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Monitoring penguin colonies in the Antarctic using remote sensing data

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Monitoring penguin colonies in the Antarctic using remote sensing data

by

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Abstract

In the context of the already observed population changes at specific time intervals and the shift in penguin breeding sites because of global warming and the fluctuations in availability of food, full-scale monitoring of Antarctic penguins seems reasonable. This report should contribute to choosing among the possible methods. Given the large number of colonies and their general inaccessibility, on-site counts can only sample bits of the breeding population. It can also be assumed that there is a considerable number of currently unidentified colonies. An extensive and comprehensive monitoring thus seems only possible based on remote sensing data.

To be able to detect preferably all the penguin colonies in Antarctica, satellite data will be required, which should be relatively cheap to acquire given the enormous quantities of data needed, and coverage of the entire region is available. In this study, the Landsat 8 data, available since 2013, appeared to be most suitable for this purpose. In contrast to its predecessor, Landsat 7, which has had an error in its scan-line corrector since May 2003, it has the advantage that the complete image can be evaluated, which allows a higher temporal coverage of the entire Antarctic coastline. If the intention is to measure precisely the size of the colonies and detect small-scale changes, satellite data are required, as they have a high spatial and temporal resolution. In such cases, high-resolution, multi-spectral satellite data with ground resolutions of less than 0.6 m have proven to be the most suitable option. First of all, the high-resolution VNIR data from Worldview 3 satellites were also successfully tested.

For the analysis, 12 high-resolution and over 50 medium-resolution, multi-spectral satellite images of the test region were obtained to investigate intra- and interseasonal variations. We were able to acquire four high-resolution, practically cloud-free images of Ardley Island in the 2014/15 season and three in the 2015/16 season despite frequent cloud cover.

Using these data, a series of methods was tested for their capacity to detect details on high- and medium-resolution satellite images. The most difficult task proved to be classifying guano on the high-resolution images. Dark-appearing guano could hardly be detected with the methods tested. In contrast, the bright orange-reddish guano was easy to spot. This demonstrates in general that the classification conducted on the continentally located Cape Bird colony was more precise than that on Ardley Island, which could be ascribed to the relatively large areas of dark guano and the great variability in geomorphology and vegetation on Ardley Island. The tested methods revealed that the maximum likelihood and ACE classifications produced the best results for the detection of guano on high-resolution images. By comparing satellite images to the ground surveys, it became evident that it is not possible to identify all nest groups on Ardley Island from satellite images, not even manually. Good results were obtained with the ACE and SAM classifications using medium-resolution Landsat 8 images of continental and maritime Antarctica. Both methods seem suitable for an automated classification of the whole of Antarctica. Schwaller et al. (2013b) and Lynch & Schwaller (2014) have already impressively demonstrated that an automated detection of Adélie penguin colonies on continental and maritime Antarctica is possible with Landsat 7 images.

To be able to evaluate the validity and the precision of information obtained from the satellite images, precise control data from the ground are required. Four different methods to obtain such reference data were investigated in this project and compared to one another. Panorama photography is the fastest method, but provides relatively imprecise results, just like GPS-based partial surveying. GPS-based full surveying produced the most accurate count of breeding pairs of all of the methods tried. It demands the greatest time investment, however, and has the disadvantage that it disturbs the breeding penguins the most. An intermediate option is

provided by surveying with very high-resolution UAV orthomosaics, which can survey large areas in a short period of time. RGB orthomosaics were found to be most suitable for identifying breeding pairs, while NIR orthomosaics were the best for detecting guano and vegetation. Thermal infrared orthomosaics have a great potential for identifying penguins on or next to a nest. However, the method is not practical given the low resolution of thermal sensors. We started with a detailed examination of the potential of UAV-supported surveying to disturb the birds. Results showed that flyovers conducted more than 50 m above the ground (corresponding to the minimum flight altitude for UAV survey flights) triggered mild reactions compared to the behaviour of penguins in response to lower flying heights.

Furthermore, we investigated whether the guano coloration of a colony varied over the course of a season or whether there were differences between species which could be recognised with remote sensing methods. The results of tests with Munsell colour charts, photography on site and UAV and satellite images from two seasons revealed that the test areas with Adélie penguins could be distinguished from the gentoo penguin areas at the beginning of one season. The distinction consisted of the relative red and green components of guano being close together at the start of the breeding season, so the guano appeared greenish. In the rest of the season, the red component predominated for all species. Given this colour difference, it was possible to distinguish the Adélie penguin nest groups from the gentoo penguin ones on high-resolution satellite images.

Along with guano coloration, the habitus as well as the breeding biology and phenology of penguins was explored as a possible distinguishing characteristic between *Pygoscelis* species using remote sensing data. It is possible to distinguish the chicks of the three species on UAV images with a ground resolution of at least 10 mm under optimal recording conditions. With adults, however, the only reliable characteristic detectable was the hourglass-shaped white patch on the top of gentoo penguins' heads, and even that only when the head is held upright. Differences in the breeding biology allowed chinstrap penguin nest groups (adults still breeding) to be distinguished clearly from gentoo penguin nest groups (chicks already hatched) using an UAV orthomosaic of Narebski Point.

The intraseasonal variation in colony expansion and occupation was also extensively investigated with GPS-based partial surveying of the nest groups and the breeding phenology on Ardley Island. Results showed that the size of nest group areas remained extremely constant over the period examined (beginning of December to beginning of January), in contrast to the number of nests and thus the density of the nest groups, which decreased greatly. It was also observed that nest groups with 1-10 nests declined most clearly in the period investigated, which could possibly be ascribed to their location on the colony periphery and thus the entailing greater predation pressure. The investigation of Cape Bird with Landsat 8 images revealed that no intraseasonal variations in colony expansion could be determined there. The likelihood that the colony is covered with snow, and thus allowing only partial or no detection, increases at the beginning and end of the season. However, high-resolution satellite images revealed clear confirmation of intraseasonal variation of the guano-covered areas on Ardley Island. The guano-covered areas of the colony increase radically at the end of the season until they decrease again under the influence of diminishing guano deposits and the constant presence of erosion. Further analysis showed that a correlation (R^2= 0.84) exists between the time at which the satellite image was taken and the mean nest density of the guano-covered areas.

The detectability of interseasonal variations in colony expansion and occupation were investigated with high- and medium-resolution satellite images of colonies on Ardley Island and Cape Bird. For Ardley Island, no correlation was found (R^2 = 0.05) between the number of nests and the nest group area determined from ground surveys. A similar result was noted for the Adélie penguin colony Cape Bird North according to high- and medium-resolution satellite images. Furthermore, Landsat images could not detect any changes in the number of breeding pairs from the guano-covered area data, not even when the number of breeding pairs more than tripled. This was the outcome of analyses of the Cape Bird North colony in the period between 1985 and 2016. The cause is probably the change in density within the nest groups.

Kurzbeschreibung

Vor dem Hintergrund der bereits punktuell beobachteten Bestandsveränderungen und Verschiebungen von Pinguinbrutplätzen im Zusammenhang mit dem globalen Klimawandel und der unterschiedlichen Verfügbarkeit von Nahrung erscheint ein möglichst flächendeckendes Monitoring der antarktischen Pinguine sinnvoll. Der vorliegende Bericht soll hierzu einen methodischen Beitrag leisten. Aufgrund der sehr großen Zahl von Kolonien und der in der Regel schwierigen Zugänglichkeit können Vor-Ort-Zählungen in Bezug auf die Größe der Brutpopulation stets nur Stichprobencharakter besitzen. Außerdem ist davon auszugehen, dass es eine nicht unbeträchtliche Anzahl bisher unbekannter Kolonien gibt. Ein weitestgehend umfassendes Monitoring erscheint daher nur auf der Basis von Fernerkundungsdaten möglich.

Um möglichst alle Pinguinkolonien der Antarktis detektieren zu können, werden Satellitendaten benötigt, die aufgrund der enormen Datenmengen sehr günstig zu akquirieren sind und zum anderen auch flächendeckend vorliegen. In dieser Untersuchung stellten sich die erst seit 2013 verfügbaren Landsat 8-Daten als die geeignetsten für diese Aufgabe heraus. Diese haben im Gegensatz zu dem Vorgänger Landsat 7, der seit Mai 2003 einen Fehler am sogenannten Scan-Line-Corrector aufweist, den großen Vorteil, dass die komplette Aufnahme ausgewertet werden kann, was eine höhere zeitliche Abdeckung der antarktischen Küstengebiete erlaubt. Wenn hingegen die Größe der Kolonien genau bestimmt und kleinräumige Veränderungen detektiert werden sollen, werden Satellitendaten benötigt, die eine sehr hohe räumliche und zeitliche Auflösung haben. In einem solchen Fall haben sich hochaufgelöste, multispektrale Satellitendaten mit Bodenauflösungen von unter 60 cm als am geeignetsten erwiesen. Erstmals wurden auch die hochaufgelösten VNIR-Daten des Worldview 3-Satelliten erfolgreich getestet.

Zur Durchführung der Analysen wurden 12 hochaufgelöste und über 50 mittelaufgelöste multispektrale Satellitenaufnahmen der Testgebiete beschafft. Insbesondere gelang es trotz der häufigen Bewölkung in der Saison 2014/15 vier und in der Saison 2015/16 drei hochaufgelöste weitgehend wolkenfreie Aufnahmen von Ardley Island für intrasaisonale Untersuchungen zu akquirieren.

Mit Hilfe dieser Daten wurde eine Reihe von Methoden auf ihre Eignung zur Detektion von hoch- und mittelaufgelösten Satellitenaufnahmen hin überprüft. Als schwierig stellte sich die Klassifikation des Guanos in den hochaufgelösten Aufnahmen heraus. Besonders der dunkel erscheinende Guano konnte kaum mit den getesteten Methoden detektiert werden. Im Gegensatz dazu ließ sich der hellere, orange-rötlichen Guano gut klassifizieren. Prinzipiell zeigte sich, dass die Klassifikationen bei der eher kontinental gelegen Cape Bird-Kolonie genauer waren als bei Adélie Land, was auf die relativ großen Flächen dunklen Guanos und der großen Variabilität der Geomorphologie und Vegetation auf Ardley Island zurückzuführen ist. Bei den untersuchten Methoden zeigte sich, dass die Maximum-Likelihood- und die ACE-Klassifikation die besten Ergebnisse für die Detektion von Guano in hochaufgelösten Aufnahmen lieferten. Beim Vergleich der Satellitenaufnahmen mit den Bodenkartierungen wurde auch festgestellt, dass es auf Ardley Island nicht möglich ist, alle Nestgruppen in

Satellitenaufnahmen zu identifizieren, auch nicht manuell. Gute Ergebnisse wurden mit der ACE- und SAM-Klassifizierung bei den mittelaufgelösten Landsat 8-Aufnahmen der kontinentalen und maritimen Antarktis erreicht. Beiden Methoden scheinen für eine automatisierte Klassifizierung der gesamten Antarktis geeignet. Das eine automatische Detektion von Adéliepinguinkolonien der kontinentalen und auch der maritimen Antarktis mit Landsat 7-Aufnamen möglich ist, wurde bereits von Schwaller et al. (2013b) und Lynch & Schwaller (2014) eindrucksvoll bewiesen.

Um die Aussagekraft bzw. die Genauigkeit der aus den Satellitenbildern gewonnenen Informationen beurteilen zu können, werden möglichst genaue Bodenkontrolldaten benötig. Vier verschiedene Methoden zur Schaffung solcher Referenzdaten wurden in diesem Projekt untersucht und miteinander verglichen. Die Panoramafotografie ist die schnellste Methode, liefert aber nur relativ ungenaue Ergebnisse, ähnlich wie die GPS-basierte Teilkartierung. Mit der GPS-basierten Vollkartierung erfolgt hingegen die genauste Bestimmung der Brutpaarzahlen aller untersuchten Methoden. Diese benötigt aber auch die meiste Zeit und hat den Nachteil, dass die brütenden Pinguine am stärksten gestört werden. Einen Mittelweg bietet die Kartierung mit sehr hochaufgelösten UAV-Orthophotomosaiken, mit der in kurzer Zeit große Gebiete untersucht werden können. Es wurde gezeigt, dass RGB-Orthophotomosaike am geeignetsten sind um die Brutpaare zu identifizieren, während sich NIR-Orthophotomosaike besonders für die Detektion des Guanos und der Vegetation eignen. Thermalinfrarot-Orthophotomosaike haben ein großes Potenzial bei der Identifizierung von Pinguinen, wenn diese sich auf oder neben einem Nest befinden. Die Methode ist aufgrund der geringen Auflösung der Thermalsensoren jedoch noch nicht praxistauglich. Erstmalig fand eine detaillierte Untersuchung des Störungspotenzials der UAV-gestützten Kartierung statt. Das Ergebnis zeigt, dass Überflughöhen von mehr als 50 m über Grund (entspricht der minimalen Flughöhe der UAV-Kartierungsflüge) nur geringe Verhaltensreaktionen der Pinguine im Vergleich zu niedrigeren Flughöhen hervorrufen.

Weiterhin wurde untersucht, ob es Unterschiede bei der Guanofärbung einer Kolonie im Saisonverlauf oder zwischen den einzelnen Arten gibt, die mittels fernerkundlichen Methoden erkannt werden können. Die Ergebnisse der Versuche mit Munsell-Farbtafeln, Fotografien am Boden sowie UAV- und Satellitenaufnahmen aus zwei Saisons zeigen, dass sich die Probeflächen mit den Adéliepinguinen am Anfang der Saison von denen mit den Eselspinguinen unterscheiden. Der Unterschied äußert sich darin, dass zu Beginn der Brutsaison der relative Rot- und Grünanteil des Guanos sehr nahe beieinander liegt, das heißt die Guanofarbe erscheint grünlich. In der restlichen Saison hingegen dominiert bei allen Arten der Rotanteil. Aufgrund dieses Farbunterschiedes war es möglich, in einer hochaufgelösten Satellitenaufnahme die Adéliepinguinnestgruppen von den Eselspinguinnestgruppen zu unterscheiden.

Neben der Guanofarbe wurde auch der Habitus sowie die Brutbiologie und -phänologie der Pinguine als mögliches Unterscheidungsmerkmal zwischen den *Pygoscelis*-Arten mit Hilfe der Fernerkundungsdaten untersucht. So ist es in UAV-Aufnahmen mit Bodenauflösungen von mindestens 1 cm unter optimalen Aufnahmebedingungen möglich, die Küken der drei Arten voneinander zu unterscheiden. Bei den Adulten hingegen konnte als einziges zuverlässiges Bestimmungsmerkmal der sanduhrförmige weiße Fleck auf dem Scheitel von Eselspinguinen ausgemacht werden, aber nur bei aufrecht gehaltenem Kopf. Auch anhand der unterschiedlichen Brutbiologie konnten Zügelpinguinnestgruppen mit noch brütenden Adulten von Eselspinguinnestgruppen mit bereits geschlüpften Küken mit Hilfe eines UAV-Orthophotomosaiks von Narebski Point zweifelsfrei voneinander unterschieden werden.

Auch die intrasaisonal Variation in der Kolonieausdehnung und –besetzung wurde ausführlich anhand von GPS-basierten Teilkartierungen und der Brutphänologie auf Ardley Island untersucht. So zeigte sich, dass die Größe der Nestgruppenflächen über den Untersuchungszeitraum (Anfang Dezember bis Anfang Januar) weitestgehend konstant blieb, im Gegenzug die Anzahl der Nester und somit auch die Dichte der Nestgruppen aber stark abnahm. Auch wurde beobachtet, dass Nestgruppen mit 1-10 Nestern am deutlichsten innerhalb des Untersuchungszeitraumes vom Rückgang betroffen waren, was möglichweise an deren Kolonierandlage und dem damit einher gehenden größeren Prädationsdruck liegt. Die Untersuchungen von Cape Bird mit Landsat 8-Aufnahmen ergaben, dass dort keine intrasaisonalen Veränderungen in der Kolonieausdehnung festgestellt werden konnten. Lediglich die Wahrscheinlichkeit, dass die Kolonie mit Schnee bedeckt ist und somit nur teilweise oder nicht detektiert werden kann, steigt am Anfang und am Ende der Saison. Mit hochaufgelösten Satellitenaufnahmen konnte bei Ardley Island hingegen eine deutliche intrasaisonale Variation der Guanoflächen festgestellt werden. So nimmt die Guanofläche der Kolonie zum Saisonende hin stark zu, bis sie unter dem Einfluss von nachlassenden Guanoeintrag bei weiterhin vorhandener Erosion wieder abnimmt. Eine weitere Analyse zeigte, dass eine Korrelation (R^2= 0,84) zwischen dem Aufnahmezeitpunkt der Satellitenaufnahme und der durchschnittlichen Nestdichte der Guanobedeckten Flächen besteht.

