore wind farms, important areas further offshore may contain birds from a variety of origins, or birds from outside the UK, e.g. migratory species that breed elsewhere. Therefore, the potential exists for catching and tagging birds from the at-sea area of interest and assessing their flight heights using tracking. Such devices would have to be long-lasting and remote-downloading, so likely GPS-PTT devices would be most suitable. To our knowledge, no studies have been conducted to date using such methods.

Table 3.1 Summary of seabird tracking telemetry studies estimating flight altitude

Method	Reference	Species	Resolution (m)	Testing / calibration	Validation with additional method of estimating flight height
Altimeter	Weimerskirch *et al*. 2003	Frigatebird	Resolution 3.3 m	Corrected for atmospheric pressure using fixed-location altimeter in colony	
Altimeter	Weimerskirch *et al*. 2004	Frigatebird		As above	
Altimeter	Weimerskirch *et al*. 2005	Red-footed booby		As above	
Altimeter	Garthe *et al*. 2013	Northern Gannet	Resolution in air 2 m; accuracy 8.4 m (1 hPa).	Correcting for air pressure (nearby weather station)	
Altimeter	Shannon *et al*. 2002a and b	American White Pelican			Comparison to altimeter data in fixed-wing aircraft
Altimeter (plane)	Shamoun-Baranes *et al*. (2003)	White Stork			
PTT altimeter	Pennycuick *et al*. 1999	Whooper Swans	Error never less than 18 m and up to ±50m above sea level	Calibrated for prevailing barometric pressure	
GPS-PTT	Klaassen *et al*. 2011	Lesser Black-backed Gull			
GPS	de Monte *et al*. (2012)	Frigatebird			Comparison to altimeter data at the same colony & species
GPS	Corman & Garthe 2014	Lesser Black-backed Gull	Most data (32%) ±10 m	Fixed position of device, error surrounding altitude assessed	
GPS	Ross-Smith et al. in prep & Thaxter et al. 2011	Lesser Black-backed Gull & great skua	±15 m precision	Fixed position of device, error surrounding altitude assessed	Compared to boat-based distributions in Johnston *et al*. (2014a)
GPS	Bouten *et al*. 2013	Honey Buzzard and White Stork	Error dependent on sampling interval; lowest for 6 s rate (CI = 0.25-3.75 m) largest for 600 s rate (CI 2.13-102.0)	Fixed position of device, error surrounding altitude assessed	
GPS-PTT	Ens *et al*. 2008	Gulls and Eurasian Oystercatcher	Vertical error better than ±22 m	Fixed position of device, error surrounding altitude assessed	
GPS-PTT	Klaassen *et al*. 2011	Lesser black-backed gull	As above	As above	
GPS-PTT	Bishop *et al*. 2015 & Hawkes *et al*. 2012	Bar-headed Goose		None stated	
GPS-PTT	Horton *et al*. 2014	Osprey		None stated	Brief boat data comparison

3.4 Radar [top]

3.4.1 Examples of use

Radar methods have been used to assess the flight patterns and altitudes of animals for many years including birds (Eastwood 1967; Cooper *et al*., 1991; Harmata *et al*., 1999; Poot *et al*. 2000; Petersen *et al*. 2006; Krijgsveld *et al*. 2011), bats (Kunz *et al*. 2007) and insects (Chapman *et al*. 2004; Jeffries *et al*. 2013). Among birds, flight heights have been obtained for passerines (Alerstam 1990; Bruderer *et al*. 1995; Hüppop *et al*. 2006; Shamoun-Baranes *et al*. 2006), raptors (Kerlinger *et al*. 1985; Cooper *et al*. 1991; Mateos-Rodriguez & Liechti 2011), as well as a variety of seabird and waterbird species (Klaassen & Biebach 2000; Krijgsveld *et al*. 2011; Dokter *et al*. 2013a,b; Blew *et al*. 2008).

The number of radar studies that have been conducted to date assessing flight altitude of birds are too numerous to list individually. However, detailed measurements of flight heights for specific species are relatively sparse in the literature due to difficulties in identifying individuals to species level (Shamoun-Baranes *et al*. 2006; Dokter *et al*. 2013a). For example, flocks of swans, geese, ducks, cranes and shorebirds were recorded using Furuno radar by Cooper *et al*. (1991) in north America, migrating waterbirds in Western Estonia using a mobile ship Furuno radar (Kahlert *et al*. 2012; range 1.8 km). Schmaljohann *et al*. (2008a) using radar alongside visual observations found that flight altitude distribution of lesser black-backed gulls was between 2,869 and 5,054 m above sea level during spring and autumn migrations across the Sahara Desert. Targeted visual surveys alongside radar enabled Krijgsveld *et al*. (2011) to monitor the movements and flight heights of seabird species in relation to offshore wind farms using radar. Krijgsveld *et al*. (2011) measured flight heights of birds up to 1,385 m, but this varied between seasons, time of day, day/night, and with weather patterns. Flight heights were lower in summer and winter, partly reflecting dominance of gulls and other local seabirds in the samples. General groups of seabird species were also examined for flight heights, for example gannets were found to generally fly below 10 m but up to 50 m foraging, gulls varied, for example, locally at 50 m but circling up to 250 m and foraging near vessels at 20 m, and other species such as alcids – typically 5 m and rarely above 50 m (Krijgsveld *et al*. 2011). The use of radar has enabled in-depth investigations into the influence of weather conditions such as wind speed, on flight altitude, with particular focus on soaring birds during migration periods (Shamoun-Baranes *et al*. 2006; Kemp *et al*. 2013).

Recently, since summer 2014, a collision avoidance study of seabirds in response to an existing offshore wind farm (Thanet, Kent UK), has been conducted using a combination of methods. This study, entitled the Offshore Renewables Joint Industry Programme (ORJIP) – Ward *et al*. (2015) – is using a Thermal Animal Detection System (TADS) camera system in digital communication with surveillance radar systems, and has also combined laser rangefinders, observers and high performance radars at the wind farm periphery. Data on flight altitudes is also being collected using these methods, and the project will inform meso- and micro-avoidance of the wind far by seabirds at the species level for the vast majority of data. Two radar systems are being used, a coastal surveillance SCANTER 5000 radar (with a range of 12 km), and 25 Local Area Weather Radar (LAWR)[5] systems (range 8 km). Both of these systems use X-band. The SCANTER system is a 2-D fully coherent pulse compression radar that can resolve very small targets. The LAWR system was developed in the late 1990s[3], is unlike conventional C-band weather radar with a resolution of at least 100x100 m.

[5] http://www.dhigroup.com/upload/publications/scribd/183447574-Local-area-weather-radar-DHI-LAWR-Systems.pdf [last accessed 13/05/2015]

3.4.2 Calibration, testing and validation

A number of offshore radar studies have calibrated the observations gathered from both weather (e.g. C-band) and marine (X-band) radar systems with those of visual methods (e.g. Poot *et al*. 2000; Schmaljohann *et al*. 2008a; Bunch & Herricks 2010; Krijgsveld *et al*. 2005, 2011). For example, Krijgsveld *et al*. (2005, 2011) used simultaneous panorama scans to quantify bird numbers in different air layers and made comparisons to radar measurements. Although this was still biased towards daylight hours, a combined "ground-truthed" dataset was built up (see also section 3.1). Previously, Poot *et al* (2000) validated panorama scans to radar, finding that under 100 m altitude, comparison of the two methods produced similar altitudes, but above 100 m, visual methods resulted in increasing underestimations compared to radar. Additionally, Dokter *et al*. (2010) compared weather radar (considered potentially coarser in resolution) to dedicated high accuracy bird radar, finding that weather radar can be used to extract bird density altitude profiles.

The detection capabilities of radars, however are often not well known (Schmaljohann *et al*. 2008a; Dokter *et al*. 2013a). In particular, the "black box" nature of systems can make interpretation difficult. Dokter *et al*. (2013a) used a validation approach to try and understand and quantify "track-while-scan" radar capabilities combining information from line-transect boat surveys, which included the flight heights of birds. A probability of detection function was obtained for flight altitude (alongside other factors of bird size, range and surface substrate), which could then be applied to obtained a corrected estimation of numbers of birds. The effective range of the X-band marine radar was ca. 1.5 km, and larger birds flying higher and in high tide periods were more likely to be detected (Dokter *et al*. 2013a). Such a validation approach has relevance for studies where birds generally fly at lower altitude rather than high altitude (i.e. for collision risk assessment), but also depends on additional uncertainty of identification classification of birds within flight height bands from boat-based methods (Dokter *et al*. 2013a). The accuracy of some radar methods are generally considered very good. For example, Shamoun-Baranes *et al*. (2006) used a Doppler radar, which in the vertical dimension to estimate flight heights, using a pencil-beam antenna, which is stated as having a vertical accuracy of ±1 m. However note, different radar systems suffer more or less error on vertical measurements – see below.