Die Detektierbarkeit intersaisonaler Variationen in der Kolonieausdehnung und –besetzung wurde mit hoch- und mittelaufgelösten Satellitenaufnahmen anhand der Kolonien von Ardley Island und Cape Bird untersucht. Für Ardley Island konnte kein Zusammenhang (R^2 = 0,05) zwischen der Anzahl der Nester und der mit Hilfe der Bodenkartierung ermittelten Nestgruppenfläche festgestellt werden. Ähnliches zeigte sich für die Adéliepinguinkolonie Cape Bird Nord anhand hoch- und mittelaufgelösten Satellitenaufnahmen. Weiterhin konnten mit Landsat-Aufnahmen keine Veränderungen der Brutpaarzahlen anhand der Guanofläche detektiert werden, selbst dann nicht, wenn sich die Brutpaarzahlen mehr als verdreifachten. Dies ergaben Analysen an der Kolonie Cape Bird Nord im Zeitraum zwischen 1985 und 2016. Die Ursache dafür liegt wahrscheinlich in der Dichteänderung innerhalb der Nestgruppen.

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List of Abbreviations

ACE	Adaptive-Coherence-Estimator
ADD	SCAR Antarctic Digital Database
ASI	Agenzia Spaziale Italiana
BWS	Both Wing Stretch
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CEMP	CCAMLR Ecosystem Monitoring Program
DOM	Digitales Oberflächen Modell
DT	Decision Tree
ENVI	ENvironment for Visualizing Images
EO-1	Earth Observing-1 NASA-Satellit
ETM+	Landsat Enhanced Thematic Mapper (Sensor)
GIS	Geographic information system
GPS	Global Positioning System
ISO	exposure index rating
KOPRI	Korea Polar Research Institute
ML	Maximum-Likelihood
NASA	National Aeronautics and Space Administration
NDVI	Normalized Differenced Vegetation Index
NIR	Near Infrarot
NN	Neural Network
OLI	Operational Land Imager
P. adeliae	Pygoscelis adeliae
P. antarctica	Pygoscelis antarctica
P. papua	Pygoscelis papua
PANGEA	Data Publisher for Earth & Environmental Science Data
RGB	Red, green, blue
SAM	Spectral-Angle-Mapper
SCAR	Scientific Committee on Antarctic Research
SWIR	Shortwave Infrared
TIRS	Thermal Infrared Sensor
TM	Landsat Thematic Mapper (Sensor)
UAV	Unmanned Aerial Vehicle
USGS	United States Geological Survey

VNIR	Visible and near-infrared

1 Summary

Penguins make up 70 % of bird biomass in the Antarctic (Everson 1977). They are marine predators that gain all of their nutritions from the sea and are, consequently, directly affected by changes in the marine ecosystem. This alone makes penguins particularly important as indicators of alterations in the ecosystem of the Southern Ocean. Surveys of individual colonies are available for various regions of the Antarctic. These surveys show clear evidence of changes in the numbers of penguins and changes in the location of their breeding sites. It is assumed that these changes are linked with global climate change and the associated altered availability of food (Ducklow et al. 2007, McClintock et al. 2008, Trivelpiece et al. 2011).

Only an incomplete picture of the real changes underway can be given by the data from the few colonies for which monitoring programmes have been carried out. It would be very difficult, however, to survey more colonies on the ground because of the enormous length of the Antarctic coasts and the difficulty of reaching them and the effort required to work there. These conditions mean that only the use of satellite remote sensing can provide nearly complete coverage of the entire Antarctic continent and provide quantitative data.

Our investigation concerns satellite detection of the three species of the penguin genus *Pygoscelis*. These three rock-breeding species occur on the Antarctic coast. Long-term observations indicate differing trends in their populations (Birdlife International 2016a, b, c).

The viability of monitoring of this kind has already been demonstrated in a feasibility study (Mustafa et al. 2012). Fretwell et al. (2012) were able to quantify the total population of emperor penguins (*Aptenodytes forsteri*) and Lynch and LaRue (2014) that of Adélie penguins. However, all the methods applied so far have been based on delineating the spreads of guano that penguins deposit in their breeding areas. Direct observations of the birds themselves are not possible. One of the crucial methodological questions is, therefore, how the signal from the surface can be interpreted quantitatively. It is often impossible to obtain satellite images for the most desirable times. This difficulty arises because of the very frequent cloud cover that particularly affects the Antarctic Peninsula region and the sub-Antarctic islands. The question is therefore not just how to interpret images from the most suitable dates of the breeding period but how to interpret images that were taken on non-optimal dates. A further challenge is to differentiate the different species in unknown colonies or in those where they breed sympatrically. To interpret the satellite images it is vital to be able to compare them with data obtained by direct observations in the field. Good quality quantitative data is, however, available only for a few colonies. The large colonies are particularly poorly represented. These considerations demonstrate that new and improved methods for surveying the numbers of breeding pairs in the field are essential to the development of satellite based monitoring of penguin colonies. Monitoring of this kind must be able to provide accurate and consistent results for the whole Antarctic. Methods must be developed, therefore, that are sufficiently efficient to cope with the huge amounts of data produced by covering the coasts of an entire continent. These methods must simultaneously be internally precise and objective. These methodological challenges give rise to a number of questions that have not yet been answered such as, for example:

- Does the extent of guano deposits represent changes of the size of a colony?
- How can penguin colonies in a satellite image be definitely assigned to the different species?
- For which time during the course of the breeding season is it optimal to acquire satellite images?

- What considerations have to be borne in mind in evaluating images that were not taken at this optimal time because of weather conditions?
- How can the enormous amounts of data be evaluated efficiently but nevertheless to a high standard?
- What methodological possibilities exist for increasing the amounts of data available from field surveys that are essential for groundtruthing the remote sensing analyses?

Our study detailed below continues the theme of the feasibility study mentioned above (Mustafa et al. (2012) and is addressed to the above questions with the aim of further developing the existing methods of satellite-based monitoring of Antarctic penguin colonies and of supplementing them with new surveying tools.

Test locations

Four test locations were selected for this project. For all four of these locations ground counts of the current penguin populations were available. These were the test sites Ardley Island, Withem Island and Narebski Point, which are situated in the northern part of the Antarctic Peninsula, and the more southerly, continentally situated test site Cape Bird. There are only chinstrap penguins breeding at Withem Island, gentoo- and chinstrap penguins at Narebski Point, at Ardley Island all three Pygoscelis species are breeding sympatrically and only Adélie penguins at Cape Bird.

Testing suitable satellite platforms

In detecting penguins the properties required of the satellite data depend on the specific aims of the project. Each aim demands data with different properties. In order to detect all the penguin colonies in the Antarctic the satellite data required must have two preeminent qualities. First, because huge amounts of data are needed, the data must be acquirable at a reasonable price. And second, it should cover the entire area. For detection, therefore, the best data are provided by intermediate resolution Landsat images (Mustafa et al. 2012; Fretwell et al. 2012; Schwaller et al. 2013). When, in contrast, the aim is accurately determine colony sizes or to detect small-scale changes, the satellite data must have a very high resolution in space and in time. For this aim, the research of Mustafa et al. (2012), Lynch et al. (2012) and Lynch & LaRue (2014) showed that high resolution (submeter) images such as Quickbird and Worldview 2 give the best results.

Because there were no Landsat 7 images available for the time span of the project, images of the new Landsat 8 satellite were tested for their suitability instead. As far as the spectral properties are concerned, the Landsat 8 data is just as suitable for detecting penguin colonies as was the Landsat 7 data. There is likewise no effect of the better spectral coverage and poorer spatial resolution of the thermal infrared. This is because this band is not used for detection because of its coarse spatial resolution. There could be, however, a decline in the ability to detect small colonies because, currently, it is not possible to pansharp the near and short wave infrared bands.

The spatial and temporal coverage of Landsat 8 is, however, clearly better than that of Landsat 7. Since 2003, Landsat 7 has suffered from a technical defect, the Scan Line Corrector Failure (NASA 2011) and since then has not been scanning correctly or completely. Landsat 8, so far, scans without any technical limitations.

A newer high-resolution satellite than Worldview 2 or Quickbird is Worldview 3, started in August 2014. This is unique in so far as has eight relatively high resolution SWIR bands (spatial resolution 3.7 m) in addition to eight high resolution VNIR bands in the visual spectrum and the near infrared (spatial resolution 1.24 m). These eight SWIR bands cover much the same region as does Landsat 8. The disadvantages are, however, that the SWIR bands are at a lower resolution than the VNIR bands and cost more to acquire.

The spatial resolution is 0.31 m at nadir (vertically below the satellite) which is much higher than previous satellites. This high resolution nevertheless does not improve detection very much however as even such a resolution is insufficient for identifying individual birds or nests reliably. Guano covered areas are already well detected with the previous 0.5 m data.

No suitable data from hyperspectral satellites was available for the test areas during the life time of the project. Start times that were planned for during the project were postponed to later dates. In consequence, it was not possible to include these data in our evaluation. There are several launch dates of hyperspectral satellites planned between now and 2020. However, there is little dependable information available on the exact status of these projects. An exception is the EnMAP (Environmental Mapping and Analysis Program) satellite with the HSI hyperspectral sensor. EnMap is in its final preparation phase. The launch is now planned, after several postponements, for 2018 (DLR 2016). That is why older hyperspectral satellite images (EO-1 Hyperion) from an area outside of our test areas were used to get a first impression of their suitability. As a result it was proved that with hyperspectral data guano can be detected. However, a quantitative estimate was not possible because of lacking ground truth data.

Obtaining suitable satellite images

In this project, in order to detect small scale changes, we used the satellite data provided by DigitalGlobe. Since the fusion of DigitalGlobe with GeoEye in 2013, this data is offered together with images from the GeoEye 1 and Ikonos satellites.

The images ordered were the high resolution satellite images from the DigitalGlobe European partner e-GEOS. These images had been captured by several different satellites including GeoEye, Quickbird, Worldview 2 and Worldview 3. New images were ordered as the four channel bundle with four multispectral bands (blue, green, red and near infrared) and the pan channel. In consequence, it was possible to acquire high resolution satellite images of all the test sites although not always for ideal times because of the frequently occurring cloud cover. It was never possible, for example, in any season, to obtain images of Ardley Island for December.

As well as the high resolution satellite images, we also acquired the free Landsat 8 images to use for the intra- and inter-seasonal analysis of the test locations. With these images, however, it is not possible to choose an acquisition data of the image in advance because Landsat 8 images every point in the Antarctic at fixed intervals. The frequency with which a point is imaged increases with the nearness of the point to the South Pole. Parts of the continental Antarctic such as Cape Bird are covered every 1-3 days. The test locations on the northerly Antarctic Peninsula, in contrast, are covered only every 2-7 days. No images were acquired for Ardley Island or Narebski Point because these colonies are too small to be detected safely with the 30 m resolution Landsat 8 images.

Trial and further development of various methods for analysing satellite images

In addition to the methods (Maximum Likelihood Classification, Ratio Approach and subpixel analysis) already investigated in the pilot study (Mustafa et al. 2012), and the methods (Landsat retrieval methods) developed and successfully applied by Schwaller et al. (2013) or Lynch & Schwaller (2014), in this project new classification procedures were tested as to their suitability for detecting areas covered in guano. To this end the methods were tested on both high-resolution and medium-resolution images. As test areas Cape Bird was chosen for continental Antarctica and Ardley Island for the maritime Antarctic.

Prior to classification, the grey scales (digital numbers) of the images were converted into Top of Atmosphere Reflectance and spectrally sharpened using the Nearest Neighbor Diffusion-Based Pan-Sharpening algorithm (Sun et al. 2014), in order to achieve a resolution of 50 cm for the images in the multispectral channels as well. All classifications were carried out using the ENVI image processing software and the results were compared with each other. The following methods were analysed: Cluster Analyse, Decision Tree, Neural Network, Spectral-Angle-Mapper and the Adaptive-Coherence-Estimator.

The analysis of the various methods for detecting penguin colonies using high-resolution images showed that the new methods tested offer no improvement of the accuracy in comparison to the previously trialled Maximum Likelihood Classification. The results of the Adaptive Coherence Estimator (ACE) classification in particular demonstrate similar accuracy. However, this method has the advantage that, unlike the Maximum Likelihood classification, it only requires one training area or one external spectral signature. Theoretically it would therefore be possible to use it for an automated classification. However, all the methods studied show major problems with the colony on Ardley Island, because of the island's very varied topography and widely scattered nests, which led to frequent false classifications in the results. In contrast, good results were achieved for the Cape Bird colony located in continental Antarctica.

With the ACE classification, better results were obtained with the medium-resolution Landsat 8 images of continental and maritime Antarctic regions. It shows fewer classification errors than the SAM classification that was also studied. It would be theoretically possible to carry out an automated classification of the whole of Antarctica with the two methods. It can be of great benefit to use the decision tree classification as a prelude to a classification, as this can considerably narrow down the areas to be classified (cf. Burton-Johnson et al. 2016) and thus minimise the risk of false classifications, for example when there are clouds.

Ground truthing count methods

Counts on the ground, as exact as possible (Ground Truth Data) are required for judging the predictive ability or the precision of information derived from satellite images. In this project we investigated and compared four different methods (panoramic images, GPS-based complete surveys, GPS-based partial survey, UAV orthomosaics) of obtaining such data. In addition disturbance experiments were performed to reveal the potential of UAV's on disturbing penguins.

To estimate the number of breeding pairs in a colony as quickly as possible panoramic images of the colony should be taken from an elevated position. The nests detectable in the image are then counted. Thereafter, the area covered in the panorama by specific, easily identifiable, groups of nests of typical density is estimated from a satellite image. This should give the average density of nests in the colony. The total area of the colony is then measured in the satellite image and the total number of nests in the colony estimated by the total area multiplied by the average nest density. To evaluate the potential of this method, panoramas were taken during the 2013/14 season from 32 different positions and three were analysed. As a result it was possible to see large areas from a raised view point, but beyond a certain distance within these large areas nests could not be seen separately.

The most accurate measure of the population size of a penguin colony is achieved by direct counts carried out on the ground by a GPS-based complete survey. The spatial arrangement of nests can also be obtained using a GPS supported survey (cf. Peter et al. 2008, Waluda et al. 2014). The disadvantages of ground counts, however, are the great investment in field work needed and the considerable disturbance to the birds. The GPS supported survey of all breeding pairs in the Ardley Island colony (about 7,000 breeding pairs) required two people for 2-3 days of work. The Ardley Island penguin colony was surveyed three times in the framework of this study in the breeding seasons 2013/14, 2014/15, and 2015/16. The number of breeding pairs was assessed each time. The methodology used was that of the previous surveys of this colony (cf. Peter et al. 2008).

The difference between a partial and a complete survey is that in a partial survey only part of the colony is surveyed using GPS and the breeding pairs counted. The density of breeding pairs is then calculated from these data. To estimate the total number of breeding pairs for all nest groups it is then necessary to determine the area covered by all nest groups. This can be done with the help of satellite images that were, where possible, taken at a time near to that when the partial survey was carried out. The number of breeding pairs in the colony can then be determined from the density of breeding pairs determined on the ground in the partial survey and the total area of all nest groups determined from the satellite images. There are two main sources of error with this method. One is the determination of breeding pair density in the partial survey. The other is the determination from satellite images of the area of the nest groups. Both of these sources of error can give rise to major imprecision in the estimations. To assess the size of the errors we tested the process using, as an example, the 2013/14 Ardley Island survey data and a high resolution Worldview 2 image of the same research areas and time. In conclusion, the results indicated that the precision of the breeding pair density estimated from a partial survey of Ardley Island is strongly dependent on the sample size. This sample size is, in its turn, limited by the amount of work required. For example, to be certain of obtaining 5 % precision, 281 nest groups have to be surveyed on the ground. This is ~93 % of all the nest groups on Ardley Island. Whether this result is also valid for other colonies could not be determined. There are, however, large differences in breeding pair density (according to Woehler & Riddle (1998) 0.1-3.1 breeding pairs per square meter).

A relatively new method (Goebel et al. 2015, Mustafa et al. 2014, Ratcliffe et al. 2015, Zmarz et al. 2015) for determining the abundance of penguin colonies is to use UAVs (Unmanned Aerial Vehicles). UAVs perform low level (15 - 300 m) flights over the colony, taking photographs of the ground. These aerial photographs are then stitched together, geo-referenced and calculated to an orthomosaic. The term ‘orthomosaic’ refers to the mosaic of individual aerial photographs stitched together and geo-referenced from which distortions caused by the terrain have been mathematically removed (orthorectified) using a digital surface model (DSM). Using a high resolution orthomosaic image (< 50 mm ground resolution) allows the nests of a colony to be counted. This method was used during the 2013/14 and 2014/15 season in the research areas of Ardley Island, Withem Island and Narebski Point. During 2014/15, however, bad weather prevented access to both Withem Island and Narebski Point. Overflights were made with sensors for several different spectral ranges (UV, RGB, NIR and thermal infrared).

With an octocopter UAV we took high resolution images (<50 mm ground resolution) of the colonies, created orthomosaics from them and, finally, from the mosaics, counted the nests. It is furthermore possible, using these images of the colonies, to produce 3D terrain models provided that the image overlaps are large enough. These models can then be used to orthorectify the satellite images with great precision.

To evaluate the quality of the count method in UAV mosaics the number of breeding pairs estimated by counting the UAV mosaic can be compared with that derived from the GPS based complete surveys carried out on the ground. The deviation between the two methods lies between -1 and +11 %. In order to determine the different specific causes of these deviations we compared the results of the UAV survey in detail with the number of nests in individual groups of nests surveyed on the ground. This comparison showed that the number of mis-classifications was higher than the absolute differences between methods. The greatest error factor was the occasional difficulty in discriminating between breeding and non-breeding individuals. Discrimination between occupied nests and penguins without nests might be improved in the future by using sensors with greater resolution. Nests could also be more easily recognized if overflights were made at a lower altitude. This is scarcely practicable, however, because it would greatly extend the time needed to cover a large area and UAVs cannot stay airborne for long. Furthermore, overflights at or below 50 m altitude bear an increased risk to disturb the penguins (Rümmler et al. 2015).

In the 2014/15 season, ultraviolet (UV) and near infrared (NIR) orthmosaics were created in addition to the RGB images. For this purpose the UV-IR cut filter of the camera Sony A6000 was removed and by the use of special filters it was able to take images in the UV, NIR or RGB ranges of the spectrum. The interpretation of the mosaics showed that the UV images provided no improvement over the RGB images for the detection of breeding pairs. This was predominantly due to the great noise present in these images, which prevented recognition of any additional detail. In the NIR, in contrast, guano covered areas are easy to identify, caused by their strong reflection in the NIR region of the spectrum. However, the vegetation present also reflects strongly in the NIR and this can lead to confusion. This problem can be avoided by localizing the vegetation using the NDVI, so that guano and vegetation can be clearly differentiated. Another possibility involves using combined NIR, red and green channels in a false colour image. This combination clearly separates guano surfaces from their background. This is a great advantage of the NIR images over purely RGB images.

UAV flights carrying thermal sensors provided novel insights into the thermal signatures of the penguins and their guano. The higher temperature of the penguins clearly separates them from the lower temperatures of the background. This improves the certainty of identifying penguins, depending on the altitude of the flight. In addition, there is a similar clear temperature difference at flight altitude of 20 m between the guano covered nests and their surroundings. This temperature difference is caused by the higher albedo of the guano.

However, from the usual altitude of 50 m, it was not possible to separate clearly the penguins on nests from those not on nests when using this method for the systematic analysis of large nest groups. Nevertheless, the thermal image allows the unambiguous recognition of penguins that are not standing or lying on the guano-covered areas. The strong contrast of temperature between penguins and guano-covered surfaces offers the potential of automatic object-based classification with the aim of replacing manual counting of the mosaics. This is less likely to be possible in RGB images because the colour contrast between penguins and their surroundings is smaller than in thermal images. This would hinder the use of automatic classification in the visible light images. In the future it might be possible to improve the detectability of structures such as nests and standing penguins from the practicable height of 50 m by using a thermal sensor of greater resolution.

When comparing all the analysed methods, it becomes clear that no method is superior to the others. Full surveying has the highest data quality, but also the greatest time investment, cost and disturbance potential. Panorama photography and partial surveying have the lowest data quality and the high resolution satellite images needed are expensive, but these methods are quick to use and their disturbance potential is limited. The UAV overflights form an intermediate option, providing good data quality while taking relatively little time, for a low cost and low disturbance potential. Its only disadvantage is the high susceptibility to weather conditions. Thus, which method to use ultimately depends entirely on the requirements of the user or on the local conditions, so all of the methods have their own advantages.

Disturbance experiments

During the 2014/15 season we investigated the effect of our UAV’s on two locally occurring penguin species, the Adélie penguin (Pygoscelis adelidae) and the gentoo penguin (Pygoscelis papua). The experiments took place over nine days and they were all carried out on the Ardley Island penguin colony. To determine the potential of drones to disturb the birds, we recorded videos of the individuals during UAV overflights. Behavioural changes were then identified and analysed using CowLog 2.0 software (Hänninen & Pastell 2009). The methods of behavioural analysis were based on the descriptions of Adélie penguins (Schuster 2010; Spurr 1975), gentoos (Van Zinderen Bakker et al. 1971) and for both species (Jouventin 1982). Our results show that the penguin species examined are noticeable affected by drones. All of the experiments revealed that even drones flying at heights of 50 m can still be noticed by the birds. This influence increases as the flight altitude decreases. For both species and flight directions, with the exception of horizontal flights over gentoo penguins, another stronger increase in disturbance below 20 m or 15 m flight altitude, respectively, was found. These results correlate well with observations made by Müller-Schwarze and Müller-Schwarze (1977), who conducted dummy trials with skuas and Adélie penguins and ascertained that reactions to the predator were evident from a flying altitude of the skua of 14 m. This could confirm the theory that the drone resembles a natural predator from the penguins' perspective and therefore would be considered a threat. When comparing the two penguin species, drone take off apparently has a greater influence on Adélie penguins than gentoo penguins, although the basic level of disquiet among gentoo penguins is greater. The reaction to take off was less for gentoo penguins, although take off took place closer to gentoos (25-35 m) than to Adélie penguins (50 m). During low level over flights the disturbance level among gentoo penguins was higher. When contrasted to the control, however, the relative disturbance appears comparable. As only three brooding groups were analysed here, this comparison cannot be considered validated and further experiments are required to confirm these outcomes.

It was ascertained for both species that vertical flights below 20 m generated greater disturbance than horizontal flights. This is explicable as a predator diving directly towards a penguin poses a greater threat than one that is just flying over a brooding group. Nevertheless, some methodological causes should also be considered: for one thing, a vertically flying drone maintains the same horizontal distance from the separate individuals and just gets closer the whole time, while a horizontally flying drone is already moving away from the first individuals encountered, which can calm down, while it is approaching the birds at the other end of the group. As the analysis looks at the mean disturbance within the group, the birds that are already calming down reduce the disturbance level during the flyover. Second, vigilance regarding a vertical flight is easier to recognise for an observer as the penguin must raise its head (and beak), while no body movement may be required if the nest is favourably oriented to watch a drone during a horizontal flight. Personal observations in the field additionally suggest that the sound of the drone is louder during vertical movements than horizontal flight.

Classifying the colour differences in penguin guano

Using remote sensing methods, it is currently possible to spot and survey seabird colonies, even when the individual animals cannot be identified (e.g. Fretwell et al. 2015; LaRue et al. 2014; Lynch & LaRue 2014). The widespread covering of guano on the ground can often be clearly distinguished from the surroundings due to its difference in colour even at lower resolution satellite images (Fretwell et al. 2015). There have already been successful attempts to define the spatial distribution of breeding sites of the different species among penguins in mixed colonies on satellite images (Lynch et al. 2012). However, these studies are just isolated cases so far. Particularly with completely unknown colonies, it is still very difficult to identify the species present from satellite images. As it is impossible to pick out single individuals reliably with the currently available ground resolution, interspecific differences in the clearly visible guano coloration could provide an important clue for species identification. The aim of this substudy was to ascertain whether there were differences in the guano coloration of a colony of one species over the course of the season or between different species (e.g. due to variations in diet). If that turns out to be the case, those differences could be used to characterise unknown colonies on satellite images based on the colour of the guano of a particular species.

To classify colour differences of the guano, it is necessary to first determine the colour of guano on site or using remote sensing methods. The guano colour is identified on the ground with the help of Munsell colour charts (Munsell 1969) and photography like UAV and satellite images. To be able to compare the colour values of both investigated species at Ardley Island from ground photographs, the mean of the measurements at all test sites was generated. This means that for Adélie penguins, one nest group could be evaluated in the 2014/15 season and three in the 2015/16 season along with three nest groups for gentoo penguins in the 2014/15 season and 13 nest groups in the 2015/16 season.

It was found, that both species examined can only be distinguished at the beginning of the season. It is apparent that the relative red and green components of the Adélie penguin guano are almost the same at the beginning of the season, while the gentoo penguin guano has a clearly higher composition of red in the colour. This is consistent with observations from field workers who noted that at the beginning of the season, Adélie penguin excrement was often green. According to Heine & Speir (1989) this colouration occurs when the penguins have not been hunting for food in the sea for a long time. Sladen (1958) claims the green coloration is due to the penguins' gall pigments, while Myrcha & Tatur (1991) state that it is due to proteins, cholic acid and undigested algae cells (the diet of krill) in the guano. Later in the season this green coloration did not appear, so the red component was stronger. Likewise, a slight increase in the relative red component of both species was evident at the end of the season.

When analysing the relative colour values extracted from the UAV images, it is striking that at the beginning of the season the red and green components are almost equal for Adélie penguins and less pronounced but similar for the gentoo penguins. In the UAV images it is evident that at these sites the guano actually does appear greenish. Later in the season this strong green component fades. Another prominent aspect is the clear increase in the blue component in January, even surpassing the red component at times. In the UAV images this guano looks very dark, almost black. From the satellite images it is striking that the relative red component is much larger than from the ground and UAV measurements. Details confirm that at the start of the season, the Adélie penguin guano has a relatively larger green component than the gentoo penguin guano. This distinction fades later in the season.

When comparing the individual methods to each other, it firstly becomes evident that the ground photos allow the results of the Munsell color charts to be reproduced. A direct comparison with the UAV and satellite images is difficult as they differ both spatially and chronologically. Nevertheless, the general changes during the season are recognisable in both. Of particular interest to this study was the question of whether colour differences exist between different species which could be recognised by photographic and remote sensing methods. This appears to be the case to a limited extent. All of the research methods could distinguish the guano colour at the test sites with Adélie penguins at the start of the season (beginning of November) from the test sites of the gentoo penguins. The difference is that the relative red and green components are equal (guano appears green in colour) or very similar. In the rest of the season in contrast, the red component predominates for all species. This is consistent with observations from the field. The cause of this colour difference could be a change in the food supply available during the season, but this was not examined in this study. Only UAV images could confirm greenish guano from gentoo penguins at the end of November, although not as pronounced as that from the Adélie penguins. It is not known why this could not be observed with the other methods, but no standardised white balancing could be done with the UAV images, which may have affected the outcome.

Possibilities of distinguishing species

The three penguin species we are interested in are easy to distinguish by habitus with the naked eye on site. In particular, their distinctive colouring is helpful in identifying them. The only reliable characteristic from air is the white, hourglass-shaped patch on the top of the head of gentoo penguins. This allows for some of the individuals to be identified. A ground resolution of 20 mm of the mosaic is often not sufficient to recognise the patch.

It is somewhat easier to differentiate the chicks of the three species examined. Small chicks still confined to the nest have few visible distinctive characteristics on aerial images. Identification is then generally derived from the parent bird present. Once they reach the créche stage, clear colour differences become visible. Other potential criteria for distinguishing species include spacing between nests, nest density and style of nest grouping. Earlier studies have already explored these possibilities (Naveen et al. 2012; Oelke 1975; Woehler & Riddle 1998; Quintana & Cirelli 2000; Kirkwood et al. 2007).We can conclude that no reliable classification of the individual species based on nest density or spacing can be created from these published data. While the range for one species across the studies is very large.

An indirect method of identifying species is based on the variations in breeding biology and phenology of the three Pygoscelis species. The seasonal timing when colonies become established on Ardley Island depends strongly on the ice conditions in the Maxwell Bay and the snow conditions on land and can vary widely from year to year (Mönke & Bick 1988; Peter et al. 1988; Zippel 1987). There is a little variation in the incubation periods between the three species. The longest hatching period is seen with the gentoo penguins, as their young first fledge after 62 - 82 days, and in extreme northern parts of their range this can extend to 85-117 days (Shirihai et al. 2002). Especially the large temporal differences in breeding phenology between Adélie and gentoo penguins compared with chinstrap penguins can help distinguishing the species if the sampling date is favourable. The difference in the state of 50 % young hatched between gentoo penguins and chinstrap penguins on Ardley Island is almost 2 weeks. As the young are clearly recognisable on UAV images, this is a potential distinguishing characteristic. This hypothesis was tested with an orthomosaic from a UAV flight above Narebski Point on 03/01/2014. It was possible to distinguish all 15 chinstrap penguin nest groups from the 80 gentoo penguin nest groups solely on the basis of the orthomosaic. The distinction was based on the fact that the adults were still breeding in the chinstrap penguin nest groups, producing a set nest structure, while in contrast the chicks had already left the gentoo penguin nest groups and the nest structure was beginning to break down. Validation was done with the KOPRI mapping data from the same season.

Using a Worldview 3 image of Ardley Island from 11/11/2014, we investigated whether Adélie penguin nest groups could be distinguished from gentoo nests and detected solely on the basis of their guano signature. Using GPS-mapped nest groups of both species, the nests were identified and their average spectral signature recorded. As a result, Adélie penguin guano has higher reflectance in the green spectral range. The two types of guano can also be distinguished visually by the green shade of the Adélie penguin guano compared with the orange gentoo penguin guano. This was also possible when only a small group of Adélie penguins was situated among a large gentoo penguin nest group. This phenomenon was only visible in the image from 11/11/2014, already in the image from 30/11/2014, it was no longer possible to distinguish the guano.

Automation of satellite-supported detection of penguin colonies

Since the study by Mustafa et al. (2013), which confirmed to a great extent the theoretical possibility of an automated analysis of satellite images for penguin monitoring, further research has been done on this question (cf. Lynch & LaRue 2014; Lynch & Schwaller 2014; Schwaller et al. 2013b). Methods have already been developed and successfully applied for using medium-resolution images (Landsat) for the automatic detection of guano-covered areas throughout Antarctica (Schwaller et al. 2013b, Lynch & Schwaller 2014). Furthermore, a method is available to automatically find clouds or ice-free land areas in Antarctica, which is important for preprocessing (Burton-Johnson et al. 2016). No method is known yet to detect guano automatically in a large amount of high-resolution satellite data from very diverse areas.

Study of intraseasonal variations in colony expansion and occupation, and the extent to which these can be detected

Many coastal areas of Antarctica have frequent cloud cover. This is true in particular for the South Shetland Islands. For this reason, it is rarely possible to take optical satellite images of the research area at the desired time. It is also often impossible to use other monitoring methods at the optimum times for logistical reasons or due to weather conditions. Detailed knowledge of intraseasonal variability of diverse measurement and target parameters could increase the informative value and transferability of data recorded at times in which conditions are sub-optimal. To this end, the Ardley Island penguin colony, or a part of it, was studied on the ground and from the air using various methods in the 2014/15 season. Depending on the individual imaging method, the number of breeding pairs, the nest group area or phenomenological criteria are then investigated and, finally, the individual results are compared with one another.

Breeding phenology of penguins on Ardley Island

During the seasons 2014/15 and 2015/16, the breeding behaviour of gentoo and Adélie penguins on Ardley Island was investigated thoroughly. The aim was to gain an overview of breeding progress and success over time. In addition, the times of significant breeding events were recorded (e.g. Peak of Egg-laying and Peak of Hatching).

The nests were investigated according to the same criteria in both seasons. For this purpose, the nests were divided into a) nests that contained at least one egg, b) nests with at least one chick, and c) abandoned nests. The comparison of the chronology of breeding in gentoo and Adélie penguins in the two seasons applies only to a limited period of time and is therefore unrepresentative. It suggests, however, that the time course of breeding between years is very similar. This is particularly true for Adélie penguins but also for gentoo penguins in overall terms. How much the time course might vary between seasons over longer periods can only be determined after many years of continued observation. The period between middle of October and the end of January should be set for these observations. Due to our data it seems obvious that the period between 25th November and 10th December matches the optimal time for counting the number of gentoo penguin breeding pairs in the South Shetlands area. For Adélie penguins the optimal period indicated is between 10th and 20th of November.

In order to test variation between seasons using Landsat 8, we attempted to obtain at least one Landsat 8 image from Cape Bird for each month. The guano areas in the images were then determined manually and, for comparison, classified automatically. It was revealed that strong decreases in area at the beginning and the end of the season were caused by a temporary cover of snow, overlaying most of the colony and thus hindering detection of guano areas.

When all three seasons are considered together, it is clear that the guano areas detectable on Cape Bird do not change during the season (apart from the changes due to snowfall mentioned above). The smaller variations between seasons in the guano areas are within the measurement error because, given the low resolution of Landsat 8 images and the small size of the colonies, even a difference of a few pixels produces large changes in the apparent areas.

For the 2014/15 season, it was possible to acquire four cloud-free high resolution images of Ardley Island from the DigitalGlobe satellite constellation. These images covered the period from the beginning of November to the beginning of February. In the following season, because of cloud cover, the earliest suitable images possible to acquire were from the beginning of January. The guano areas in these images were assessed using manual image interpretation in order to investigate the intraseasonal variation in guano area.