3.4.3 Advantages and disadvantages

Radar can generally be divided into three types, weather surveillance (e.g. Doppler C-Band), tracking radar (such as those tracking aircraft targets and missiles), and marine radar (X band) (see Desholm *et al*. 2004, Desholm *et al*. 2006 and Kunz *et al*. 2007 for detailed reviews). General migratory patterns can be observed using Doppler weather radar (e.g. Dokter et al. 2013b) but cannot give high resolution altitudinal data over small spatial scales (ca. 250 m resolution), nor can it give information at or below turbine height (Kunz *et al*. 2007; Dokter *et al*. 2010), although see Dokter *et al*. (2010) and discussion above. Individual tracks of birds and their altitude can be obtained using tracking radar (e.g. Liechti *et al*. 1995), but does not provide a broad view of migration over an area of interest, such as an offshore wind farm, and is expensive and not widely available (Kunz *et al*. 2007). A more common method for assessing flight altitudes of species, in particular in relation to operational wind farms, is through marine X-band vertical marine radar to detect flux and flight altitude (e.g. Desholm *et al*. 2006, Krijgsveld *et al*. 2011). The placement of these radars may be fixed for example if measuring targets in relation to offshore wind farms (Krijgsveld *et al*. 2011) or alternatively mobile, as has been used on ships covering a wider area (Kahlert *et al*. 2012). Such systems are advantageous over the two other radar methods in that they are available off-the-shelf and are less expensive (Kunz *et al*. 2007).

The performance of radar depends on species and associated flight behaviour of birds as well as aspects to do with the terrain of the study site and weather / atmospheric conditions (Petersen *et al*. 2006; Krijgsveld *et al*. 2011). Clutter is often evident in many studies (Cooper *et al*. 1991; Krijgsveld *et al*. 2011). Dokter *et al*. (2013) found that clutter was worse over land than over sea, and a smooth sea surface improves this situation, however clutter issues closer to the sea surface worsen when conditions at sea deteriorate (e.g. large waves), reducing target detection probability where bird echoes become indistinguishable from sea clutter (Brand *et al*. 2011). Therefore, although clutter can be filtered, this can lead to underestimations of flight heights close to the sea (Hüppop *et al*. 2006). Radars over land can also miss lower-flying birds (Kerlinger & Gauthreaux 1985). Radar may also detect larger flocks easier than smaller ones, may struggle identifying an echo as a group of birds or an individual bird, and can also have a size bias as it is easier to detect a larger bird than a smaller one (Krijgsveld *et al*. 2011; Kahlert *et al*. 2012). Generalisations of altitude bands sometimes occur in radar studies, which may be too coarse to enable finer scale assessment of collision risk. Additionally, as discussed above, unlike telemetry methods, radar cannot identify repeated movements of individual birds across the scanned area and may not be able to determine the origin of these birds (e.g. in relation to a protected site). Consequently, radar is less likely to be able to relate flight height behaviour to particular breeding colonies and protected sites.

Species identification for radar is often not possible. However, this can be achieved using other systems or visual observations alongside radar. For instance Shamoun-Baranes *et al*. (2006) used Doppler radar to obtain flight altitudes of birds and identified species using a video camera parallel to the radar and classification using wing beat frequencies. Krijgsveld *et al*. (2011) used visual methods to identify species. For species identification, Schmaljohann *et al*. (2008a) also tracked birds through the daytime at the same time as the radar to visually identify flocks of lesser black-backed gulls using a telescope.

Although it has been shown that human experts can reliably recognise bird signals from radar, further automation of radar data processing can also remove any potential for human error. For example, Zaugg *et al*. (2008) developed an algorithm to identify bird targets with radar using patterns of wing flapping. This reduced the dependency on human interpretations.

3.5 Laser rangefinder [top]

3.5.1 Examples of use

Laser rangefinders are typically equivalent to a pair of hand-held binoculars that can measure distance, altitude and direction of a target using a laser beam (Skov *et al*. 2012). Together this information can be used to derive three-dimensional information of movement of birds. This is a direct method, and can therefore circumvent the estimation of flight heights visually by observers, for example in reference to a boat mast.

Mendel *et al*. (2014) used a laser rangefinder to estimate the flight altitudes of six seabird species in the German North Sea for the Alpha Ventus offshore wind farm test site, taking at least two measurements from the rangefinder per target. These data produced flight height distributions (represented as boxplots) in relation to the operational height window of offshore wind turbines. Mendel *et al*. (2014) found that kittiwakes, little gulls, and northern gannets flew below the window, between 10 and 20 m (median 15-18 m), whereas those larger gulls species such as lesser black-backed gull, greater black-backed gull and herring gull flew within the window (median, 30-35 m, upper boxplot whisker reaching over 60-70 m. No additional validation of the method was carried out, however, Johnston *et al*. (2014a) suggest a similar distribution from a separate study using boat-based data. Skov *et al*. (2012) used a laser rangefinder on a stable platform to estimate the flight altitude of birds in relation to the Horns Rev 1 and 2 wind farms. The rangefinder was "fired" at targets at *ca* 10-15 sec intervals, with altitudes and positions logged through GPS, allowing 1,047 three-dimensional tracks of birds to be estimated. Skov *et al*. (2012) generated altitude distributions for several species over increasing distance from the wind farm. Most species were found to fly at low altitude, but Herring Gull, Lesser Black-backed Gull and Great Black-backed Gull (as well as raptors, pigeons and passerines) generally flew at rotor height (Rotor sweep, 21.5-114.5 m and 30-110 m for horns rev 1 and 2, respectively) close to the wind farms. Similarly, Kahlert *et al*. (2012) used a laser rangefinder alongside vertical radar (Furuno FAR2127BB; 25 kW, X-band) on a stable platform to study flight altitudes in relation to weather of migrating waterbirds in Western Estonia. This is discussed in more detail below.

Recently, military grade laser rangefinders have been used alongside radar, visual and thermal detection systems as part of the ORJIP project (see radar section) for the Thanet offshore wind farm (Kent, UK) (Ward *et al*. 2015). At that site, 3D bird trajectories and flight altitudes are currently being collected (since summer 2014) from a stable observer platforms at the wind farm. This work will provide valuable information on flight altitudes, and avoidance behaviour of bird species in relation to the wind farm. Of note however, is the safety issue with the deployment of human observers on platforms in marine environments. Therefore, this risk could be minimised for example considering the use of remote systems to gather data.

3.5.2 Calibration, testing and validation

The quality of laser rangefinders varies considerably, with consequences for the data that is obtained. There is a vast array of different hand held devices on the market – these have been reviewed previously[6,7]. The main reasons for variations include: (1) Beam aspects, including divergence and how focused the beam is, the quality of laser in the type of pulses, wavelength, and

[6] http://precisionrifleblog.com/2013/12/03/rangefinder-binoculars-reviews-field-tests-overall-results-summary/ [last accessed 30/04/2015]
[7] http://precisionrifleblog.com/2013/10/29/how-do-rangefinders-work/ [last accessed 30/04/2015]

sharpness, all of which influences how easy it is to get the beam on target; (2) Optics – high quality lenses and better magnification can improve the ability to recognise a target; (3) Aperture – the opening size of the receiver optic capturing return readings, which can impact the amount of data collected, and performances at greater distances, and precision/accuracy at shorter distances; and (4) Function and interpretation of measurements by the device – for example using many small pulses to increase sample size per "fire" of the device, analysing outliers, and display of results to the user. Studies using rangefinders for flight heights of marine birds in relation to offshore wind farms have tended to use the highest quality equipment ("military grade"), for instance the Vector 21 AERO Rangefinder, Vectronix AG (Kahlert *et al*. 2012, Skov *et al*. 2012, Mendel *et al*. 2014, Ward *et al*. 2015), which are more expensive and also heavier. These, however, tend to have superior distance coverage, accuracy/precision for the points of variation listed above, scoring highest, making them most appropriate in the context of estimating flight height distributions for offshore wind farms. Skov *et al*. (2012) found that the Vectronix 21 above allowed measurement of flight heights over a distance of 2-3 km from the observer (Skov *et al*. 2012), and Kahlert *et al*. (2012) reported the vertical accuracy of ±1 m for this device. However, even for the best available devices, this distance also depends on other factors such as the size of the bird (larger birds are more detectable), the angle of view, and flight behaviour such as gliding, soaring or flapping (Skov *et al*. 2012) as well as other environmental factors such as atmospheric conditions that may reduce visibility.