There is generally a clear increase in the guano area during the course of the season. Examining the results in more detail, it can be seen that the guano areas are the same size in October/November at the beginning of the season. The increase starts only thereafter. Because there is no increase in the number of nests after the beginning of December the cause of the increase in area covered by guano might be the result of guano distribution. This is suggested by interpretation of the satellite images. There are two mechanisms that might be responsible for the spread of guano over the surface. One is fluvial processes (erosion) and the other is distribution by the penguins themselves. Both these processes are particularly evident at the end of the season when the snow has melted and the chicks have already formed crèches. They therefore correlate well with the increase in area observed that takes place at the same time. The images of the research area for October and November 2014 show considerable snow cover whereas hardly any large areas of snow can be seen between nest groups in images from January and February. It can also be observed that new guano-covered areas form near the beach at the end of the season. These are just the areas where crèches can be frequently found. As can be seen in the images from mid of February, reductions in the guano areas can also occur very late in the season. Such reductions are possibly caused by the increase in abandoned nests and the consequent reduction in guano addition from adults, in combination with erosion going on at the same time.

Matching breeding phenology with guano area from satellite images

It is sometimes possible, when satellite images are acquired, that the only images that can be obtained of particular areas are from times late in the season. By this time the penguin chicks have already gathered together in crèches and the former clear boundaries between nests are obliterated. At this point the area of the colony covered with guano is much larger than at the beginning of the season even though the number of nests steadily declines in the course of the breeding season. If the number of nests was then to be calculated solely on the basis of the area covered with guano, the result for the end of the season would be an unrealistically high number. In order to evaluate data even from these late and inconvenient time points, we investigated how much the guano areas change during the season and whether there is any connection between these changes and the breeding phenology of the colonies concerned. We therefore calculated the mean density of nests in the guano covered areas of the Ardley Island colony for the four seasons 2005/06 and 2013/14 - 2015/16. The number of nests was derived from the field counts of active nests made during the full surveys of the same four seasons. The area covered with guano was determined from the high resolution satellite images. The average nest densities were correlated (R^2 = 0.84) with the date on which the satellite images were taken. The nest density of guano covered areas of the Ardley Island colony thus declines continually during the course of the seasons examined. In this analysis, however, it must be taken into account that only one image was available for two of the seasons and that it was not possible to analyse any image from mid of December.

Investigating interseasonal variations in colony expansion and occupation and their detectability

The detectability of interseasonal variations in colony expansion and occupation was investigated with high- and medium-resolution satellite images of colonies on Ardley Island and Cape Bird. For Narebski Point, only one snow- and cloud-free high-resolution satellite image was available for the study, and thus the analysis could not include this region.

Due to the large seasonal variability on Ardley Island, no interseasonal comparison can be made with the guano-covered areas detected on high-resolution satellite images. Therefore, we looked for a correlation between the number of nests and the area of the nest groups obtained from ground surveys. The surveys from eight seasons on Ardley Island (2003/04 - 2005/06 and 2012/13 - 2015/16) were evaluated. The result of the analysis shows no such correlation for Ardley Island (R^2 = 0.05). A possible reason for this result, and one previously described by Mustafa et al. (2005), could be that a change in the number of breeding pairs alters the density among the nest groups rather than the area of the nest groups. This would mean that on Ardley Island, no changes in the number of breeding pairs can be detected based on the nest group area. If there is a radical increase or decrease in the number of breeding pairs, however, a significant change in the nest group area could be expected.

In the research area located in East Antarctica, Cape Bird, we also investigated whether interseasonal fluctuations in breeding pairs could be detected with high-resolution satellite images. The database for the study was provided by six high-resolution satellite images from six different seasons in the period 2007/08 to 2015/16, in which the guano-covered areas of the Cape Bird North colony could be delimited manually. They were compared with the census data from the New Zealand Landcare Research (Landcare Research 2016) culled from aerial images from flyovers (Taylor et al. 1990). This comparison showed that the guano-covered area of the colony did not change significantly during the period of investigation, whereas in the same period the number of breeding pairs rose by 40 %. Thus, changes in the number of breeding pairs of Cape Bird North cannot be detected by the guano-covered surface area.

We also investigated whether interseasonal fluctuations in breeding pairs could be detected on the medium-resolution Landsat images. The number of breeding pairs (Landcare Research 2016) was again compared with the manually determined guano-covered areas of Cape Bird North on Landsat images. For this analysis, 17 cloud-free Landsat images at 30 m ground resolution were evaluated, which had been recorded between 1985 and 2015 with a variety of sensors (TM, ETM+ and OLI).

The results show no correlation between the guano-covered areas detected and the number of breeding pairs. The colony's area barely changed at three different time points, although the number of breeding pairs more than tripled between 1984/85 and 2014/15. Thus Landsat images did not allow detection of any changes in the number of breeding pairs at Cape Bird North according to the guano-covered area, even when the population more than tripled. The cause is assumed to be a change in density within the borders of the colony or nest groups.

Outlook

In the sections above we described the potential and the limitations of using remote sensing data to monitor Antarctic penguin colonies. We investigated how appropriate are current high resolution and intermediate resolution satellites in terms of their spatial, temporal, structural and scalar aspects. This investigation indicated that high resolution images were highly capable of detecting even small colonies. However, intermediate resolution Landsat 8 images had limited ability to detect small or structurally complex colonies. Nevertheless, these images have the advantage that they can be classified automatically. This has not yet been possible for high resolution images from a variety of different areas because of the limited spectral coverage of these images. This limitation might be alleviated by the SWIR bands of the Worldview 3 satellite. Also promising are the spectral configuration of the new intermediate resolution sensors such as Sentinel 2 which are like those of Landsat. In this respect, hyperspectral sensors, the intensive development of which has already begun, should also be considered.

It has not yet been possible to discriminate between different species of penguins in satellite pictures. Initial analyses of guano colours suggest that these colours could be classification characteristics. However, the development of a consistent method requires further investigation using in-situ data, particularly in order to account for the great inter- and intra-seasonal differences. The results of species differentiation from satellite images should also be verified using images from other seasons and other colonies.

The study also determined that differences between seasons in the numbers of breeding pairs were not very precisely reflected by changes in the area of ground covered by guano. In this respect, too, therefore, additional analyses must be carried out to determine the spatio-temporal associations of these changes. Equally, reliable methods must be developed to convert guano area signals into numbers of breeding pairs of penguins.

Strong changes of the guano extent during the season were found in the test locations. Owed to the frequent cloud coverage of the test locations it is hardly possible to acquire satellite images at a standardized date. Hence, it is necessary to understand the patterns of these changes to allow a temporally differentiated interpretation of the spatial signal. Possible approaches are intensive analyses of the breeding phenologies of the different species and an improved understanding of its regional and wheather-dependend variability. These information could be combined with more precise data on the variability of the spatial signal (e.g. by repeated ground mapping or UAV surveys).

Counts on the ground, as exact as possible (Ground Truth Data) are required for judging the predictive ability or the precision of information derived from satellite images. There are a number of approaches for the further development of such count methods. As such, a reliable method to derive breeding pair numbers from UAV orthomosaics of penguin colonies has to be found, answering the question of non-breeding individuals staying in the breeding area. Possible solutions are the use of high resolution thermal imagery as well as new count methods on the basis of total individuals instead of penguin nests.

The use of UAV technology in the Antarctic strongly increases. During this study first systematic analyses were performed to evaluate the influence of UAV overflights on breeding penguins. These analyses should be extended to include different flight situations, other UAV models, more penguin species and other breeding birds. To increase the reliability of such behavioral analyses the analysis could be extended qualitatively by physiological methods (e.g. heart rate measurements).

A major challenge for a supraregional monitoring strategy is the linking of data sets with different temporal and spatial scales, different qualities and from very different sources. Data base approaches have to be found to ensure this linkage.

Previous studies on the detection of colonies of rock-breeding penguins mainly focus on Adélie penguins. Large-scale studies on the other species of Pygoscelis penguins are rare. Particularly for Chinstrap penguins, major uncertainties exist on the dimension of the total population. For many colonies quantitative data is missing.

This study confirmed the feasibility of an Antarctic–wide monitoring of penguin colonies. However, there still is a need for research to ensure the necessary quality to achieve reliable results and an efficiency that allows a regularly monitoring across the whole area.

2 Zusammenfassung

Pinguine machen 70 % der durch Vögel gestellten Biomasse in der Antarktis aus (Everson 1977). Als mariner Prädator ernähren sie sich ausschließlich im Meer und sind damit von Veränderungen des marinen Ökosystems direkt betroffen. Allein hierdurch kommt den Pinguinen eine besondere Bedeutung als Indikator für Veränderungen des Ökosystems Südozean zu. Aus verschiedenen Regionen der Antarktis vorliegende, punktuelle Beobachtungen einzelner Kolonien zeigen deutliche Bestandsveränderungen bei verschiedenen Pinguinarten und räumliche Verschiebungen von deren Brutplätzen. Es wird angenommen, dass dies im Zusammenhang mit dem globalen Klimawandel und der damit einher gehenden veränderten Verfügbarkeit von Nahrung steht (Ducklow et al. 2007, McClintock et al. 2008, Trivelpiece et al. 2011).

Aufgrund der enormen Ausdehnung der antarktischen Küste und ihrer schwierigen und aufwendigen Zugänglichkeit ergeben die wenigen Kolonien, an denen Monitoringprogramme durchgeführt werden, nur ein unvollständiges Bild von den tatsächlichen Veränderungen. Unter solchen Verhältnissen bietet einzig die Anwendung von Satellitenfernerkundung die Möglichkeit, weitestgehend flächendeckend für die gesamte Antarktis quantifizierbare Informationen zu erhalten.

Die vorliegende Untersuchung beschäftigt sich mit der satellitenbasierten Detektion der drei an den antarktischen Küsten vorkommenden felsbrütenden Pinguinarten der Gattung *Pygoscelis*. Langzeitbeobachtungen zeigen teilweise unterschiedliche Trends in der Entwicklung der Populationen dieser Arten (Birdlife International 2016a, b, c).

In einer Machbarkeitsstudie (Mustafa et al. 2012) wurde bereits die methodische Durchführbarkeit eines solchen Monitorings aufgezeigt. Fretwell et al. (2012) konnten inzwischen schon die Gesamtpopulation der Kaiserpinguine (*Aptenodytes forsteri*) quantitativ abschätzen und Lynch and LaRue (2014) die der Adéliepinguine. Alle bisher angewendeten Methoden basieren jedoch nicht auf der direkten Beobachtung der Tiere, sondern auf der Abbildung der Guanoablagerungen, die sie in Ihrem Brutareal hinterlassen. Somit ist die quantitative Interpretation des Flächensignals eine der wichtigsten methodischen Fragestellungen. Aufgrund der insbesondere im Bereich der Antarktischen Halbinsel und der subantarktischen Inseln sehr häufigen Bewölkung ist es oft nicht möglich, Satellitenaufnahmen zum gewünschten Zeitpunkt zu akquirieren. Damit stellt sich nicht nur die Frage nach dem für die Interpretation geeignetsten Aufnahmezeitpunkt während des Brutverlaufs, sondern auch die nach der Interpretation der Aufnahmen, die nicht zum optimalen Zeitpunkt gemacht wurden. Eine weitere Herausforderung besteht in der Unterscheidung der verschiedenen Arten in unbekannten Kolonien oder solchen, in denen sie sympatrisch brüten. Für die Interpretation der Satellitenaufnahmen ist der Vergleich mit direkt im Gelände erhobenen Daten unerlässlich. Qualitativ hochwertige Daten liegen jedoch nur für wenige Kolonien vor - insbesondere große Kolonien sind hier deutlich unterrepräsentiert. Daher ist auch die Weiter- und Neuentwicklung von Geländemethoden zur Brutpaarerfassung wichtig für die Entwicklung eines satellitenbasierten Monitorings von Pinguinkolonien. Ein solches Monitoring soll für die gesamte Antarktis korrekte und konsistente Ergebnisse erbringen. Daher müssen Methoden erarbeitet werden, die effizient genug sind, die gewaltigen Datenmengen zur Abdeckung der Küsten eines ganzen Kontinents zu bewältigen. Gleichzeitig müssen diese Methoden auch inhaltlich präzise und objektiv sein.

Aus diesen methodischen Herausforderungen ergeben sich eine Reihe bisher noch nicht beantworteter Fragen, wie z.B.:

- Werden Änderungen der Größe einer Kolonie durch die detektierte Guanoausdehnung repräsentiert?
- Wie können Pinguinkolonien auf einem Satellitenbild eindeutig den verschiedenen Arten zugeordnet werden?
- Welcher Zeitpunkt im Verlauf einer Brutsaison ist optimal für die Akquise eines entsprechenden Satellitenbildes?
- Was ist bei der Auswertung von Aufnahmen zu berücksichtigen, die aufgrund der Witterung nicht zu diesem optimalen Zeitpunkten gemacht werden konnten?
- Wie lässt sich die große Datenmenge effizient und trotzdem qualitativ hochwertig auswerten?
- Welche methodischen Möglichkeiten gibt es, die Menge der zur Verfügung stehenden und für die Validierung der Fernerkundungsanalysen essentiellen Bodenkontrolldaten zu erhöhen?

Die nun vorliegende Studie schließt inhaltlich an die oben genannte Machbarkeitsstudie von Mustafa et al. (2012) an und widmet sich den genannten und weiteren Fragestellungen mit dem Ziel, die zur Verfügung stehenden Methoden zum satellitenbasierten Monitoring von Pinguinkolonien in der Antarktis weiter zu entwickeln und um neue Werkzeuge zu ergänzen.

Testgebiete

Für die Untersuchungen in diesem Projekt wurden insgesamt vier Testgebiete ausgewählt, für welche aktuelle Bodenzähldaten zu den Pinguinbeständen zur Verfügung stehen. Dies waren die im Bereich der Antarktischen Halbinsel gelegenen Kolonien Ardley Island, Withem Island und Narebski Point sowie das südlicher, kontinental gelegene Testgebiete Cape Bird. In den jeweiligen Testgebieten befinden sich Pinguinkolonien aller Pygoscelis Arten. Auf Withem Island brüten nur Zügelpinguine, auf Narebski Point Esel- und Zügelpinguine, auf Ardley Island alle drei Pygoscelis Arten und auf Cape Bird nur Adéliepinguine.

Prüfung geeigneter Satellitenplattformen

Für die Detektierung von Pinguinkolonien werden je nach Zielstellung unterschiedliche Anforderungen an die Eigenschaften der Satellitendaten gestellt. Um alle Pinguinkolonien der Antarktis detektieren zu können, werden Satellitendaten benötigt, die aufgrund der enormen Datenmengen sehr kostengünstig zu akquirieren sind und zum anderen auch flächendeckend vorliegen. Für diesen Anwendungszweck sind nach Mustafa et al. (2012), Fretwell et al. (2012) und Schwaller et al. (2013b) die mittelaufgelösten Landsat 7-Aufnahmen am besten geeignet. Wenn hingegen die Größe der Kolonien genau bestimmt und kleinräumige Veränderungen detektiert werden sollen, werden Satellitendaten benötigt, die eine sehr hohe räumliche und zeitliche Auflösung haben. In diesem Fall ergaben die Untersuchungen von Mustafa et al. (2012), Lynch et al. (2012) und Lynch & LaRue (2014), dass hochaufgelöste Aufnahmen im Submeterbereich, wie z. B. von Quickbird und Worldview 2, die besten Ergebnisse liefern.

Da Landsat 7-Aufnahmen der Antarktis im Projektverlauf nicht mehr zur Verfügung standen, wurden die Aufnahmen des Nachfolgesatelliten Landsat 8 auf die Eignung zur Pinguinkoloniedetektierung überprüft. Betrachtet man die spektralen Eigenschaften, sind die Landsat 8-Daten im gleichen Umfang für die Pinguinkoloniedetektion geeignet wie die Daten von Landsat 7. Die spektrale Verbesserung bzw. die räumliche Verschlechterung des thermischen Infrarotbereiches spielt in diesem Zusammenhang keine Rolle, da diese aufgrund der groben räumlichen Auflösung nicht für die Detektion verwendet werden. Eine Verschlechterung bei der Detektion kleiner Kolonien tritt aber ein, da in der Praxis zum aktuellen Zeitpunkt kein sogenanntes Pansharpening der Spektralkanäle des nahen und kurzwelligen Infrarots mehr durchgeführt werden kann. Eine deutliche Verbesserung ergibt sich aber in Bezug auf die räumliche und zeitliche Abdeckung durch Landsat 8 im Vergleich zu Landsat 7. Letzterer war seit 2003 vom einen technischen Defekt betroffen, dem sogenannten Scan Line Corrector Failure (NASA 2011) und konnte seitdem nicht umfassend und fehlerfrei aufzeichnen. Landsat 8 ist bisher ohne technische Einschränkungen einsetzbar.