Skov *et al*. (2012) also recorded flight altitude from a fixed platform estimated in 25 m categories, but information comparing these visual methods and rangefinder altitudes was not found. Kahlert *et al*. (2012) used their laser rangefinder during the day and the vertical radar at night, with the rangefinder used to measure flight altitude of specific birds or flocks visible to the observer (Kahlert *et al*. 2012). Kahlert *et al*. (2012) found the flight height distribution of individuals and flocks were higher at night than during the day (radar-only measurement at night), being a mean of 125 m (95% CI, 117-133 m), after correcting for a bias in greater detection probability of larger flock sizes. Moreover, compared to radar, the laser rangefinder tended to underestimate the flight altitude recorded by radar during the day (Kahlert *et al*. 2012). However, the presence of clutter in radar measurements close to the sea may have also missed some flight altitudes closer to the sea surface. During the day, the distribution of flight heights was below ca. 100 m (from both radar and rangefinder methods) (Kahlert *et al*. 2012). But given the mixture of methods in this study, Kahlert *et al*. (2012) express caution in their interpretation; an attempt to reduce this bias was also made by using spatial information of migration patterns from horizontal radar assisting the observers in the field using rangefinders (Kahlert *et al*. 2012). The "true" flight distribution was therefore unknown and both radar and visual rangefinders may be considered to have differing biases towards higher and lower altitudes, respectively.

3.5.3 Advantages and disadvantages

The flight altitudes measured by laser rangefinders currently rely on initial visual detection by observers, and therefore may introduce human error and a potential to confuse individuals and flocks of birds at greater distances. In comparison to boat-based surveys that use a snapshot method (Camphuysen *et al*. 2004), visual detection is not considered a problem within 300 m of the boat. A recent study by RSPB (2015) on the south of Corran Ferry in Loch Linnhe, has also trialled the use of a hexacopter to compare the ability of six independent observers to visually identify the height of known altitudes of the hexacopter into bands (670 observations) and to the nearest 5 m (300 observations). RSPB (2015) found that 61% of observations were placed in the correct height band (67% of the incorrect ones being overestimates), and only 19% were correct to the nearest 5 m. The study also trialled the use of a laser rangefinder on the boat surveys, thus representing novel use on an unstable platform. However, the use of the rangefinder was unsuccessful since the movement of

the boat prevented targets being locked onto. The mean error of the rangefinder from RSPB (2015) was 10 m, with a maximum error of 40 m. Depending on the quality of instrument used (see above), the disadvantages of the methods may also be more pronounced without the more superior devices, for example reliable detection range being more limited.

The methods may also overestimate bird occurrences at lower altitudes since higher altitude detection is more unreliable with greater distance from the observer. This is affirmed in the Kahlert *et al*. (2012) study. There, Kahlert *et al*. (2012) attempted to counteract this bias using horizontal radar to assist the observers measuring flight altitudes using the rangefinder. Kahlert *et al*. (2012) therefore provide a very useful validation comparison of radar and laser rangefinders. As discussed above, the laser rangefinder tended to underestimate flight heights compared to radar (Kahlert *et al*. 2012). With increasing distance from the observer, identifying birds to species level becomes increasingly difficult and more prone to error. Laser rangefinders may therefore represent a relatively affordable method of refining flight altitude above that of visual estimation, which may also be useful in turn to validate such visual records.

The use of laser rangefinders and also inclinometers (see following section) has been restricted (to our knowledge) to use on stable platforms. Unstable platforms such as use on boat surveys has received very limited use of these technologies, and would in all probability greatly increase measurement error potential over longer distances or reduce the range of target detection. Such effects are therefore considered here as likely but unknown, and for example in very calm conditions, the methods could be used more feasibly. However, a bias to more clement weather conditions also may then introduce further bias in overall flight height distributions. These methods are therefore more likely to be restricted in overall area coverage, limited to the vicinity around the stable platform. By contrast, boat surveys using visual observers can cover a wider geographical area.

3.6 Inclinometer [top]

3.6.1 Examples of use

Flight heights can also be estimated using an inclinometer that digitally measures the angle to an observed target, from which flight height can then be derived (e.g. Krijgsveld *et al*. 2011; Stantial 2014, Johnston *et al*. 2014b). For example, Johnston *et al*. (2014b) used an inclinometer (resolution 0.5 degrees) to measure the angle of inclination of golden eagles from a stable platform and calculated altitude using distance estimated from the observer, and simple trigonometry. Data were collected upon the bird being detected by the observer within 2 km, using 6-12 sequential point locations per bird. Johnston *et al*. (2014b) analysed the flight heights of eagles (above ground level) pre and post-construction of the wind farm, finding that the distribution (boxplot) of flight heights increased from a *ca*. median of 200 m (60 tracks, one season) before construction to a median of over 400 m after construction (148 tracks, two seasons, graph-derived estimates quoted). No additional validation or error assessment was carried out for inclinometer measurements. Kerlinger & Gauthreaux (1985) also used a visual inclinometer alongside a vertical fixed-beam radar to estimate the flight heights above ground level of migrating raptors from a stable platform (12 species identified) at Cape May Point, New Jersey. Mean flight height distributions from radar were between 551-745 m, but difficulties were encountered using inclinometers for heights over 900 m, thus leading to greater reliance on radar measurements.

The use of estimated distances (e.g. Johnston *et al*. 2014b) alongside inclinometers has potential for increasing error in the final altitude measurements. A recent study used a further modification to the inclinometer method to estimate the flight heights of Hen Harriers in relation to inland wind

farms (Hovarth *et al*. submitted). The method uses two observers watching the same bird simultaneously through telescopes, with an electronic compass mounted on each to record bearing and pitch angles, from which altitude was derived using trigonometry.

3.6.2 Calibration, testing and validation

For inclinometers, similar to rangefinders, the quality of the sensor used can affect the precision of the output – hence there are a range of different products available. For instance, some inclinometer sensors vary in precision typically between 1/100th to 1/1000th of a degree. However, the absolute accuracy includes cumulative additional errors including zeroing offset, sensor sensitivity, and temperature gradients. Therefore, accuracy can range typically 0.01-2 degrees. To our knowledge, there have been very limited comparisons or validations between inclinometers and other survey methods.

However, for the study investigating the alternative trigonometric approach for Hen Harriers, Hovarth *et al*. (submitted) and Stanek (2013) carried out validation of vertical accuracy of the triangulation methodology. A moving drone (14 flights) was used with an on-board altimeter to provide a reference height, with the distance between observers and the drone then calculated over increasing heights of 100-700 m and angles of 30-120° between observers. Variation in the drone flights was apparent, but errors were largest at very small and high heights, typically between -7 to +8 m of the altimeter value at worst cases, but showed a reasonably high level of accuracy within a rotor swept zone of 23-124 m. Pitch calibration of compasses was also carried out in reference to known reference heights, and observer-to-observer calibration of angles (Hovarth *et al*. submitted).

3.6.3 Advantages and disadvantages

Aspects relating to laser rangefinders also apply here for inclinometers, for example that they have potential aspects of: human error in identification, distance of targets from the observer, variation in different devices that can be used (which carry different degrees of instrument error) and typically they require stable platforms. Hence their potential use on unstable platforms in the offshore environment is unclear. Moreover, little work has been done to assess the bias of particular inclinometer observations for birds in relation to other methods. However, the alternative approach to inclinometry is to use a refined trigonometric approach ("flight triangulation") such as that of Hovarth *et al*. (submitted) and Stanek (2013). These methods have some advantages over solely visual surveys, such as boat-based surveys, in providing a value (with error) rather than a distance band estimate. Further advantages of the Hovarth method may also be apparent over inclinometers that for example have sometimes used less accurate horizontal distances to targets (Johnston *et al*. 2014b). However, flight triangulation requires substantial extra effort to collect bird flight data and twice as many observers using simultaneous observations. Plus, it is only valuable if the same individual bird can be identified by both observers and followed without confusion (Hovarth *et al*. submitted). Faster flying birds may be less amenable to these methods as well. As with inclinometry, flight triangulation has been used on a stable platform inland, but the applicability of the method on an unstable platform offshore has not been tested. Using the method offshore where there are many birds of varying size and speed, flock size, as well as further issues such as the need for more than one vessel (and associated financial costs), potentially makes this less of a plausible approach for monitoring flight heights of birds offshore.

3.7 Acoustic monitoring: audible microphones [top]

3.7.1 Examples of use

Acoustic monitoring devices have been used to study the movements of birds and to understand bird migration (e.g. Balcomb 1977, Thake 1981; Evans 2000), with particular focus during nocturnal periods (Kunz *et al*. 2007). These methods can be used to obtain flight heights of birds, with the use of more than one microphone separated in space and multi-channel recording (Evans 2000). Cross-correlation among several identical microphones generally produces better latency measures and better estimates of height (Kunz *et al*. 2007). Altitudes of birds flying over a proposed wind-energy facility in Nebraska, USA were assessed using sound monitoring (Howe *et al*. 2002), whereby differences in sound arrival-times at two microphones vertically aligned at different altitudes on a tower, allowed flight heights of calling birds to be assessed. Evans (2000) also report on flight height distributions of warbler/sparrow and thrushes in a study in New York, however, this could not be separated further into individual species. Notably, the altitudes of acoustically-located birds and altitudes of birds near the turbines were strongly correlated with vertical beam radar carried out simultaneously, giving additional validation (Evans 2000). The altitude of passing migrants in relation to wind farms from these studies has been assessed both pre-construction (Evans 2000, Howe *et al*. 2002) and post-construction (Evans 2000) using multiple microphones (Kunz *et al*. 2007). Krijgsveld *et al*. (2011) also used call registration software and audible microphones at a local wind farm, as well as human identification of species passing fixed offshore Metmast positions. The microphones detected sounds in the volume of air above wind turbines, and thus were not influenced by background noise from waves and turbines (Krijgsveld *et al*. 2011).

3.7.2 Calibration, testing and validation

Calibration of the audio equipment through microphone settings is conducted in all studies prior to data collection. However from the review carried out, no studies were identified that had independently validated the flight height data collected from acoustic techniques alongside other methods. To our knowledge the use of acoustic monitoring has not been widely used in the offshore environment to monitor the flight altitudes of birds.

3.7.3 Advantages and disadvantages

An advantage of acoustic monitoring is the lack of lower limit in estimating flight altitude. For example, vertical beam radar sometimes has issues detecting very low flight heights due to problems of scatter (see above). As such, acoustic monitoring is potentially useful in understanding issues surrounding wind farms. However, this may carry a disadvantage in that it cannot provide a full height distribution (e.g. analogous to GPS/altimeters), and the validation of flight heights of many species from this method is unknown. Furthermore, the use of the method may be location-specific, and some species may vocalise more than others. For instance, Dierschke (1989) in appraisal of the method for studying flight heights of migrant passerines, found that few species vocalised intensively over the North Sea, and therefore estimations of flight heights were biased towards a few species. A further bias towards species migrating at low altitudes could also be recorded, which in turn differs between areas (Dierschke 1989). Of potentially greater concern is the background noise that is likely to be apparent from rotating turbines and sea noise, especially in less clement weather conditions. Detecting calls of birds in those situations offshore therefore provides substantial difficulties in using acoustic monitoring as a sole purpose method for estimating flight

height distributions of seabirds offshore. It is also not presently clear whether audio methods have merit alongside other techniques such as radar and thermal imagery in the offshore environment.

3.8 Thermal and night vision infrared imaging [top]

3.8.1 Examples of use

Night-vision imaging has been used to record low level flight heights (ca. < 150 m) (Kunz *et al*. 2007, Calbrade & Henderson 2009), for example see Mabee *et al*. (2006). Detailed local behavioural data can be gathered using this method (such as hovering, circling etc.). Thermal infrared imaging uses heat signatures producing a distinct image against a cooler background (Kunz *et al*. 2007, McCafferty 2013). Many studies have used thermal infrared imaging to study birds and bats (Desholm 2003, Desholm *et al*. 2006). Desholm *et al*. (2004) and Desholm *et al*. (2006) describe the use of a thermal animal detection system (TADS) to provide information on aspects such as avoidance behaviour, flock size and flight altitude in relation to wind turbine blades. This was originally developed by NERI as a means of obtaining information on collision rates, flight behaviour, and avoidance rates of birds in relation to offshore wind farms in Denmark (Desholm *et al*. 2004). This was motivated by a need to improve upon human detection. Most recently, as part of the ORJIP project (see radar section), a thermal animal detection system (TADS) has also been used alongside radar and laser rangefinders, and is contributing to gathering of data of flight altitudes of birds in relation to the Thanet offshore wind farm (Kent, UK) – see Ward *et al*. (2015). The TADS system uses infrared camera equipment to image passages of birds passing a scene, triggered by movements of warm bodies (refined for particular sizes, shapes and temperatures of targets), thus removing the need for human reviewing and facilitating remote capture (Desholm *et al*. 2004). This method can give reasonable species ID based on size, shape, flight behaviour and wing-beat frequency (Desholm *et al*. 2004). The CAMS system (discussed in section 2.8 above) is a fixed platform system that has also been developed to have near-infra-red capability (Mellor & Hawkins 2013).

3.8.2 Calibration, testing and validation

The use of the TADS technology in the ORJIP project involves links with other radar systems whereby the radar directs the camera onto a target (Ward *et al*. 2015). This information is providing a combined means of estimating flight altitude and results of this study are not yet available. However, it is likely the study could independently validate flight height distributions from different technologies, for example radar and observer based methods, laser rangefinder tracks, compared to TADS and LAWR tracks. Thermal imagery has also been combined with radar previously to estimate flight height distributions of birds. For example, Gauthreaux *et al*. (2006) used a vertical radar beam simultaneously with a vertically pointed thermal imaging camera of individual migrant birds, but independent validation of both methods is not presented.

3.8.3 Advantages and disadvantages

Thermal imagery could be useful at considerable distance, for example Zehnder *et al*. (2001) detected migrants passing at 3,000 m from the ground using a Long-Range-Infrared System (LORIS, IRTV-445L), although resolution of measurements at such altitudes is unknown. The cost of the TADS system is also expensive (Desholm *et al*. 2004, Kunz *et al*. 2007), but is useful in poor visibility and darkness (Desholm *et al*. 2004). The use of night vision imagery offers some advantages in that detailed altitude-referenced behavioural data can be gathered, and the potential for thermal imagery is encouraging, with high altitude flights of migrants identified. The thermal imagery system used by Gauthreaux *et al*. (2006) was also concluded as being costly, and has an operational window above 25 m. However, costs of this technology are now reducing with increasing availability

(McCafferty 2013). There may be additional issues of cloud cover and atmospheric conditions such as high humidity preventing accurate assessment of altitude (Desholm *et al*. 2004, Kunz *et al*. 2007). The field of view is also limited, and detection distances of birds are relatively short restricting to local airspace (Desholm *et al*. 2004). However, the system can be considered an improvement in poor conditions over that of the naked eye (Desholm *et al*. 2004).

Given some of these limitations, the use of the thermal imagery systems as a sole purpose method for estimating flight heights of birds in the marine environment is considered less suitable. However, the system is likely to be a very useful supplementary method and in combination with other methods such as radar, as used in the ORJIP project, is a valuable addition. In particular the advantages this technology has in coverage of poor visibility and night-time periods, potential for species recognition, and remote use on stable platforms, is likely to see this technology continue to be used in the offshore environment for assessment of flight altitude.

3.9 Ornithodolite [top]

3.9.1 Examples of use

Ornithodolites are sometimes used to estimate speed (Tucker 1988; Pennycuick 1987; Pennycuick *et al*. 2013), however this method can also be used estimate altitude (Pennycuick 2008). The principle of obtaining height from ornithodolites is essentially the same as that of tracking radar, consisting of timed observations of azimuth, angular altitude and range – see Pennycuick (2008) for a detailed discussion of methodology. Modern ornithodolites can be considered similar to laser rangefinders however they are kept distinct here as a separate category – if the data obtained are fed directly to a computer, the instrument is referred to as an ornithodolite (Pennycuick 1982). For example Tucker (1988) and Tucker (1991) recorded descending flights of white-backed vultures between 200-500 m using an ornithodolite. Akos *et al*. (2008) used an ornithodolite to compare human and bird soaring strategies, observing descending flights of peregrine falcons and white storks, for example observing a peregrine falcon descent from 500 m.

3.9.2. Calibration, testing and validation

Akos *et al*. (2008) independently used paragliding pilots alongside birds however this was to gauge the soaring strategies of birds, rather than independently verify altitude measurement. Pennycuick *et al*. (2008) compared the results from ornithodolite observations with predictions from flight theory. Further reference should be made to laser rangefinders and their validation methods above.

3.9.3. Advantages and disadvantages

As with laser rangefinders, flight altitudes of individual species can be mapped in detail using ornithodolites, and therefore may be very useful for targeted studies in an area. However similar to these additional methods, they have restrictions on the upper altitude of measurement. Additionally, with greater horizontal distance from the observer, this method is also likely to suffer an increase in error of measurements, however the extent of this error is not known. With targeted focus on individual birds, other individuals moving through may be missed, i.e. it is likely not possible to record all individuals moving through as radar can. The restriction to daylight hours and sensitivity to ambient conditions and weather (which could also increase error in measurements) is another disadvantage this method shares with laser rangefinders, and ornithodolites have typically been used on land. However, ornithodolites can give very detailed observations of flight altitude (e.g. Akos *et al*. 2008), giving three dimensional information, and operate over a range in which offshore wind farms require information on flight altitudes of birds. They could therefore be used on a fixed (e.g.

metmast) platform at an offshore wind farm site to give equivalent data to that already gathered to estimate flight heights of marine birds.