Ein relativ neuer hochauflösender Satellit ist der im August 2014 gestartete Worldview 3. Dieser ist insofern einzigartig, als dass er neben acht hochauflösenden VNIR-Bändern im visuellen Spektrum und im nahen Infrarot (visible and near-infrared; räumliche Auflösung = 1,24 m) auch acht relativ hochauflösende SWIR-Bänder (räumliche Auflösung = 3,7 m) besitzt, die ähnliche Spektralbereiche wie Landsat 8 abdecken. Ein Nachteil ist jedoch, dass die SWIR-Bänder deutlich schlechter aufgelöst sind als die VNIR-Bänder und bei der Anschaffung extra Kosten verursachen. Die räumliche Auflösung ist mit 31 cm im Nadir (senkrecht unter dem Satelliten) sehr hoch im Vergleich zu bisherigen Satelliten. Die höhere Auflösung kann die Detektion jedoch nicht deutlich verbessern, da sie immer noch zu gering ist, um Einzeltiere bzw. Nester zuverlässig zu erkennen. Die mit guanobedeckten Flächen wurden bereits gut mit den herkömmlichen 50 cm Daten detektiert.

Während der Projektlaufzeit waren keine geeigneten Daten von Hyperspektralsatelliten für die Untersuchungsgebiete verfügbar. Geplante Starttermine wurden auf Zeitpunkte nach dem Projektende verschoben. Es war daher nicht möglich, diese Daten zu berücksichtigen und auszuwerten. Bis 2020 sind eine Reihe von Starts von Hyperspektralsatelliten geplant, wobei es aber nur sehr wenige zuverlässige Informationen über den genauen Projektstand gibt. Eine Ausnahme bildet beispielsweise der EnMAP (Environmental Mapping and Analysis Program)-Satellit mit dem HSI Hyperspektralsensor, der sich in der finalen Vorbereitungsphase befindet. Der Start ist nach mehreren Verzögerungen nun für 2018 geplant (DLR 2016). Daher wurden ältere Hyperspektralsatellitendaten (EO-1 Hyperion) von einem Gebiet außerhalb der Testgebiete hinsichtlich ihrer Verwendbarkeit geprüft. Im Ergebnis wurde festgestellt, dass mit den Hyperspektraldaten der Guano bestimmt werden konnte. Eine quantitative Einschätzung der Ergebnisse ist aufgrund fehlender Bodendaten aber nicht möglich gewesen.

Anschaffung geeigneter Satellitenbilder

Um kleinräumige Veränderungen detektieren zu können, wurden in diesem Projekt die durch DigitalGlobe vertriebenen Satellitendaten verwendet, da nach der Fusion mit GeoEye im Jahr 2013 auch Aufnahmen der Satelliten GeoEye-1 und Ikonos mit angeboten werden. Bestellt wurden die hochaufgelösten Satellitenbilder bei dem europäischen DigitalGlobe Vertriebspartner e-GEOS. Die hochaufgelösten Aufnahmen wurden von verschiedenen Satelliten beschafft, darunter GeoEye, Quickbird, Worldview 2 und Worldview 3. Neue Aufnahmen wurden als 4-Kanal-Bundle mit vier Multispektralkanälen (Blau, Grün, Rot & nahes Infrarot) und dem Pan-Kanal bestellt. Im Ergebnis gelang es, von allen Untersuchungsgebieten hochaufgelöste Satellitenbilder zu akquirieren, aufgrund der häufigen Bewölkung aber nicht immer zum idealen Zeitpunkt. So gelang es beispielsweise in keiner Saison, Aufnahmen vom Dezember von Ardley Island zu erhalten.

Neben den hochaufgelösten Satellitenbildern wurden auch die kostenfreien Landsat 8-Aufnahmen für die intra- und intersaisonalen Analysen von den Untersuchungsgebieten akquiriert. Allerdings kann hier der Aufnahmezeitpunkt nicht im Vorfeld durch den Endnutzer bestimmt werden, da Landsat 8 jeden Punkt der Antarktis in definierten Intervallen abbildet. Die Häufigkeit, mit der ein Punkt aufgenommen wird, nimmt dabei zu, je näher dieser am Südpol liegt. So werden die Gebiete der kontinentalen Antarktis wie Cape Bird alle 1-3 Tage, die Untersuchungsgebiete auf der nördlichen Antarktischen Halbinsel hingegen nur alle 2-7 Tage von Landsat 8 abgedeckt. Von Ardley Island und Narebski Point wurden keine Aufnahmen beschafft, da diese Kolonien zu klein sind, um mit den 30 m Landsat 8-Aufnahmen sicher detektiert zu werden.

Erprobung und Weiterentwicklung verschiedener Methoden zur Analyse von Satellitenbildern

Zusätzlich zu den bereits in der Pilotstudie (Mustafa et al. 2012) untersuchten Methoden (Maximum-Likelihood-Klassifizierung, Ratio-Ansatz und Subpixel-Analyse) und der von Schwaller et al. (2013b) bzw. Lynch & Schwaller (2014) entwickelten und erfolgreich angewandten Methode (Landsat-retrieval-Methode) werden in diesem Projekt neue Klassifikationsverfahren auf ihre Eignung hin getestet, mit Guanobedeckte Flächen zu detektieren. Dafür wurden die Methoden exemplarisch sowohl an hochaufgelösten als auch an mittelaufgelösten Aufnahmen getestet. Als Testgebiete wurde Cape Bird für die kontinentale Antarktis und Ardley Island für die maritime Antarktis ausgewählt. Vor der Klassifizierung wurden die Grauwerte der Aufnahmen in Reflexionswerte über der Atmosphäre (Top of Atmosphere Reflectance) umgewandelt und mit dem Nearest-Neighbor-Diffusion-Based-Pan-Sharpening-Algorithmus (Sun et al. 2014) spektral geschärft, um bei den Aufnahmen auch in den multispektralen Kanälen eine Auflösung von 50 cm zu erreichen. Alle Klassifikationen wurden mit dem Bildanalyseprogramm ENVI durchgeführt und die Ergebnisse miteinander verglichen. Untersucht wurden die Klassifikationen Clusteranalyse, Decision Tree, Neuronale Netzwerke, Spectral-Angle-Mapper und die Adaptive-Coherence-Estimator.

Bei der Analyse der verschiedenen Methoden zur Detektion von Pinguinkolonien bei hochaufgelösten Aufnahmen stellte sich heraus, dass die neu getesteten Methoden keine Verbesserung bei der Genauigkeit zu der schon erprobten Maximum-Likelihood-Klassifizierung bietet. Vor allem die Ergebnisse der Adaptive-Coherence-Estimator (ACE)-Klassifizierung zeigen eine ähnliche Güte. Die Methode hat jedoch den Vorteil, dass im Gegensatz zur Maximum-Likelihood-Klassifizierung nur ein Trainingsgebiet benötigt wird bzw. nur eine externe spektrale Signatur. Theoretisch wäre somit eine automatisierte Klassifizierung möglich. Alle untersuchten Methoden zeigen jedoch große Probleme mit der Kolonie Ardley Island aufgrund ihrer sehr diversen Oberflächenstrukturen und verstreuten Nestgruppen, was im Ergebnis zu häufigen Fehlklassifizierungen führt. Bei der in der kontinentalen Antarktis gelegenen Kolonie Cape Bird wurden hingegen gute Ergebnisse erzielt.

Bessere Ergebnisse wurden mit der ACE-Klassifizierung bei den mittelaufgelösten Landsat 8-Aufnahmen der kontinentalen und maritimen Antarktis erreicht. Diese weist weniger Klassifizierungsfehler auf als die ebenfalls untersuchte SAM-Klassifizierung. Mit beiden Methoden wäre die Anwendung einer automatisierten Klassifizierung auf der gesamten Antarktis theoretisch möglich. Der Einsatz der Entscheidungsbaumklassifizierung kann als Vorstufe zu einer Klassifizierung große Vorteile in dem Sinne bieten, dass dadurch die zu klassifizierenden Bereiche stark eingegrenzt werden können (vgl. Burton-Johnson et al. 2016) und so die Gefahr von Fehlklassifizierungen z. B. bei Wolken minimiert wird.

Terrestrische Zählmethoden

Zur Beurteilung der Aussagekraft bzw. Genauigkeit der aus den Satellitenbildern gewonnenen Informationen werden möglichst genaue Bodenkontrolldaten (Ground-Truth-Daten) benötigt. Vier verschiedene Methoden (Panoramafotografie, GPS-basierte Vollkartierung, GPS-basierte Teilkartierung und UAV-Orthomosaike) zur Beschaffung solcher Referenzdaten wurden in diesem Projekt untersucht und miteinander verglichen. Zusätzlich wurden Störungsexperimente an brütenden Pinguinen durchgeführt, um das Störungspotenzial von UAV-Überflügen zu untersuchen.

Um die Brutpaarzahl einer Kolonie möglichst schnell abzuschätzen zu können, lassen sich im Idealfall von einer Erhöhung Panoramabilder der Kolonie anfertigen und die darin erkennbaren Nester zählen. Anschließend wird mit einem Satellitenbild die Fläche von einigen gut identifizierbaren vorher fotografierten Nestgruppen mit repräsentativer Dichte bestimmt und mit den im Panorama gezählten Nestern die Dichte dieser Nestgruppen ermittelt. Im letzten Schritt wird im Satellitenbild die gesamte Fläche der Kolonie vermessen und mit der zuvor errechneten Dichte die Gesamtanzahl der Nester dieser Kolonie berechnet. Um das Potenzial dieser Methode zu ermitteln, wurden in der Saison 2013/14 von 32 unterschiedlichen Standorten Panoramen aufgenommen und drei ausgewertet. Dabei stellte sich heraus, dass die Nester nur bis zu einer bestimmten Entfernung, ausgehend von der Position des Fotografen, im Panorama zu identifizieren sind.

Die präziseste Erfassung der Populationsgröße einer Pinguinkolonie ist durch die direkte Datenaufnahme am Boden mit der GPS-basierten Vollkartierung erreichbar. Unter Verwendung eines GPS-unterstützten Kartiersystems (vgl. Peter et al. 2008, Waluda et al. 2014) ist es zudem möglich, die räumliche Verteilung der Nester festzustellen. Nachteile der Methode sind der hohe Aufwand an Geländearbeit und das relativ hohe Maß an Störung, dem die Tiere dabei ausgesetzt sind. So benötigen beispielsweise für die vollständige GPS-gestützte Brutpaarkartierung der Kolonie Ardley Island (ca. 7.000 Brutpaare) zwei Personen ca. 2-3 Arbeitstage. Die Pinguinkolonie Ardley Island wurde im Rahmen dieser Studie dreimal während der Brutsaison (2013/14, 2014/15, 2015/16) vollständig kartiert und die Anzahl der Brutpaare erfasst. Die dabei verwendete Methodik entspricht der der vorangegangenen Kartierungen dieser Kolonie (vgl. Peter et al. 2008).

Bei der Teilkartierung wird im Gegensatz zur Vollkartierung nur ein Teil einer Kolonie mit GPS kartiert und die Brutpaare gezählt. Anhand der gemessenen Fläche der untersuchten Nestgruppen und der Anzahl der Brutpaare in diesen Nestgruppen kann die Dichte der Brutpaare in den Nestgruppen berechnet werden. Um auf die Gesamtzahl der Brutpaare aller Nestgruppen zu schließen, wird die gesamte Fläche aller Nestgruppen benötigt. Diese Fläche kann mit Hilfe von Satellitenaufnahmen bestimmt werden, die möglichst nahe am Zeitpunkt der Kartierung aufgenommen wurden. Anhand der am Boden bestimmten Brutpaardichte in den Nestgruppen und der aus den Satellitenbildern bestimmten Fläche aller Nestgruppen kann schließlich auf die Anzahl der Brutpaare einer Kolonie geschlossen werden. Bei dieser Methode gibt es zwei Hauptfehlerquellen: zum einem die Bestimmung der Brutpaardichte am Boden und zum anderen die Bestimmung der Nestgruppenfläche in den Satellitenbildern, wobei jede Fehlerquelle für sich zu erheblichen Ungenauigkeiten führen kann. Um die Größe der Fehlerquellen abschätzen zu können, wurde das Verfahren exemplarisch mit Hilfe der Kartierdaten von 2013/14 von Ardley Island und einer hochaufgelösten Worldview 2-Aufnahme vom selben Untersuchungsgebiet und Zeitraum getestet. Im Endeffekt bedeuten die Ergebnisse, dass die Genauigkeit der Bestimmung der Brutpaardichte bei einer Teilkartierung von Ardley Island stark von der Stichprobengröße abhängt, wobei diese wiederum vom möglichen Arbeitsaufwand begrenzt wird. So müssen beispielsweise, um mit Sicherheit eine Genauigkeit von 5 % zu erreichen, mindestens 281 Nestgruppen am Boden (ca. 93 % aller Nestgruppen auf Ardley Island) kartiert werden. Inwieweit sich dieses Ergebnis auf andere Kolonien übertragen lässt, konnte nicht überprüft werden. Die Untersuchungen von Woehler & Riddle (1998) deuten aber drauf hin, dass es größere Unterschiede (zwischen 0,1 und 3,1 Brutpaare pro m^2) bei den Koloniedichten gibt.

Eine relativ neue Methode (vgl. Goebel et al. 2015; Mustafa et al. 2014; Ratcliffe et al. 2015; Zmarz et al. 2015) zur Bestimmung der Abundanz bei Pinguinkolonien ist der Einsatz von UAVs (Unmanned Aerial Vehicles). Mit diesen werden die Kolonien in relativ niedriger Höhe (50 –

300 m) überflogen und währenddessen Luftbildaufnahmen gemacht. Diese Aufnahmen können anschließend mosaikiert, georeferenziert und zu Orthomosaiken verrechnet werden. Unter Orthomosaiken versteht man aus einzelnen Luftbildern zusammengesetzte georeferenzierte Bildmosaike, in denen geländebedingte Verzerrungen mit Hilfe eines Digitalen Oberflächenmodells (DOM) entfernt wurden (orthorektifiziert). Anhand von hochaufgelösten Orthomosaiken (<5 cm Bodenauflösung) können die Nester einer Kolonie gezählt werden. Zum Einsatz kam diese Methode während der Saisons 2013/14 und 2014/15 in den Untersuchungsgebieten Ardley Island, Withem Island und Narebski Point. In der Saison 2014/15 konnten aufgrund von schlechtem Wetter Withem Island und Narebski Point nicht erreicht werden. Die Befliegungen fanden mit verschiedenen Sensoren in jeweils unterschiedlichen Spektralbereichen statt (UV, RGB, NIR und Thermalinfrarot).

Mit einer Oktokopter-UAV wurden hochaufgelöste Aufnahmen (<5 cm Bodenauflösung) der Kolonien angefertigt, daraus Orthomosaike erstellt und anhand der Mosaike schließlich die Nester ausgezählt. Zudem ist es möglich, mit den Bildern der Kolonie bei entsprechend großer Bildüberlappung 3D-Oberflächenmodelle zu erstellen, mit denen wiederum Satellitenbilder sehr genau orthorektifiziert werden können. Zur Kontrolle der Güte der Zählmethode in UAV-Aufnahmen wurden die Anzahlen der Brutpaare, die durch Auszählung der UAV-Mosaike ermittelt wurden, denen der GPS-unterstützten Vollkartierung am Boden gegenübergestellt. Die Abweichung zwischen beiden Methoden beträgt zwischen -1 und +11 %. Um die Ursachen für diese Abweichungen zu differenzieren, wurde das Ergebnis der UAV-Kartierung mit der Anzahl der Nester der einzelnen am Boden kartierten Nestgruppen detailliert verglichen. Dabei zeigt sich, dass die Anzahl der Fehlklassifikationen höher ist als die absolute Differenz beider Methoden. Die größte Fehlerursache ist die gelegentlich schwierige Unterscheidung zwischen brütenden und nichtbrütenden Individuen. Das Unterscheiden von besetzten Nestern und Pinguinen ohne Nest könnte künftig durch höher aufgelöste Sensoren verbessert werden. Niedrigere Flughöhen würden die Erkennbarkeit zwar verbessern, sind jedoch kaum praktikabel, da sich die notwendige Gesamtflugzeit zur Abdeckung einer größeren Fläche deutlich verlängern würde. Zudem wurde in Rümmler et al. (2015) bereits gezeigt, dass bei einer Flughöhe von 50 m und darunter eine signifikante Störung der Pinguine feststellbar ist.