Rangefinders, ornithodolites and use of the boat-mast to estimate flight height from boat-surveys are all visual methods and are restricted to daytime use. Similarly, ceilometers and moon-watching are techniques used at night-time (see section 3.10). Other methods that can measure throughout a 24 hour period, have recorded different flight altitude of birds between daytime and night-time periods. For example Krijgsveld *et al*. (2011) using vertical X-band radar observations found that during the day in summer and winter, flight activity was higher during the day than at night, reflecting local seabirds that are active in the day and less active at night; note although nocturnal migrant activity in the migratory season gave higher flight heights than during the day (Krijgsveld *et al.* 2011). Similarly, Ross-Smith *et al*. (in prep) using GPS found that Lesser Black-backed Gulls flew lower during the night than during the day, including in at-sea areas. A restriction to daytime or night-time observations only would therefore bias the picture should an overall 24-hour flight height distribution (arguably most representative of the species) be desired, having excluded the potentially different altitudes used by birds within the unobserved period. In the context of offshore surveys, this could represent an incorrect distribution that could feed into collision risk modelling. Although Kahlert *et al*. (2012) found that visual rangefinder methods recorded higher measurement occurrences at lower altitudes than radar, Ross-Smith *et al*. (in prep) found that visual boat-based methods gave similar distributions compared to GPS data during daylight hours. Therefore, further validation is required for a larger sample of studies before firm conclusions of any daytime altitude bias of visual methods can be drawn.

It is worth also noting that the wind farm itself could influence the flight height and behaviour of the bird if particular species have strong macro-avoidance tendencies such as gannets many kilometres from the wind farm (e.g. Krijgsveld *et al*. 2011). Hence, although wind farms offer stable platforms, using methods with limited range may not provide the most representative flight height distributions.

3.10 Moon-watching, artificial light and ceilometers [top]

Some studies have also used the light of the moon to enable visual observation flight paths, termed "moon-watching" (Zehtindjiev & Liechti 2003; Krijgsveld *et al*. 2005). Flight altitude data is also possible from these data by using a standard crater of the full moon as a reference point to the size silhouette of the bird viewed through a telescope, allowing nocturnal altitudes of flying birds to be studied (Krijgsveld *et al*. 2011). Leichti *et al*. (1995) compared moon-watching with observations from radar and found that moon-watching was useful below *ca*. 1 km height. Above this height a large proportion of birds were missed by moon-watchers (Leichti *et al*. 1995). However, the study period was limited to within three days of the full moon and restricted to clear periods. Hence, the timing of visits and coinciding with that of other methods to compare to daytime measurements has not always been successful (Krijgsveld *et al*. 2011). These restrictions are therefore a disadvantage of the method, typically limiting it to a supplementary tool (Liechti *et al*. 1995; Liechti 2001). In response to these limitations when the moon was not visible, Gauthreaux (1969) developed a portable ceilometer to observe low-altitude nocturnal migrations. This involved an auxiliary light source to illuminate a portion of the night sky that could then be surveyed using binoculars or a telescope. However, visible light may attract birds and insects, and flight altitude data from this method is likely to be biased due to the greater probability of detecting lower flying birds (Kunz *et al*. 2007).

Table 3.2 Summary of advantages and disadvantages of methods reviewed that have estimated flight heights of birds.

Method		Advantage	Disadvantage
Visual and Boat-based Surveys		Follows well-established protocols, and has a very high rate of species ID for flight height analysis (for example much greater than radar).	Generic flight height bands used rather than individual flight estimates, making assessment of changing turbine heights and collision risk restricted by the range chosen, but this can be overcome through modelling approaches. Data restricted to good weather conditions and daylight hours. Disturbance issues from the vessel on the birds.
Digital high definition imagery	Aerial stills and video	More cost effective than boat surveys. Data can be stored and re-analysed at a later date valuable to further analytical advances and quality assurance. Flight altitude of the survey plane is high enough to cause no disturbance issues to birds below.	Previous older datasets suffered a disadvantage of species ID being imperfect (i.e. restricted to general family groupings in many cases), which has now been overcome through technological development. Survey restrictions for some systems in clear conditions when the plane can be steady (i.e. not foggy or too windy), but new systems available allowing survey up to Beaufort Scale 6. Problems of glare have also been overcome for some systems. Data collection restricted to day-time but further infra-red improvements may overcome this.
	Spectro-graphic techniques	Same advantages as above, but can also survey both daytime and night time. Three-dimensional tracks of animals can be obtained.	As above – survey conditions up to Beaufort scale 6 (but considered sufficient for EIAs of UK offshore wind farms). Limited to a range from turbines up to 500 m.
Telemetry	Altimeter (bird-borne)	*1. Altimeter-specific* Potentially smaller error in altitude measurements than GPS-PTT's. Increasing miniaturisation and development of technology would allow future altimeters to be smaller, lighter, and packaged in the same device with other sensors, allowing a wider range of species to be tracked locally in 3D space within and far away from a wind farm – complex modelling of movements can therefore be carried out. *2. General telemetry.* Wider spatial focus obtained (e.g. in relation to radar). Can give specific flight height distributions linked to particular breeding colonies and protected sites. Not restricted to hospitable weather conditions and can monitor throughout the day and night.	1. *Altimeter-specific* Previous devices were heavy, preventing use on lighter species, and dual deployment alongside other positional devices wasn't possible. Requires calibration with local pressure, but species can range widely, hence increasing potential for error. 2. *General telemetry* (GPS and altimeter) Potential to alter the behaviour of animals. Sample sizes smaller for telemetry than e.g. radar raising questions of population-level representativeness. Shorter-life devices restrict temporal focus, restriction potentially on capture and re-capture of some species. Limited continuous use across the year for some species due to potential attachment constraints.
	Plane-based altimetry	Useful as a verification method for other techniques. Direct observing of birds at height also possible.	Disturbance potential to animals, restricted use and spatio-temporal coverage, expensive for plane time
	GPS	*1. GPS-specific* Requires no additional devices to be deployed on the bird. Localised 3D data can be obtained.	1. *GPS-specific* High estimation factor due to mathematical earth representation hence greater potential for error surrounding

Method		Advantage	Disadvantage
		Increasingly capable of tracking smaller species using lighter GPS devices than previously possible using altimeters. Sampling rate and modelling techniques can be used to understand and account for potential error on estimations. Combining with PTT or GSM transmission systems, allows study of birds away from breeding colonies, e.g. at sea. 2. General telemetry tagging points are the same as above for altimeter.	estimates, requiring validation. 2. General telemetry tagging points are the same above for altimeter.
Radar	Weather surveillance Doppler	Wide ranging spatial area coverage up to 200 km, as with all radar, nocturnally functioning.	Generally, cruder altitude measurement, coarse resolution (ca. 250 m) generally expensive but can be cheap if making use of existing weather surveillance networks; poor low-altitude coverage, but with careful analysis can be used to extract altitude profiles of birds (Dokter *et al*. 2010).
	Tracking radar	As above for weather radar, although less wide ranging. Altitude profiles more refined and 3D movement can be identified in a similar manner to the ornithodolite method (Pennycuick 2008).	In comparison to telemetry devices, represents a narrower coverage (10-20 km range), but coverage is greater than that obtained under boat-based and digital aerial survey methods. In the UK and likely elsewhere, potential legal / Strategic Defence issues as the system can track aircraft. Expensive, not widely available
	Marine X-band	Flight height accurately measured (e.g. ±1 m). Good for specific location studies. Superior use in different weather conditions (i.e. not influenced by number of satellites and cloud cover, and greater penetration compared to lasers). Inexpensive, off-the-shelf.	Clutter may lead to underestimations of flight heights close to the sea. Radar may detect larger flocks than smaller ones. Species identification often not possible for some taxon groups. Restricted in wider spatial coverage (e.g. <12 km). Potentially expensive. As with all radar methods, cannot always identify individual species or movements of individual birds. Can obtain vertical or horizontal measurements, not both at the same time (i.e. not 3D), compared to tracking radar and telemetry methods. Use restricted to general vertical distribution over a single horizontal space.
Other	Laser rangefinder and inclinometer	Useful additional method or verification to aid where disadvantages of some methods become an issue (such as close ground observations and radar scatter); Can identify individual species.	To date has been restricted to daytime use through human observers – greater tendency to miss targets at higher altitude further from the observer. In the marine environment, likely unsuitable for use on an unstable platform, but very useful on fixed platforms at a wind farm.
	Audible microphones	Useful additional verification to other methods. Can identify individual species	Interference with ambient sound – likely to be an issue for marine environment, small range, restricted vertical usage
	Thermal / night vision infrared imaging	Useful additional verification to other methods, and detailed local behavioural data can be gathered. Thermal imagery has been used up to high altitudes. Can identify individual species.	Coarse altitude resolution if calibrated with vertical radar and then used alone (Kunz *et al*. 2007); affected by cloud cover and other atmospheric conditions.
	Ornithodolite	Can record detailed flight height and behavioural information at lower altitudes; good for targeted	Restriction to lower altitude range, and spatial range away from the observer is a limiting factor; requires targeted effort and could

Method		Advantage	Disadvantage
		investigation to assess detailed flight behaviour in relation to extrinsic factors. Useful additional verification method. Individual species ID possible. Can give three-dimensional flight height information.	potentially miss other birds moving through. Restricted to daylight hours, and affected by ambient conditions in which observations can be conducted. Greater distance from observer increases potential error of measurement. Applicability over a wider area is uncertain. Typically used from land, and likely not suitable on an unstable platform.
	Moon-watching, artificial light & Ceilometer	Useful additional verification to other methods, relatively inexpensive. Can identify individual species.	Limited vertical range, restricted period of observation to full moon and clear conditions. Light attraction bias if artificial light source used, and may not be applicable in an offshore context; only of use at night.

4. DISCUSSION [top]

4.1 Comparison of methods [top]

This review has assessed boat based and aerial based surveys, and the alternative methodologies to estimate flight heights. These methods were reviewed to appraise their potential use in estimating flight height distributions of different species, and for their use in collision risk modelling for impact assessments of wind farms. Particular focus was placed on the relative advantages and disadvantages of each method, and the validation of methods that have been carried out.

Table 3.2 provides a general summary of all the advantages and disadvantages of the methods reviewed in this report. The methods were then tallied against one another, weighing up these relative strengths and weaknesses (Table 4.1) to assess which are the most generally preferred methods. Further recommendations of use could then be made while highlighting additional research gaps. A simple approach was used to rate each approach as a primary method on a scale of very good (+++) to very poor (- - -). This was achieved by evaluating each method for its relative expense and ease of use, error precision on measurements, species restrictions, species-specific ID possibility, full flight height distribution availability, general applicability to the marine environment, spatial scale covered, measurement through the 24-hour day, measurement through the year, influence of environmental conditions, sample size of birds of species and life-history status (e.g. breeding, non-breeding) of individuals determined.

Potentially, primary methods to derive flight height distributions included high definition imagery, telemetry methods, and radar. High definition methods in particular, are a relatively new tool, resulting in a limited amount of data available for this review, but they also have considerable further potential. These three families, along with those boat survey transect methods that have been most used to date are summarised further below revisiting the relative strengths and weaknesses of each. This final summary revealed that currently, no single method is a clear preference in a general context (hence no "+++" given to any method in Table 4.1). The required flight height distributions will be strongly driven by the needs of individual studies. This will also differ greatly between studies collecting data as part of baseline assessments before a wind farm has been constructed, as opposed to collision risk and avoidance assessment for existing wind farms (e.g. ORJIP study). Therefore although all methods have some disadvantages, this does not totally preclude their use, dependent also on the research question posed.

Table 4.1 Summary ranking of relative suitability of all techniques as a primary method for estimating flight height distributions in the offshore environment; criteria for a primary method include: Expense and ease of use, error precision on measurements, species restriction - e.g. tags too heavy or attachment impractical, species-specific ID possible, full flight height distribution, general applicability to the marine environment, spatial scale covered, measurement through the 24-hour day, measurement through the year, influence of environmental conditions, sample size of birds of species, life-history status (e.g. breeding/non-breeding) of individuals determined.

Method		**Rating as a primary method (+++ very good, - - - very poor)**	**Reasoning**
Visual and Boat-based Surveys		+	Expensive, good species ID accuracy but problematic generalisation of flight height bands.
Digital high definition imagery	Aerial stills and video	++	Currently uncertain. Affordable and no disturbance to animals, but mainly covers the daytime period only, dependent to an extent on suitable survey conditions.
	Spectrographic techniques [a]	+	Three-dimensional capability and through the day monitoring in most survey conditions – restricted range, needs some further testing.
Telemetry	Telemetry: GPS and altimeter	Altimeter: ++ GPS ++	Allows observations linked to breeding colonies, in all weather conditions, across the day; potentially throughout the year. Small number of birds considered representative of a larger population. Needs careful study of attachment and device effects on birds. As above, plus GPS error potentially bigger than altimeter but modelling techniques can be used to address this.
	Telemetry: plane-based altimetry	-	Too labour- and cost-intensive for a primary method.
Radar	Weather surveillance Doppler	-	Wide ranging but cruder measurement, expensive, species ID issues with all radar.
	Tracking radar	-	Can give 3D movements, but expensive, not widely available.
	Marine X-band radar	++	Accurate, wide range of species monitored, large number of birds, but has species ID issue, scattering at low altitude.
Other	Laser rangefinder	+	Not suitable on unstable platform, restricted vertical usage. But suitable on fixed platform at wind farm periphery (e.g. ORJIP).
	Audible microphones	- -	Interference with background marine noise, restricted vertical usage.
	Thermal / night vision infrared imaging	+	Species specific, nocturnal, but coarse resolution, affected by atmospheric conditions.
	Moon-watching & Ceilometer	- -	Restriction on altitude range, spatial range, not suitable on unstable platform, restricted to nocturnal hours.
	Ornithodolite	+	Restriction on altitude range, spatial range, not suitable on unstable platform, restricted to daylight hours.

[a] This technique is potentially deemed a good method (++), potentially of primary use, but here it is classed as (+) being in its infancy, having been successfully trialled at one location (see text for more information).

4.1.1 Visual estimation and high definition imagery

Visual estimation from boat-based surveys and platform-based panorama scans at sea have provided key estimates of flight heights of different species for studies, and boat-based estimates have been used within environmental impact assessments for assessing collision risk of offshore wind farms. Johnston *et al*. (2014a) provide a full discussion of the strengths and weaknesses of boat-based data. A key advantage of current boat-based methods is that they offer species-specific flight information following well-established protocols (Camphuysen *et al.* 2004). However, the use of generic flight height bands has been of recent concern for obtaining estimates of flight height distributions, as different surveys may use different band classifications. Johnston *et al*. (2014a) used novel modelling methods to obtain continuous flight height distributions from boat-based data for the majority of UK species of conservation concern. However additional points of concern include the restriction to daytime use – recent radar and telemetry studies suggest slight behaviour can differ between day and night (Krijgsveld *et al.* 2011, Ross-Smith *et al.* in prep). The disturbance that survey vessels have on species of interest is also of concern. Therefore more recently, high definition aerial methods have been used that can not only survey abundance and distribution of species in a given area, but can also estimate flight altitudes of individual birds. Previous concerns of imperfect species identification from high definition aerial surveys have now largely been overcome. Attempts at validating and understanding flight heights estimated from aerial survey data are still ongoing. However, should these methods be suitable, they may offer an unbiased assessment of flight altitude of different species. Aerial surveys are more cost-effective than boat surveys making them an attractive survey tool, in particular for more offshore areas. This also makes HD methods potentially advantageous over radar where there is no stable platform offshore, for example during pre-construction baseline assessment far offshore. Restriction on area coverage though is still a limitation for any defined survey area, and telemetry methods offer additional wider focus for a smaller sample of individuals. Given the variety of newer techniques to estimates flight heights and their status as potential primary methods, it is therefore likely that there may be a reduced reliance on visual and boat-based information in future studies.

Validation of flight height estimates from observers at sea has recently been compared to estimates using laser rangefinders by RSPB (2015) on the south of Corran Ferry in Loch Linnhe. Furthermore, flight height estimations for Lesser Black-backed Gulls during the daytime from GPS telemetry matched the distributions recorded from visual boat-based surveys. Such validation studies are welcomed, and are considered an important future research area to enable potential biases in distributions from particular methods to be assessed.

4.1.2 Telemetry

The use of tracking telemetry has emerged as a useful potentially primary tool with which to estimate flight heights of birds. In comparison to some other methods such as radar, to date, relatively few studies have explored telemetry for use in flight height estimations, mainly because the advance of such technologies has occurred relatively recently. For example the first altimeter studies were conducted in the 1990's (Pennycuick *et al*. 1999; Weimerskirch 2003), and only very recently has GPS telemetry been explored as an alternative to obtaining flight height distributions of species (Ens *et al*. 2008; Corman & Garthe 2014).

A key advantage of telemetry over radar is that it can be used over a wide spatial scale, and can therefore give a very wide coverage for estimating flight heights, much greater than even the longest range weather radar (200 km). Moreover, flight height distributions can be obtained for specific colonies of interest, being certain that individuals are of particular breeding status, which is not possible from other methods. Relative flight height distributions can also be modelled to account

for potential differences that may occur in different habitats, better reflecting more general behaviour and giving a wider ecological context (Ross-Smith *et al* in prep). Furthermore, the method can be used throughout a 24-hour period and observations can be made in all weather conditions.

However, telemetry has some disadvantages. Much study of seabird behaviour has focused on the breeding season when birds can be captured at their breeding colonies, and tags can be attached to birds. The attachment method using GPS and altimeters, is a limiting factor that currently for many species is restricted to feather attachments, and therefore shorter-term focus on flight altitudes during the breeding season. For some species such as large gulls, harnesses have been used successfully during the non-breeding season (e.g. Ens *et al*. 2008, Klaassen *et al*. 2011; Thaxter *et al*. 2015), but wider use of harnesses on many species such as diving species is at present uncertain. For all telemetry methods, careful assessment of the correct device, attachment method, assessment of device and attachment effects and licensing are also required before any data on flight heights can be gathered. The number of individuals that can be studied using telemetry is also limited to the number of devices or birds that can reliably be studied from the population. Therefore, careful consideration is needed so that results obtained are representative of the study population through appropriate power analyses (Soanes *et al*. 2013). For radar methods, multiple tracks over a period of time can represent the same individual. However, in comparison to telemetry, radar covers all the individuals moving through the area with much greater sample sizes. Sample size issues are also apparent for those "near-field" methods - see below. Therefore, for focused study in a particular area across a wide range of species, methods such as high definition imagery and radar are therefore potentially advantageous.