Zusätzlich zu den RGB-Aufnahmen wurden in der Saison 2014/15 auch Orthomosaike im ultravioletten (UV) und nahinfraroten (NIR) Spektralbereich erstellt. Dazu wurde der UV-NIR-Sperrfilter der Kamera Sony A6000 entfernt. Mit Hilfe von speziellen Filtern war es somit möglich, entweder im UV-, NIR- oder RGB-Spektralbereich Bilder aufzunehmen. Bei der Interpretation der Bilder stellte sich heraus, dass mit den verwendeten UV-Aufnahmen kein Vorteil zu den RGB-Aufnahmen bei der Detektierung der Brutpaare festzustellen war. Dies lag vor allem daran, dass die Aufnahmen zu stark verrauscht waren, um weitere Details erkennen zu können. Im NIR hingegen sind die mit guanobedeckten Bereiche sehr gut durch die starke Reflexion in diesem Wellenlängenbereich zu erkennen. Allerdings reflektiert auch die vorhandene Vegetation im NIR sehr stark, sodass es hier zu Verwechslungen kommen kann. Vermieden werden kann dieses Problem, indem die Vegetation mit Hilfe des NDVI abgegrenzt wird, sodass Guano und Vegetation eindeutig unterschieden werden können. Eine andere Möglichkeit besteht in der Kombination von NIR, rot, und grün als Falschfarbenbild, da sich mit dieser Kombination Guanoflächen deutlich von der Umgebung abheben, was ein großer Vorteil der NIR-Aufnahmen gegenüber den reinen RGB-Aufnahmen darstellt.

UAV-Befliegungen mit Thermalsensor führten zu neuartigen Erkenntnissen hinsichtlich der thermischen Signatur der Pinguine und des Guanos. Deutlich heben sich die höheren Körpertemperaturen der Pinguine gegenüber der Temperatur des Untergrundes ab. In Abhängigkeit von der Flughöhe ist damit eine sichere Detektion von Pinguinen möglich.

Zudem zeigt sich bei einer Flughöhe von 20 m eine ebenfalls deutliche Temperaturdifferenz zwischen den von guanobedeckten Nestern und der Umgebung. Die Ursache dieser Temperaturdifferenz liegt in der hohen Albedo des Guanos. In der systematischen Auswertung großer Nestgruppen war mit dieser Methodik bei üblichen Aufnahmehöhen von 50 m jedoch keine eindeutige Trennung zwischen auf dem Nest befindlichen Pinguinen und nicht auf einem Nest befindlichen Pinguinen möglich. Eindeutig ließen sich im Thermalbild aber Pinguine erkennen, die nicht auf mit guanobedeckten Bereichen stehen oder liegen. Die starken Temperaturkontraste der Pinguine zu den Guanoflächen bilden Potenzial für automatisierte objektbasierte Klassifizierungsverfahren mit dem Ziel, das manuelle Auszählen der Mosaike zu ersetzen. Im RGB-Bild fallen die Kontraste der Farbwerte der Pinguine zur Umgebung geringer aus, was die Anwendung vergleichbarer Klassifizierungsverfahren für das RGB erschwert. Perspektivisch könnte durch den Einsatz einer höher aufgelösten Thermalkamera die Detektierbarkeit von Strukturen wie Nestern und stehenden Pinguinen in praktikablen Flughöhen (50 m über Grund) verbessert werden.

Beim Vergleich aller untersuchten terrestrischen Zählmethoden wird klar, dass es keine Methode gibt, die allen anderen überlegen ist. Die Vollkartierung hat die höchste Datenqualität, die sich aber durch den höchsten Zeitbedarf, hohe Kosten und ein großes Störungspotenzial erkauft wird. Die Panoramafotografie und die Teilkartierungen hingegen haben die niedrigste Datenqualität und die benötigten hochaufgelösten Satellitenbilder sind relativ teuer, dafür sind diese Methoden schnell durchzuführen und ihr Störungspotenzial hält sich in Grenzen. Einen Mittelweg bilden die UAV-Befliegungen, die eine gute Datenqualität liefern, dabei aber nur relativ wenig Zeit in Anspruch nehmen, wenig kosten und ein geringes Störungspotenzial haben. Einzige Kehrseite ist die hohe Witterungsabhängigkeit der UAV-Befliegungen. Welche Methode letztendlich eingesetzt wird, hängt demnach ganz von den Anforderungen des Anwenders bzw. den örtlichen Gegebenheiten ab, sodass alle Methoden ihre Einsatzberechtigung haben.

Störungsexperimente

Im Laufe der Saison 2014/15 wurde an 9 Versuchstagen der Einfluss unseres Oktokopters auf zwei lokal vorkommende Pinguinarten, den Adéliepinguin (*Pygoscelis adelidae)* und den Eselspinguin (*Pygoscelis papua)* untersucht. Alle Untersuchungen wurden in der Pinguinkolonie Ardley Island durchgeführt. Um das Störungspotenzial des Oktokopters zu ermitteln, wurden Veränderungen des Verhaltens der untersuchten Individuen während UAV-Überflügen per Videokamera aufgezeichnet und mit Hilfe der Software CowLog 2.0 (Hänninen & Pastell 2009) analysiert. Die Verhaltensanalysen basieren methodisch auf den Beschreibungen von Schuster (2010) und Spurr (1975) für Adéliepinguine, Van Zinderen Bakker et al. (1971) für Eselspinguine und Jouventin (1982) für beide Arten. Unsere Ergebnisse zeigen, dass es einen Einfluss des Oktokopters auf die untersuchten Pinguinarten gibt. Aus allen Untersuchungen lässt sich schließen, dass der Oktokopter selbst in großen Flughöhen von 50 m noch wahrnehmbar für die Tiere ist. Der Einfluss erhöht sich mit sinkender Flughöhe. Für beide Arten und Flugrichtungen, mit Ausnahme der Horizontalflüge bei Eselspinguinen, wurde ein weiterer starker Anstieg der Störung unterhalb von 20 m bzw. 15 m Flughöhe festgestellt. Diese Ergebnisse passen gut zu Beobachtungen von Müller-Schwarze & Müller-Schwarze (1977), die Attrappenversuche mit Skuas (Raubmöwen) an Adéliepinguinen durchführten und dabei feststellten, dass Reaktionen auf den Prädator ab einer Flughöhe von 14 m zu beobachten waren. Das könnte für die Theorie sprechen, dass der Oktokopter aus Perspektive der Pinguine einem natürlichen Prädator ähnelt und daher als Bedrohung wahrgenommen wird. Vergleicht man beide Pinguinarten, so scheint der Start einen größeren Einfluss auf Adéliepinguine als auf Eselspinguine zu haben, wohingegen die grundlegende Unruhe bei Eselpinguinen größer ist.

Die Reaktion auf den Start war bei Eselpinguinen geringer, obwohl die Startdistanzen mit 25 – 35 m hier geringer waren, als bei Adéliepinguinen (hier etwa 50 m). Während der Überflüge in geringen Flughöhen war das Störungslevel bei Eselspinguinen höher. Bezieht man jedoch die Unterschiede zur Kontrolle ein, scheint die relative Störung vergleichbar zu sein. Da hier nur 3 Brutgruppen in die Analyse eingingen, ist dieser Vergleich als nicht gesichert anzusehen und weitere Experimente sollten diese Ergebnisse stützen. Es wurde außerdem für beide Arten festgestellt, dass unterhalb von 20 m Vertikalflüge eine größere Störung auslösen als Horizontalflüge. Dies ist möglicherweise damit erklärbar, dass ein Prädator, der sich direkt auf den Pinguin herabstürzt, eine größere Gefahr darstellt als einer, der die Brutgruppe nur überfliegt. Jedoch sollten auch einige methodische Ursachen in Betracht gezogen werden: zum einen hat ein UAV im Vertikalflug immer den gleichen horizontalen Abstand zu den einzelnen Individuen und nähert sich während der gesamten Zeit allen an. Eine horizontal fliegende UAV dagegen entfernt sich bereits von den ersten Tieren, so dass sich diese bereits beruhigen können, während sie sich Tieren am anderen Ende der Gruppe gerade erst annähert. Da für die Analysen die durchschnittliche Störung innerhalb der Gruppe betrachtet wurde, reduzieren solche sich bereits beruhigenden Tiere das Störungslevel bereits während des Überfluges. Zum anderen ist Vigilanz im Vertikalflug für den Beobachter leichter zu erkennen, da der Pinguin notwendigerweise den Kopf bzw. Schnabel anheben muss, während er im Horizontalflug bei günstiger Ausrichtung im Nest keine Körperbewegung benötigt, um den Oktokopter zu beobachten. Persönliche Beobachtungen im Feld deuten außerdem drauf hin, dass die Lautstärke des Oktokopters während vertikaler Bewegungen im Vergleich zum Horizontalflug erhöht ist.

Klassifizierung von Farbunterschieden des Pinguinguanos

Aktuell ist es mittels fernerkundlicher Methoden bereits gut möglich, Seevogelkolonien zu erkennen und zu vermessen, selbst wenn die einzelnen Tiere nicht erkennbar sind (z.B. Fretwell et al. 2015; LaRue et al. 2014; Lynch & LaRue 2014). Die großflächige Guanobedeckung des Bodens lässt sich in vielen Fällen auch bei geringer Auflösung durch ihre farblichen Unterschiede zum umgebenden Boden gut ausmachen (Fretwell et al. 2015). Auch gab es bei Pinguinen in gemischten Kolonien schon erfolgreiche Versuche, die Brutareale der verschiedenen Arten im Satellitenbild voneinander abzugrenzen (Lynch et al. 2012). Solche Studien sind bisher allerdings Einzelfälle. Gerade bei völlig unbekannten Kolonien fällt es weiterhin sehr schwer, die dortige(n) Art(en) nur anhand eines Satellitenbildes zu bestimmen. Da die einzelnen Individuen bei der aktuell verfügbaren Bodenauflösung unmöglich angesprochen werden können, könnten interspezifische Unterschiede der gut sichtbaren Guanofärbung einen wichtigen Hinweis zur Artbestimmung liefern. Ziel dieser Teiluntersuchung war festzustellen, ob es Unterschiede bei der Guanofärbung einer Kolonie einer Art im Saisonverlauf oder zwischen den einzelnen Arten gibt (z. B. durch unterschiedliche Nahrung bedingt). Sollte dies der Fall sein, könnten solche Merkmale verwendet werden, um unbekannte Kolonien auf Satellitenbildern anhand ihrer Guanofarbe einer bestimmten Art zuzuordnen. Zur Klassifizierung von Farbunterschieden des Guanos ist es zunächst erforderlich, die Farbe des Guanos vor Ort oder mit Hilfe der Fernerkundung zu bestimmen. Die Guanofarbe wurde am Boden mit Munsell-Farbtafeln (Munsell 1969) und mit Fotografien sowie in UAV- und Satellitenaufnahmen bestimmt.

Um die Farbwerte der beiden auf Ardley Island untersuchten Arten per vom Boden aufgenommen Fotos vergleichen zu können, wurde jeweils der Mittelwert von den Messungen an allen Teststellen gebildet. Das bedeutet, dass für Adéliepinguine in der Saison 2014/15 eine und in der Saison 2015/16 drei Nestgruppen ausgewertet werden konnten sowie drei Nestgruppen für Eselspinguine in der Saison 2014/15 und 13 Nestgruppen in der Saison

2015/16. Es wurde festgestellt, dass sich die beiden untersuchten Arten lediglich am Saisonbeginn unterscheiden lassen. Es lässt sich erkennen, dass die relativen Rot- und Grünkomponenten des Adéliepinguinguano am Saisonanfang fast gleich groß sind, während Eselspinguinguano hier eine deutlich rotere Färbung aufweist. Dies deckt sich mit Beobachtungen der Geländearbeiter, die feststellten, dass zu Saisonbeginn Adéliepinguinausscheidungen oftmals grün waren. Nach Heine & Speir (1989) tritt diese Färbung dann auf, wenn die Pinguine längere Zeit nicht im Meer waren, um Nahrung zu suchen. Die Grünfärbung kommt nach Sladen (1958) von Gallenpigmenten der Pinguine oder nach Myrcha & Tatur (1991) von Proteinen, Cholsäure und unverdauten Algenzellen (der Nahrung des Krills) im Guano. Später in der Saison trat diese Grünfärbung aber nicht mehr auf, zugunsten eines höheren Rotanteils. Ebenfalls deutet sich zum Saisonende hin eine leichte Zunahme der relativen Rotkomponente bei beiden Arten an.

Bei Betrachtung der aus den UAV-Aufnahmen extrahierten relativen Farbwerte fällt auf, dass am Anfang der Saison bei den Adéliepinguinen und nicht ganz so stark ausgeprägt auch bei Eselspinguinen die Rot- und Grünkomponenten fast gleich groß sind. In den UAV-Aufnahmen ist an diesen Stellen erkennbar, dass der Guano tatsächlich grünlich erscheint. Später in der Saison verschwindet der starke Grünanteil aber wieder. Auffällig ist weiterhin, dass im Januar der Blauanteil deutlich zunimmt und teilweise sogar den Rotanteil übertrifft. Im UAV-Bild erscheint dieser Guano sehr dunkel, fast schwarz.

Bei den Satellitenaufnahmen wird erkennbar, dass der relative Rotanteil viel größer ist als bei den bodengebundenen- und UAV-Aufnahmen. Im Detail zeigt sich wieder, dass am Anfang der Saison der Adéliepinguinguano einen deutlich größeren relativen Grünanteil hat als der Eselspinguinguano. Dieser Unterschied verschwindet allerdings später in der Saison.

Vergleicht man die einzelnen Methoden miteinander, so zeigt sich zuerst, dass es mit den Bodenfotos möglich ist, die Ergebnisse der Munsell-Color-Charts zu reproduzieren. Ein direkter Vergleich mit den UAV- und Satellitenaufnahmen ist schwierig, da sich diese sowohl zeitlich als auch räumlich unterscheiden. Dennoch lässt sich der generelle Saisonverlauf auch bei diesen wiedererkennen. Von besonderem Interesse bei dieser Untersuchung war die Frage, ob Farbunterschiede zwischen den einzelnen Arten existieren, die mittels fotographischer und fernerkundlicher Methoden erkannt werden können. Dies scheint in begrenztem Umfang der Fall zu sein. So zeigt sich bei allen Untersuchungsmethoden, dass sich die Guanofarbe an den Teststellen mit Adéliepinguinen am Anfang der Saison (Anfang November) von den Teststellen der Eselspinguine unterscheiden. Der Unterschied äußert sich darin, dass der relative Rot- und Grünanteil gleichgroß ist (Guanofarbe erscheint grünlich) bzw. sehr nahe beieinander liegt. In der restlichen Saison hingegen dominiert bei allen Arten der Rotanteil. Dies deckt sich auch mit den Beobachtungen aus dem Feld. Die Ursache für diese Farbunterschiede könnte auf eine Veränderung in der Nahrungsverfügbarkeit innerhalb der Saison zurückzuführen sein, was aber in dieser Studie nicht untersucht wurde. Nur in den UAV-Aufnahmen wurde ebenfalls grünlicher Guano bei Eselspinguinen Ende November festgestellt, wenn auch nicht so deutlich ausgeprägt wie bei den Adéliepinguinen. Der Grund, warum dies mit den anderen Methoden nicht beobachtet werden konnte, ist nicht bekannt. Möglicherweise spielt es aber eine Rolle, dass bei den UAV-Aufnahmen kein standardisierter Weißabgleich durchgeführt werden konnte.

Möglichkeiten der Artunterscheidung

Die drei untersuchten Pinguinarten lassen sich am Boden bei Betrachtung mit bloßem Auge leicht am Habitus unterscheiden. Vor allem ihre unterschiedliche Färbung ermöglicht dabei eine sofortige Artbestimmung. Als einziges zuverlässiges Bestimmungsmerkmal aus der Luft konnte der sanduhrförmige weiße Fleck auf dem Scheitel von Eselspinguinen ausgemacht werden. Damit ließ sich ein Teil der Tiere sicher identifizieren. Bereits eine Bodenauflösung des Mosaiks von 2 cm reichte jedoch oft nicht mehr aus, um den Fleck erkennen zu können. Etwas besser ist die Differenzierbarkeit der Küken der drei untersuchten Arten. Bei kleinen Küken, die noch im Nest liegen, sind die auf dem Luftbild sichtbaren Unterschiede sehr gering. Hier erfolgt die Bestimmung in der Regel ohnehin über den anwesenden Elternvogel. Im Kindergartenstadium sind hingegen deutliche Farbunterschiede sichtbar. Weitere mögliche Kriterien zur Unterscheidung der Arten sind Nestabstand, Nestdichte und die Art der Nestgruppierung. Hierzu existieren bereits ältere Untersuchungen (Naveen et al. 2012; Oelke 1975; Woehler & Riddle 1998; Quintana & Cirelli 2000; Kirkwood et al. 2007). Insgesamt lässt sich aus diesen publizierten Daten keine sichere Klassifizierung der einzelnen Arten bezüglich Dichte oder Nestabstand erkennen. Stattdessen ist die Schwankungsbereite innerhalb einer Art zwischen den Studien sehr groß.