This review suggests that altimeters generally have lower measurement error (e.g. up to 1 m) compared to GPS (up to 20 m) – e.g. Weimerskirch *et al*. (2005), Ens *et al*. (2008). Altimeter precision depends on suitable atmospheric data for calibration and some rigorous assessments have been conducted comparing performance and accuracy of plane-based altimeters and altimeters to be deployed on birds (Shannon *et al*. 2002b). Likewise, GPS telemetry systems have been ground-truthed to understand potential biases in the data (Ens *et al*. 2008; Thaxter *et al*. 2011), and further studies have been carried out into the error surrounding altitude measurements under different sampling rate protocols (Bouten *et al*. 2013). The calibration, testing and validation of any method used for estimating flight heights is important to ensure that flight height distributions are robust. Previously altimeters were too heavy to deploy on some species and individual altitude measurements to accompany latitude/longitude measurements (three dimensional geo-referencing), has traditionally not been possible with some heavier altimeters. Advances in technology are now permitting altimeters to be included alongside GPS devices to give a powerful method of estimating flight heights from different methods simultaneously. To our knowledge, there have been no concurrent comparisons between GPS and altimeter derived altitudes, nor compared to radar and other methods. Such further relative comparisons are very important.

4.1.3 Radar

Radar has been a general preferred method for many offshore studies. The cost of some radars are high, and for some the altitude data resolution and error is too coarse to be of any use in relation to offshore wind farm collision risk assessment (Table 2). However, marine X-band radars are more affordable. The most sophisticated bird-borne GPS telemetry systems can also be expensive, although much cheaper telemetry alternatives are available but with currently restricted temporal focus. Therefore, the cost-benefit of these advantages and disadvantages needs to be weighed up for any given study.

Generally with radar systems, a wider spatial coverage results in a coarser resolution. Therefore, radar methods as a general grouping vary quite widely in the potential error surrounding altitude measurements (Kunz *et al*. 2007, Table 3.2). However some studies report very small error on actual estimates (e.g. Shamoun-Baranes *et al*. 2006) and marine X-band radars, although being more restricted in range, are considered to have a small error on flight height measurements (e.g. up to 1 m). This is highly suitable to specific location studies, with these methods being widely used to estimate flight heights at number of existing offshore wind farms. However, their range (e.g. <12 km) makes study of sites further offshore less feasible, progressively moving towards wider-scale but coarser resolution weather and Doppler radars. Radar is advantageous in less hospitable weather conditions. For instance, flight heights can be obtained at a time when visual boat-based and digital aerial surveys cannot be undertaken. This makes radar an attractive prospect if a stable platform offshore is available. However, the clutter from background scatter close to the sea surface makes underestimation of flight heights close to the sea a possibility, and radar may detect larger flocks than smaller ones.

Arguably one of the biggest concerns with radar is that species identification is often not possible, therefore additional methods such as laser rangefinders (Krijgsveld *et al*. 2011) and thermal imagery/radar detection systems (Ward *et al.* 2015) have often been used alongside radar (e.g. Kahlert *et al*. 2012; Shannon *et al*. 2002b). This has enabled some level of validation and comparison of different flight height distributions of different methods – see for example Kahlert *et al*. (2012) comparing radar to laser rangefinders, and Dokter *et al*. (2013a) and Krijgsveld *et al*. (2011) comparing radar to boat-based or fixed metmast visual methods. However, not all studies have validated their measurements in this way, and other methods such as inclinometers have been solely relied upon without such additional validation (e.g. Johnston *et al*. 2014b). However, across all methods, validation is one aspect the review found particularly lacking. Although some studies have begun to compare different distributions, there is still a pressing need to further simultaneously compare flight height distributions of these different technologies.

4.1.4 Relative use of other "near-field" methods

A range of different methods were also reviewed, including laser rangefinders, inclinometers, sound of calling birds, infrared imaging, moon-watching, ceilometers and ornithodolites. These methods can give species-specific information and many have merit, but are not considered to be primary methods for use in estimating flight heights of birds in the offshore environment. All can be considered "near-field" with relatively restricted horizontal focus from the observation platform. These methods also suffer reduced sample sizes when compared to radar and can be affected by inclement weather and/or atmospheric conditions. Radar can also have issues distinguishing birds from background scatter at very low altitudes, especially in more adverse weather conditions (Dokter *et al*. 2013a), and biases in size of birds recorded and confusion between individual birds and groups of birds can also occur (Kahlert *et al*. 2012). Therefore, these alternative methods have been used alongside radar to provide this additional information (e.g. Kerlinger & Gauthreaux 1985;

Kahlert *et al*. 2012, Ward *et al*. 2015). However, many of these have a restriction to lower altitude – although note thermal imagery has been used to give information on higher flight heights (Zehnder *et al*. 2001). The potential for observer error is also present, and further restrictions (with the exception of thermal imagery) to daytime observations are also a potential problem. These alternative methods may therefore be useful as an additional validation or supplementary tool. For example, if the goal of the study is for an existing wind farm with a suitable observation platform, then most of these methods have some supplementary value in combination with other approaches – the current ORJIP study is a good example of this. If the relative vertical use of an offshore wind farm (e.g. including all potential altitudes for a species) is not required such approaches may be feasible. Furthermore, many species of seabird have lower flight heights at particular times of the year, such as during breeding in comparison to migration (e.g. Schmaljohann *et al*. 2008a,b; Krijgsveld *et al*. 2011), meaning that the potential for higher flight heights and missing such information is less likely. The use of acoustic monitoring is at present considered less certain in the marine environment and where turbine noise may provide too much background interference.

4.2 Comparison of estimates produced from different survey methods [top]

The methods summarised here have a very wide applicability across many different industries and sectors. However, a key focus of this report was on the potential for different methods to provide flight height distributions to inform collision risk of different species in relation to offshore wind farms. Therefore, for a suite of key marine species (e.g. see Johnston *et al*. 2014a), we assessed whether the different methods produced similar flight height distributions, given the advantages and disadvantages each has, and their applicability as a primary method. A simple traffic-light system was used to highlight potential risk of each species in relation to vertical offshore wind farm rotor sweep zone derived from different methods for different species (see methods for further details).

Although the thresholds used to delineate different risk categories were subjective, some patterns across different species and methods emerged. Northern gannet in particular was summarised as medium risk across all methods. Flight heights of diver species also matched those conclusions reached using radar methods, as did alcid species. Results from telemetry and boat-based methods were also in agreement for Great Skua. Another species of key concern for collision risk is Black-legged Kittiwake, and reassuringly, three of the four methods all agreed this species was at medium risk (Table 4.2).

For some species there were differences recorded across the methods for the three-level categorisation applied. Lesser Black-backed Gulls have been particularly well studied across key primary methods and laser rangefinders. Some methods for this species agreed well, such as some telemetry studies, boat-based methods and radar, but some other studies have obtained estimates that would place this species at more or less risk. Sandwich Tern also spanned all three low/medium/high risk levels for different techniques (Table 4.2). However, some caution is needed here. Radar is classed as a primary ("++") method, yet the restriction to species-groupings and additional uncertainty in translating subjective information from the literature into quantitative categories prevented firm conclusions being drawn. The choice of threshold of 30 m as a lower rotor sweep limit (LSL) also resulted in some species being classified in separate categories for different methods, even though values across studies were very similar – e.g. Lesser Black-backed Gull 28.2% in RSZ (boat-based), compared to 31.2% from a key tagging study (Table 4.2). The treatment of studies with robust confidence limits alongside more subjective information was also of concern. Therefore, while this approach was a useful descriptive exercise, caution is still needed and it is not the intention here to provide final definitive estimates or recommendations from any one specific method or study. Furthermore, given the limited research that has been conducted, flight altitudes

of birds from different methods are likely to be confounded by other factors, which in turn prevented further formal analyses being conducted. These are likely to include a difference in location where studies have been conducted, in turn influenced by local weather, topography and other physical processes, and potentially different foraging conditions and prey availability at the time of study. Where possible such differences were highlighted. Table 4.2 further highlights the continued need for contemporaneous validation of different methods for different species. Results on species flight height distributions from high definition imagery were not available at the time of this review. However further work is underway to investigate these digital imagery datasets and will provide valuable assessments of this technique alongside other methods, such as comparisons between boat-based and digital aerial survey data.

4.3 Conclusions [top]

Flight height information is a crucial aspect determining the collision risk of birds with wind turbines (Cook *et al*. 2012). However, the flight height data reviewed and presented in this report are likely to be of value not just in relation to offshore wind farms, but to other sectors, such as the aviation industry. For example, GPS telemetry has also been used to model the three-dimensional movements in relation to aircraft to identify risk of collisions (see Belant *et al*. 2013).