Eine indirekte Methode der Artunterscheidung beruht auf der unterschiedlichen Brutbiologie und -phänologie der drei Pygoscelis-Arten. Der Zeitpunkt der Besetzung der Kolonien auf Ardley Island hängt stark von den Eisverhältnissen in der Maxwell Bay und den Schneeverhältnissen an Land ab und kann von Jahr zu Jahr deutlich schwanken (Mönke & Bick 1988; Peter et al. 1988; Zippel 1987). Die Nestlingszeiten der Arten unterscheiden sich wenig. Die längste Nestlingszeit weisen die Eselspinguine auf, die erst nach 62 bis 82 Tagen, im weiter nördlichen Verbreitungsgebiet sogar erst nach 85 bis 117 Tagen flügge werden (Shirihai et al. 2002).

Vor allem die große zeitliche Differenz der Brutphänologie von Adélie- und Eselspinguinen zu den Zügelpinguinen kann eine Artunterscheidung erlauben, wenn der Aufnahmezeitpunkt günstig ist. So liegt der Unterschied z. B. zwischen 50 % geschlüpften Jungen bei Eselspinguinen und Zügelpinguinen auf Ardley Island bei fast 2 Wochen. Da die Jungen auch im UAV-Bild gut erkennbar sind, wäre dies ein mögliches Unterscheidungsmerkmal. Dieser Ansatz wurde anhand des Orthomosaiks der UAV-Befliegung von Narebski Point 03.01.2014 getestet. So gelang es, nur mit dem Orthomosaik, alle 15 Zügelpinguinnestgruppen von den 80 Eselspinguinnestgruppen sicher zu unterscheiden. Die Unterscheidung beruhte allein darauf, dass in den Zügelpinguinnestgruppen die Adulten noch brüten, es also eine feste Neststruktur gibt und im Gegensatz dazu in den Nestgruppen der Eselspinguine die Küken schon geschlüpft sind, wobei sich bereits die Neststruktur aufzulösen beginnt. Die Validierung erfolgte anhand der Kartierdaten des KOPRI aus der gleichen Saison.

Anhand einer Worldview 3-Aufnahme vom 11.11.2014 von Ardley Island wurde untersucht, ob sich Adélie- von Eselspinguinnestgruppen allein aufgrund der Guanosignatur unterscheiden und detektieren lassen. Dazu wurden mit Hilfe der per GPS kartierten Nestgruppen beider Arten die Nester identifiziert und deren durchschnittliche spektrale Signatur erhoben. Das Ergebnis war, dass der Adéliepinguinguano eine höhere Relfexion im grünen Spektralbereich aufweist. Auch visuell ließen sich beide Guanoarten anhand des deutlichen Grünstichs des Adéliepinguinguanos im Vergleich zum orangen Eselspinguinguano voneinander unterscheiden. Dies war auch dann möglich, wenn sich innerhalb einer großen Eselspinguinnestgruppe nur ein kleinerer Bereich mit Adéliepinguinen befand. Dieses Phänomen war aber nur in der Aufnahme vom 11.11.14 sichtbar. In der Aufnahme vom 30.11.2014 unterschied sich der Guano nicht mehr.

Automatisierung der satellitengestützen Detektion von Pinguinkolonien

Seit der Studie von Mustafa et al. (2013), die die theoretische Möglichkeit einer automatisierten Auswertung von Satellitenaufnahmen zum Pinguin-Monitoring weitgehend bestätigte, sind weitere Forschungen zu dieser Problematik durchgeführt worden (vgl. Lynch & LaRue 2014, Lynch & Schwaller 2014, Schwaller et al. 2013b). Für mittelaufgelöste Aufnahmen (Landsat) wurden Methoden entwickelt und erfolgreich angewandt, mit denen Guanobedeckte Gebiete in der gesamten Antarktis automatisch detektiert werden können (Schwaller et al. 2013b, Lynch & Schwaller 2014). Ebenfalls existiert eine für die Vorprozessierung wichtige Methode, mit der sich wolken- bzw. eisfreie Landgebiete in der Antarktis automatisch finden lassen (Burton-Johnson et al.2016). Eine Methode, mit der Guano automatisch in einer großen Anzahl von hochauflösenden Satellitendaten von unterschiedlichsten Gebieten detektiert werden kann, wurde bis jetzt noch nicht gefunden.

Untersuchung intrasaisonaler Variationen in der Kolonieausdehnung und -besetzung und deren Detektierbarkeit

Viele Küstengebiete der Antarktis sind häufig bewölkt. Dies gilt in besonderem Maße für die Südshetlandinseln. Daher ist es nur selten möglich, das Arbeitsgebiet zum gewünschten Zeitpunkt durch optische Satellitenaufnahmen abzubilden. Auch andere Monitoringmethoden können aus logistischen oder witterungsbedingten Gründen oftmals nicht zu optimalen Zeitpunkten eingesetzt werden. Ein detaillierteres Wissen zur intrasaisonalen Variabilität verschiedener Meß- und Zielparameter könnte die Aussagekraft und Übertragbarkeit von Daten erhöhen, die zu nicht optimalen Zeitpunkten erhoben wurden. Hierfür wurde die Pinguinkolonie Ardley Island bzw. ein Teilgebiet davon in der Saison 2014/15 mit verschiedenen Methoden am Boden und aus der Luft untersucht. Anschließend wurden je nach Aufnahmemethode die Brutpaaranzahl, die Nestgruppenfläche oder phänologische Kriterien untersucht und letztlich die jeweiligen Ergebnisse miteinander verglichen.

Brutphänologie der Pinguine auf Ardley Island

Während der Saison 2014/15 und der Saison 2015/16 wurde auf Ardley Island das Brutverhalten von Esels- und Adéliepinguinen ausführlich untersucht. Ziel war es, einen Überblick über den zeitlichen Verlauf der Brut und deren Erfolg zu erlangen. Außerdem wurden Zeitpunkte von markanten Brutereignissen ermittelt (z. B. Peak of Egg-laying und Peak of Hatching). In beiden Saisons wurden die Nester mit den gleichen Kriterien untersucht und die Daten ausgewertet. Dabei wurden die Nester unterteilt in a) Nester, in denen mindestens ein Ei vorhanden ist, b) Nester mit mindestens einem Küken und c) verlassene Nester. Der Vergleich der Brutchronologien von Eselspinguinen und Adéliepinguinen in den beiden Saisons betrifft nur einen begrenzten Zeitabschnitt und ist daher nicht repräsentativ. Es deutet sich jedoch an, dass der zeitliche Verlauf des Brutgeschehens insbesondere für Eselspinguine, aber ansatzweise auch für Adéliepinguine recht ähnlich ist. Wie stark der Verlauf des Brutgeschehens zwischen verschiedenen Saisons langfristig variiert, kann erst durch langjährige Beobachtungen ermittelt werden. Hierfür sollte jeweils ein Zeitraum von Mitte Oktober bis Ende Januar angesetzt werden. Die vorliegenden Daten legen nahe, dass der optimale Zeitpunkt zur Erfassung von Brutpaarzahlen im Bereich der Südshetlandinseln für Eselspinguine zwischen 25. November und 10. Dezember liegt. Für Adéliepinguine deutet sich ein optimaler Zeitraum zwischen 10. und 20. November an.

Um die intrasaisonale Variation mit Landsat 8 zu überprüfen, wurde versucht, in monatlichem Abstand mindestens eine Aufnahme von Cape Bird zu beschaffen. Anschließend wurde die Guanofläche in den Aufnahmen manuell bestimmt und zum Vergleich automatisiert klassifiziert. Im Ergebnis wurde festgestellt, dass es starke Einbrüche bei der Guanofläche am Saisonanfang und Saisonende gibt, die auf eine temporäre Schneedecke zurückzuführen sind, die den größten Teil der Kolonie bedeckte und so eine Detektierung der Guanoflächen verhinderte. Betrachtet man alle drei Saisons zusammen, wird ersichtlich, dass sich, abgesehen von den Schneefallereignissen, die detektierbare Guanofläche bei Cape Bird im Saisonverlauf nicht ändert. Die kleineren intersaisonalen Schwankungen der Guanofläche liegen hingegen im Bereich der Messungenauigkeit, da aufgrund der geringen Bodenauflösung der Landsat-Aufnahmen und der geringen Größe der Kolonien schon wenige Pixel Unterschied zu großen Flächenabweichungen führen.

Für die Saison 2014/15 gelang es mit Hilfe der Satellitenkonstellation von DigitalGlobe, vier wolkenfreie hochaufgelöste Aufnahmen von Anfang November bis Anfang Februar von Ardley Island zu akquirieren. In der darauffolgenden Saison gelang dies aufgrund der Wolkenbedeckung erst mit Aufnahmen von Anfang Januar. Um die intrasaisonale Variation der Guanoflächen zu untersuchen wurde in diesen Satellitenaufnahmen die Fläche des Guanos durch manuelle Bildinterpretation bestimmt. Im Ergebnis zeigt sich ein deutlicher Anstieg der Guanoflächen über den Saisonverlauf. Im Detail wird erkennbar, dass die Guanoflächen am Anfang der Saison im Oktober/November noch gleich groß sind und erst danach ansteigen. Da die Anzahl der Nester aber ab Anfang Dezember nicht mehr zunimmt, könnte die Ursache für die Flächenzunahme der guanobedeckten Gebiete im Verteilen des Guanos liegen. Dies legt auch die Interpretation der Satellitenaufnahmen nahe. Für das flächenhafte Verteilen des Guanos sind vermutlich zwei Ursachen verantwortlich: fluviale Prozesse (Erosion) und das Verteilen durch die Pinguine selbst. Beide Prozesse treten besonders stark am Ende der Saison auf, wenn der Schnee geschmolzen ist und sich bereits Kindergärten gebildet haben. Sie korrelieren damit gut mit dem beobachteten Flächenanstieg, der zum selben Zeitpunkt stattfindet, denn das Untersuchungsgebiet ist in den Aufnahmen von Oktober und November 2014 stark schneebedeckt, während in den Aufnahmen von Januar und Februar kaum noch größere Schneeflächen zwischen den Nestgruppen vorhanden sind. Auch wurde in beiden Saisons beobachtet, dass sich am Ende der Saison neue Guanoflächen in Strandnähe bilden, wo häufig auch die Kindergärten zu finden sind. Wie mit Hilfe der Aufnahmen von Mitte Februar festgestellt wurde, kann es sehr spät in der Saison auch wieder zu einer Abnahme der Guanoflächen kommen. Mögliche Ursachen sind die Zunahme von verlassenen Nestern und damit auch die Abnahme des Guanoeintrages durch adulte Pinguine bei gleichzeitiger Erosion des Guanos.

Gegenüberstellung der Brutphänologie mit der Guanofläche aus Satellitenaufnahmen

Bei der Akquise von Satellitenaufnahmen kann es vorkommen, dass Aufnahmen von bestimmten Gebieten nur zu einem späten Zeitpunkt verfügbar sind, an denen sich bereits Kindergärten gebildet haben und die klaren Nestgrenzen verwischt sind. Die mit Guanobedeckte Koloniefläche ist dann deutlich größer als am Anfang der Saison, obwohl sich die Zahl der besetzten Nester im Laufe der Brutsaison kontinuierlich verringert. Wird nun die Zahl der Nester allein aus der Guanofläche berechnet, ergibt sich besonders für das Ende der Saison eine unrealistische Zahl von Nestern der Kolonie einer Saison. Um auch Daten von diesen ungünstigen späten Zeitpunkten noch verwerten zu können, wurde untersucht, wie stark sich die Guanoflächen innerhalb der Saison verändern und ob es einen Zusammenhang mit der Brutphänologie innerhalb der betreffenden Kolonie gibt. Dazu wurde die mittlere Nestdichte der guanobedeckten Flächen der Kolonie Ardley Island in vier Saisons (2005/06, 2013/14 - 2015/16) anhand der in hochaufgelösten Satellitenaufnahmen bestimmten Guanoflächen und der am Boden gezählten aktiven Nester der Vollkartierungen aus den gleichen Saisons bestimmt. Dabei wurde eine Korrelation (R^2= 0,84) zwischen dem Aufnahmezeitpunkt der Satellitenaufnahme und der durchschnittlichen Nestdichte der guanobedeckten Flächen bei der Kolonie Ardley Island festgestellt. So nimmt die Nestdichte der mit guanobedeckten Koloniefläche in Bezug auf den Kartierzeitpunkt kontinuierlich im Laufe der untersuchten Saisons ab. Beachtet werden muss bei dieser Analyse, dass für zwei Saisons nur jeweils eine Aufnahme zur Verfügung stand und dass keine Aufnahme von Mitte Dezember ausgewertet werden konnte.

Untersuchung intersaisonaler Variationen in der Kolonieausdehnung und -besetzung und deren Detektierbarkeit

Die Detektierbarkeit intersaisonaler Variationen der Kolonieausdehnung und –besetzung wurde mit hoch- und mittelaufgelösten Satellitenbildern anhand der Kolonien von Ardley Island und Cape Bird untersucht. Für Narebski Point stand für die Untersuchung nur eine schnee- und wolkenfreie hochaufgelöste Satellitenaufnahme zur Verfügung. Aus diesem Grund konnte für dieses Untersuchungsgebiet keine entsprechende Analyse durchgeführt werden.

Ein Vergleich der in hochaufgelösten Satellitenbildern detektierten und mit guanobedeckten Flächen ist aufgrund der großen saisonalen Variabilität auf Ardley Island nicht möglich. Daher wurde untersucht, ob ein Zusammenhang zwischen der Anzahl der Nester und der mit Hilfe der Bodenkartierungen ermittelten Nestgruppenfläche besteht. Dazu wurden die Kartierungen aus acht Saisons von Ardley Island (2003/04 - 2005/06 und 2012/13 - 2015/16) ausgewertet. Das Ergebnis der Untersuchung zeigt jedoch, dass ein solcher Zusammenhang für Ardley Island nicht besteht (R^2 = 0,05). Eine mögliche Ursache für diesen Umstand, der auch schon zuvor von Mustafa et al. (2005) beschrieben wurde, könnte darin liegen, dass es bei einer Veränderung der Brutpaarzahlen eher zu einer Änderung der Dichte in den Nestgruppen kommt, anstatt zu einer Änderung der Nestgruppenfläche. Das bedeutet, dass auf Ardley Island keine Änderungen der Brutpaarzahl aufgrund der Nestgruppenfläche detektiert werden können. Lediglich bei einer sehr starken Ab- oder Zunahme der Brutpaare kann eine signifikante Änderung der Nestgruppenfläche erwartet werden.

Auch für das in der Ostantarktis gelegene Untersuchungsgebiet Cape Bird wurde untersucht, ob intersaisonale Schwankungen der Brutpaare mit hochauflösenden Satelliten detektiert werden können. Als Datengrundlage für die Untersuchung dienten sechs hochaufgelöste Satellitenaufnahmen aus sechs verschiedenen Saisons innerhalb des Zeitraums 2007/08 bis 2015/16, in denen die Guanoflächen der Kolonie Cape Bird Nord manuell deliniert wurden. Diese wurden den Zensusdaten des neuseeländischen Landcare Research (Landcare Research 2016), die anhand von Luftbildbefliegungen (Taylor et al. 1990) erstellt wurden, gegenübergestellt. Dabei zeigt sich, dass sich die guanobedeckte Fläche der Kolonie über den Untersuchungszeitraum nicht signifikant änderte, während im selben Zeitraum die Anzahl der Brutpaare um 40 % stieg. Dies bedeutet, dass allein anhand der Guanofläche keine Änderungen der Brutpaarzahlen von Cape Bird Nord im Untersuchungszeitraum detektiert werden konnten.

Auch anhand der mittelaufgelösten Landsat-Aufnahmen wurde untersucht, ob intersaisonale Schwankungen der Brutpaare detektierbar sind. Dafür wurden wiederum Brutpaarzahlen (Landcare Research 2016) mit den aus Landsat-Aufnahmen manuell bestimmten Guanoflächen von Cape Bird Nord verglichen. Für die Analyse wurden 17 wolkenfreie Landsat-Aufnahmen mit 30 m Bodenauflösung ausgewertet, die zwischen 1985 und 2015 mit verschiedenen Sensoren (TM, ETM+ und OLI) aufgenommen wurden. Im Ergebnis zeigte sich, dass kein Zusammenhang zwischen der detektierten Guanofläche und der Brutpaarzahl besteht. Verdeutlicht wird dies durch den Umstand, dass die Koloniefläche an drei verschiedenen Zeitpunkten ihre Fläche kaum änderte, obwohl sich die Brutpaarzahlen zwischen 1984/85 und 2014/15 mehr als verdreifachten. Demnach können mit Landsat-Aufnahmen keine Veränderungen der Brutpaarzahlen von Cape Bird Nord anhand der Guanofläche detektiert werden, selbst dann nicht, wenn sich die Brutpaarzahlen mehr als verdreifachen. Die Ursache dafür liegt auch hier vermutlich wieder an der Dichteänderung innerhalb der Koloniegrenzen bzw. Nestgruppen.