Within the context of offshore wind farms, the exact research question posed will determine the level of detail required and ultimately will have a key part in determining the method(s) to be used. The requirements of a pre-construction study may be different to those of post-construction, and existing offshore wind farms may offer stable platforms upon which particular technologies can be used. A further crucial aspect for use of flight height information from any method is the reliability (accuracy and precision) of flight height distributions, which most importantly depend on:

(1) the representativeness of the data for the species - e.g. spatial and temporal coverage, and vertical swathe covered – e.g. are flight heights in the vicinity of the turbines required (e.g. 500 m) or do the full flight height distributions across a wider 3D space need to be obtained?;
(2) the error surrounding the measurements obtained;
(3) the validation of the method that has been conducted;

In addition, to actually gathering the data required, consideration is also needed over:

(4) the practicalities and costs of actually obtaining the data for the study – e.g. does one need to physically mark birds or just following them remotely, or need to deploy observers on platforms to record data offshore?

Modelled flight height distributions that take into account sources of error or bias have been produced for boat based transect (e.g. Johnston *et al*. 2014a) and telemetry methods (Ross-Smith *et al*. in prep). Such studies are valuable in providing a level of error surrounding estimates, and have proved very useful in CRMs. In theory, other methods could also produce such confidence limits, which should therefore remain a priority for further work if such methods are to be used as primary or in-combination methods.

A cost-benefit of the needs of any individual study needs to be weighed up, balancing the goals of the study alongside the financial and practical costs. Currently, boat-based and high definition imagery are considered primary methods. However, telemetry and radar are also considered suitable as primary methods, with some other techniques such as laser rangefinders and infra-red imaging, offering supplementary value. Several studies are now incorporating different technologies to investigate flight heights of birds (such as Krijgsveld *et al*. 2011, Kahlert *et al*. 2012, Ward *et al*. 2015) Combinations of approaches are likely to lead to the most powerful assessment of flight height distributions. However, further validation of all methods is required, and combining different

approaches into one flight height distribution may require more complex statistical treatment of the data, which as yet has not been thoroughly explored.

Table 4.2 Summary of flight height distribution data from different methods for UK species. Information is presented where sufficient data was available for key methods to facilitate a comparison of methods across species. Comparisons are tempered by how each method was rated as a primary technique, based on information from Table 4.1 (+++ very good to - - - very poor). For radar, information was primarily extracted for species groups, in turn extrapolated across individual constituent species. Flight height data was summarised in two ways: (1) As a percentage of the flight height distribution (for example, % time/birds/GPS fixes), at or below minimum turbine height where risk of collision is reduced – based on the studies reviewed, we assumed a vertical turbine rotor sweep zone (RSZ) of 30-150 m (very few data were recorded above 150 m); and (2) Percentage of the distribution at collision risk height using study-specific RSZs. Highlighted cells indicate a subjective gradation of risk (green = low, yellow = medium, red = high) based on these two data summaries (see key). Where studies only quoted categorisation such as "most" or "nearly always", these were subjectively assigned to quantitative categories. Data for multiple studies per species and other information such as time of year, or summaries from the distribution (altitude confidence intervals [CI's], means, ranges or boxplot information) are also retained. Study references are denoted by subscripts (see footnote).

Species	Visual methods (+)		Tags GPS and altimeter (++)	Radar[b] (++)	Laser rangefinder[h] (+)
	Boat[a]	Visual Panorama[b]			
Common Eider	34.6% [3.5-55.8 CI] in RSZ			Marine duck species: <100 m, most <10m	
Common Scoter	1.9% [0.1-10.9 CI] in RSZ	*ca* 30% at RSZ outside WF			
Red-throated diver	6.2% [1.5-32.3 CI] in RSZ			Diver species: Variable, generally low <30 m ASL.	
Black-throated diver	8.1% [6.8-33.1 CI] in RSZ				
Grebe spp				Variable, generally low <50 m ASL.	
Northern Fulmar	1.0% [0.0-9.2 CI] in RSZ				
Manx Shearwater	0% [0.0-0.0 CI] in RSZ				
Northern Gannet	12.6% [6.2-20.0 CI] in RSZ	41% at RSZ outside WF, 21% inside	Plunge-dives, most at 11–60 m (mean±SE = 37.1±2.8 m; range 3-105 m)[c]	Most <10 m, some foraging up to 50 m searching for food. Gannets plunge from 10-30 m.	Boxplot whisker range: 1.7-40.5 m, median 18.8 m, whisker RSZ overlap 26.3%, IQR overlap 0%
Great Cormorant	1.7% [0.8-27.1 CI] in RSZ	24% at RSZ outside WF, 33% inside		Cormorant species: Low-intermediate altitude most <5m not higher than 75m	
European Shag	12.6% [2.0-64.3 CI] in RSZ				

Species	Visual methods (+)		Tags GPS and altimeter (++)	Radar[b] (++)	Laser rangefinder[h] (+)
	Boat[a]	Visual Panorama[b]			
Arctic Skua	2.6% [1.7-10.0 CI] in RSZ				
Great Skua	5.9% [3.5-17.9 CI] in RSZ		<5 m; 4.4% daytime collision risk height[d]		
Black-legged Kittiwake	15.0% [11.7-17.3 CI] in RSZ	ca 50% at RSZ outside WF, ca 40% inside		Gull species: see below	Boxplot whisker range: 1-34.8 m, max ca. 80 m; median 16.6 m, whisker RSZ overlap 13.9%, IQR overlap 0%
Black-headed Gull	13.9% [5.7-25.5 CI] in RSZ	41% at RSZ outside WF, 21% inside		Migrating flocks mostly in the RSZ and above; gull species see below	
Little Gull	0.0% [0.0-100.0 CI] in RSZ			Gull species: Locally < 50 m above sea level, mean (foraging, travelling during breeding) up to 250 m.	Boxplot whisker range: 8.6-24.5 m, max ca. 48 m; median 18.8 m, whisker RSZ overlap 0%, IQR overlap 0%
Common Gull	21.9% [19.0-30.1 CI] in RSZ	46% at RSZ outside WF, 55% inside			
Lesser Black-backed Gull	28.2% [20.3-43.1 CI] in RSZ	>50% at RSZ outside/inside WF	89 % fixes below 20 m[e] Typically <20 m, most <5 m; 31.2% daytime at collision risk height [d] Estimation from figure 6: Spring and Autumn migration travel ca. >70% values <250 m AGL (coarse banding)[f] ca.90% flying fixes < 25m (Fig 5.12); 3.7% >75 m; Lesser Black-backed Gulls were more common than Herring Gulls >75 m (5.2 and 2.4%)[g]		Boxplot whisker range: 0-69.6 m; median 26.3 m, whisker RSZ overlap 56.0%, IQR overlap 37.4%; max, ca 131 m
Herring Gull	31.9% [25.2-41.2 CI] in RSZ	>50% at RSZ outside/inside WF	ca.90% flying fixes < 25m (Fig 5.12); 3.7% >75 m; Lesser Black-backed Gulls were more common than Herring Gulls >75 m (5.2 and 2.4%)[g]		Boxplot whisker range: 0-74.2 m; median 32.4 m, whisker RSZ overlap 58.0%, IQR overlap 42.2%; max, ca 180 m

Species	Visual methods (+)		Tags GPS and altimeter (++)	Radar[b] (++)	Laser rangefinder[h] (+)
	Boat[a]	Visual Panorama[b]			
Great Black-backed Gull	32.5% [28.5-42.8 CI] in RSZ	>50% at RSZ outside/inside WF			Boxplot whisker range: 6.1-66.1 m; median 34.4 m, whisker RSZ overlap 59.5%, IQR overlap 66.9%
Sandwich tern	7.0% [6.1-14.9 CI] in RSZ	ca 50% at RSZ outside WF, ca 30% inside		Tern species: Generally up to 20 m average, but through RSZ on migration	
Common Tern	7.4% [4.4-9.9 CI] in RSZ				
Arctic Tern	4.0% [0.6-14.3 CI] in RSZ				
Common guillemot	0.4% [0.0-10.2 CI] in RSZ			Alcid species: Hardly ever higher than 50m and nearly always very low <5m	
Razorbill	2.7% [0.0-13.7 CI] in RSZ				
Little Auk	3.6% [0.0-5.0 CI] in RSZ				
Atlantic Puffin	0.0% [0.0-6.8 CI] in RSZ				

a Johnston *et al*. 2014a; b Krijgsveld *et al*. 2011; c Garthe *et al*. 2014; d Ross-Smith *et al*. (unpubl data); e Corman & Garthe (2014); f Klaassen *et al*. (2011); g Ens *et al*. (2008); h Mendel *et al*. (2014, extracted from Fig 11.12).

Key
Green = <10% time/birds/fixes > 30 m; <10% at collision risk height (in RSZ)
Yellow = 10-30% time/birds/fixes > 30 m or <30% at collision risk height (in RSZ)
Red = >30% time/birds/fixes >30m; or more than 30% at collision risk height (in RSZ)
Grey = Hard to categorise or lacking full distribution

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