Ausblick

In den vorangegangenen Abschnitten wurden Möglichkeiten und Grenzen des Monitorings von Pinguinkolonien in der Antarktis mittels Fernerkundungsdaten beschrieben. Die Eignung von aktuellen hoch- und mittelauflösenden Satelliten wurde hinsichtlich räumlicher, zeitlicher, struktureller und skalarer Aspekte untersucht. Dabei zeigte sich eine sehr gute Detektierbarkeit auch von kleinen Kolonien in hochaufgelösten Aufnahmen. Die Eignung von mittelaufgelösten Landsat-8-Aufnahmen ist bei kleinen und strukturell komplexen Kolonien begrenzt. Vorteilhaft ist jedoch deren Möglichkeit zur automatisierten Klassifikation. Für hochaufgelöste Aufnahmen von unterschiedlichen Gebieten gelang dies noch nicht, vor allem aufgrund der geringen spektralen Auflösung. Erfolgversprechend könnten hier die SWIR-Bänder des Satelliten Worldview-3 sein. Potenzial verspricht auch die spektrale Konfiguration neuer mittelösender Sensoren wie Sentinel-2, deren Kanäle denen von Landsat ähnlich sind. Die begonnene verstärkte Entwicklung von Hyperspektralsensoren sollte in solche Betrachtungen ebenfalls einbezogen werden.

Die Unterscheidung der verschiedenen Pinguinarten im Satellitenbild ist bisher noch nicht gelöst. Erste Analysen der Färbung des Guanos deuten an, dass dies ein Klassifizierungsmerkmal sein könnte. Für die Entwicklung einer sicheren Methode bedarf es jedoch weiterer Untersuchungen von in-situ Daten, insbesondere um die großen intrasaisonalen und intrasaisonalen Unterschiede ausschließen zu können. Auch die Ergebnisse der Artunterscheidung aus Satellitenbildern sollten durch Aufnahmen aus weiteren Saisons und von anderen Kolonien als den bereits untersuchten verifiziert werden.

Nachdem in dieser Studie festgestellt wurde, dass sich intersaisonale Veränderungen von Brutpaarzahlen nur bedingt in Veränderungen der Guanoausdehnung widerspiegeln, sollten hier weitere Analysen zu zeitlichen und räumlichen Zusammenhängen von Veränderungen durchgeführt werden. Ebenso müssen Methoden entwickelt werden, die das Signal der Guanoausdehnung in zuverlässige Brutpaarzahlen umsetzen können.

In den untersuchten Gebieten wurden starke Veränderungen der Guanoausdehnung im Saisonverlauf festgestellt. Insbesondere in den von häufiger Bewölkung betroffenen Gebieten ist es kaum möglich, zu einem standardisierten Zeitpunkt Satellitenbilder zu akquirieren. Daher ist es wichtig, die Muster dieser Veränderungen zu erkennen, um dadurch eine zeitlich differenzierte Interpretation des Flächensignals zu ermöglichen. Zu den möglichen Ansätzen gehört hier eine intensive Beschäftigung mit der Brutphänologie der einzelnen Arten und ein verbessertes Verständnis ihrer regionalen- und witterungsabhängigen Variabilität. Diese Informationen wiederum können mit präziseren Daten zur Variabilität des Flächensignals (z.B. aus wiederholten Kartierungen oder UAV-Befliegungen) verschnitten werden.

Zur Validierung von Satellitenbildanalysen sind qualitativ hochwertige Kontrolldaten notwendig. Für die Weiterentwicklung der zur Verfügung stehenden terrestrischen Zählmethoden gibt es eine Reihe von Ansatzpunkten. So muss noch eine verlässliche Methode zur Auszählung der UAV-Orthomosaike der Pinguinkolonien gefunden werden, die das Problem der sich im Nestbereich aufhaltenden nicht brütenden Individuen löst. Hierzu bieten sich Aufnahmen mit hochaufgelösten Thermalsensoren an, wie auch neue Zählverfahren, die nicht auf den Pinguinnestern sondern auf Individuen basieren.

Die Nutzung von UAV-Technologie in der Antarktis nimmt stark zu. Erste systematische Untersuchungen zur Einschätzung des Störungspotenzials für brütende Pinguine wurden im Rahmen dieser Studie durchgeführt. Diese Untersuchungen sollten auf weitere Aspekte von UAV-Überflügen erweitert werden. Dazu gehören noch nicht berücksichtigte Flugsituationen, andere UAV-Modelle und weitere Arten von Pinguinen und anderen Brutvögeln. Die

Aussagekraft der Verhaltensanalysen könnte durch physiologische Methoden (z.B. Messung der Herzschlagraten) qualitativ erweitert werden.

Eine wesentliche Herausforderung für eine überregionale Monitoringstrategie ist es, Datensätze verschiedener zeitlicher und räumlicher Maßstäbe mit unterschiedlichen Qualitäten und aus verschiedenartigsten Quellen miteinander zu verknüpfen. Hier müssen noch Datenbankansätze gefunden werden, die diese Verknüpfung ermöglichen.

Bisherige Studien zur Detektion von Kolonien felsbrütender Pinguine aus Satellitendaten konzentrieren sich vor allem auf Adéliepinguine. Großräumige Studien zu den anderen Pygoscelis-Arten gibt es kaum. Vor allem für Zügelpinguine gibt es noch erhebliche Unsicherheiten über deren Gesamtbestand. Für viele Kolonien gibt es noch keine quantitativen in-situ Daten.

Insgesamt ist festzustellen, dass diese Studie Machbarkeit eines antarktisweiten Monitorings von Pinguinkolonien bestätigt. Es gibt jedoch noch erheblichen Forschungsbedarf, um die notwendige Qualität für die Erlangung aussagekräftiger Ergebnisse zu erreichen und eine Effizienz, die ein regelmäßiges flächendeckendes Monitoring ermöglicht.

3 Introduction

Penguins make up 70 % of bird biomass in the Antarctic (Everson 1977). They are marine predators that gain all of their nutritions from the sea and are, consequently, directly affected by changes in the marine ecosystem. This alone makes penguins particularly important as indicators of alterations in the ecosystem of the Southern Ocean. In addition, hardly any other group of animals in the south polar region is potentially observable from space and, therefore, for which a survey of all the area inhabited can be made, at least in theory. Isolated surveys of individual colonies are available for various regions of the Antarctic. These surveys show clear evidence of changes in the numbers of penguins and changes in the location of their breeding sites. It is assumed that these changes are linked with global climate change and the associated altered availability of food (Ducklow et al. 2007, McClintock et al. 2008, Trivelpiece et al. 2011).

Our investigation concerns satellite detection of the three species of the penguin genus *Pygoscelis*. These three species occur on the Antarctic coast and breed on rock and bare ground instead of ice. Long-term observations of these species indicate differing trends (Birdlife International 2016a, b, c).

The population of Adélie penguins is estimated at about 3.52-4.10 million breeding pairs (Lynch & LaRue 2014, Birdlife International 2016a). This is an increase of about 27 % compared to the numbers from the 1990s (without the inclusion of new colonies discovered since that time) (Woehler 1993, Woehler & Croxall 1997). This species is currently classified as of “least concern” by the IUCN, the lowest degree of threat. The increase in the population of Adélie penguins has occurred predominantly in the East Antarctica and in the southern part of the Antarctic Peninsula (Lyver et al. 2014, Southwell et al. 2015, Sailley et al. 2013). In contrast, the populations in the northern Antarctic Peninsula have been stable or in decline (Lynch et al. 2012, Fraser et al. 1992). Despite the current increases Ainley et al. (2010) have stated that, given an average rise in the tropospheric global temperature of 2°C over pre-industrial levels, conditions for colonies north of 70°S will become more difficult and that colonies north of 67-68°S will completely disappear. Hinke et al. (2017) lent weight to the idea that the northernmost colonies will disappear. Based on modelled nest census data, they predict a continuous decline of numbers in colonies on the northern Antarctic Peninsula until 2041. These alterations are very likely to be influenced by changes in sea ice cover. This is because Adélie penguins need the presence of sea ice in order to reach krill blooms in areas of upwelling water. Ice presence is particularly necessary during the short periods of light during winter. Similarly problematic is the increase in spring snow cover that has been observed, particularly in regions of the Antarctic Peninsula. This snow cover has a negative effect on early-breeding Adélie penguins (Erdmann 2011, McClintock et al. 2008, Ainley et al. 2010). It is difficult, nevertheless, to estimate what the changes in penguin populations will really be. The extent of sea ice is subject to numerous different trends and the origins of these trends are by no means understood (Turner et al. 2015, Mustafa et al. 2016, Stammerjohn & Maksym 2017). The overall effect of climate change on the population of Adélie penguins is also exceedingly complex because different factors affect breeding, feeding, and migration. Climate change will probably have very localized effects on this species (Cimino et al. 2016). Youngflesh et al. 2017 stated, that the influence of climate change on the reproductive cycle did not cause a decrease in Adélie penguin breeding success in terms of the match-mismatch hypothesis of Cushing (1990). They suggest, that mismatches are rather driven by intraseasonal variability of environmental conditions than by climate change.

With up to 90 cm body lengths gentoo penguins are the largest of the genus and the third largest of all extant penguin species. Their distribution if centred around 46-66°S, considerably to the north of the Adélie penguins. Their total numbers are estimated at 387,000 breeding pairs (Lynch & LaRue 2014) which is a clear increase over the 314,000 reported a decade earlier (Wöhler 1993). This rise in numbers has been confirmed by most studies of individual colonies despite considerable annual variation (e.g. Baylis et al. 2013, Trathan et al. 1996, Peter et al. 2008). Only a few populations in the south western Indian Ocean show declining trends (Crawford et al. 2014, Lescroël & Bost 2006). The threat level for the gentoo penguin is thus also judged as of "least concern", the IUCN's lowest category. The causes of the population increase are not yet known but are thought to be related to alterations in the marine food-web (Birdlife International 2016b). McClintock et al. (2010) assume that gentoo penguins, which tend to avoid sea ice, have greater access to feeding areas the more the sea ice retreats. Gentoos also, in contrast to Adélies, have a lower risk of breeding failure because of increased spring snow fall. Their risk is low because they tend to start breeding later than Adélies.

The chinstrap penguin (*Pygoscelis antarctica*), just like the two species previously mentioned, is categorized as of "least concern" by the IUCN. This categorization is based most of all on the enormous size of the total population which is estimated at about 4 million breeding pairs (Convey et al. 1999). Nevertheless, there is considerable uncertainty about the real number of chinstraps because there are no population figures for several colonies (Birdlife International 2016c). There was a clear rise in the numbers of birds in many colonies until the middle of the twentieth century. This rise was predominantly ascribed to reduced competition for food with whales and seals, animals that were severely hunted by humans (del Hoyo et al. 1992). More recently, however, declines in population have been reported from several colonies (e.g. Woehler et al. 2001, Sander et al. 2007a, Sander et al. 2007b, Trivelpiece et al. 2011, Barbosa et al. 2012, Naveen et al. 2012). Lynch et al. (2012) estimated that the total population was then declining at about 1.1±0.8 % per year. However, local trends are very varied. Increases have been recorded at some sites (e.g. Fraser et al 2016) but at others the population appears to be stable (e.g. Lynch et al. 2016). The idea accepted until recently was that chinstrap penguin would increase in numbers because this species prefers to feed in ice-free waters during the winter and therefore would benefit from the reduction in the extent of the pack ice (Fraser et al. 1992, Smith et al. 1999, Ducklow et al. 2007, McClintock et al. 2008). However, this idea is increasingly questioned. Trivelpiece et al. (2011), for example, state that the influence of pack ice on chinstrap penguins is not borne out by field evidence. These authors instead focus on changes in the abundance of krill, the chinstraps most important food source. It is exactly such questions that show the necessity for more exact information and better data on the dynamics of penguin populations in order to determine the functional connections between different changes in the Antarctic ecosystem.

Only an incomplete picture of the real changes underway can be given by the data from the few colonies for which monitoring programmes have been carried out. It would be very difficult, however, to survey more colonies on the ground because of the enormous length of the Antarctic coasts and the difficulty of reaching them and the effort required to work there. These conditions mean that only the use of satellite remote sensing can provide nearly complete coverage of the entire Antarctic coast and provide quantitative data.

The viability of monitoring of this kind has already been demonstrated in a feasibility study (Mustafa et al. 2012). Fretwell et al. (2012) were able to quantify the total population of emperor penguins (*Aptenodytes forsteri*) and Lynch & LaRue (2014) that of Adélie penguins. However, all the methods applied so far have been based on delineating the spreads of guano that penguins deposit in their breeding areas. Direct observations of the birds themselves have are not possible. One of the crucial methodological questions is, therefore, how the signal from the surface can be interpreted quantitatively. It is often impossible to obtain satellite images for the most desirable times. This difficulty arises because of the very frequent cloud cover that particularly affects the Antarctic Peninsula region and the sub-Antarctic islands. The question is therefore not just how to interpret images from the most suitable dates of the breeding period but how to interpret images that were taken on non-optimal dates. A further challenge is to differentiate the different species in unknown colonies or in those where they breed sympatrically. To interpret the satellite images it is vital to be able to compare them with data obtained by direct observations in the field. Good quality quantitative data is, however, available only for a few colonies. The large colonies are particularly poorly represented. These considerations demonstrate that new and improved methods for surveying the numbers of breeding pairs in the field are essential to the development of satellite based monitoring of penguin colonies. Monitoring of this kind must be able to provide accurate and consistent results for the whole Antarctic. Methods must be developed, therefore, that are sufficiently efficient to cope with the huge amounts of data produced by covering the coasts of an entire continent. These methods must simultaneously be internally precise and objective. These methodological challenges give rise to a number of questions that have not yet been answered such as, for example:

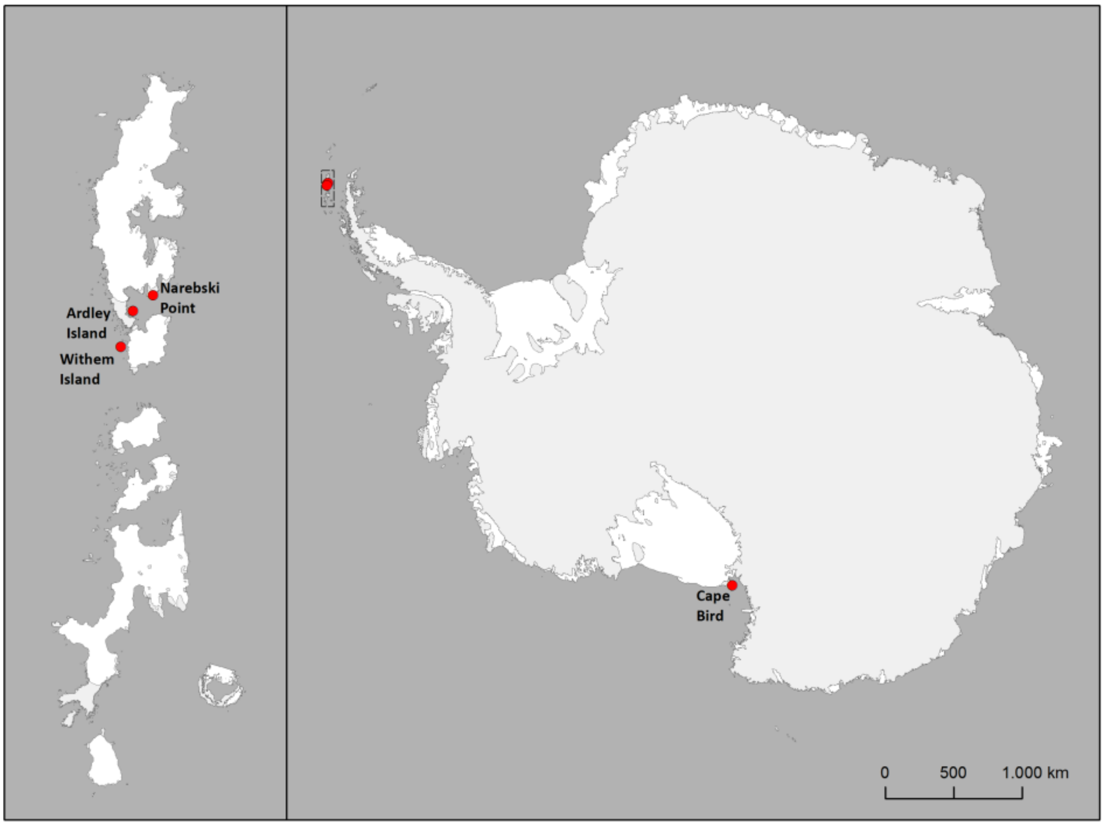
- How can the number of breeding pairs be derived from the area of guano detected?
- How can penguin colonies in a satellite image be definitely assigned to species?
- For which point during the course of the breeding season is it optimal to acquire satellite images?
- What considerations have to be borne in mind in evaluating images that were not taken at this optimal time because of weather conditions?
- How can the enormous amounts of data be evaluated efficiently but nevertheless to a high standard?
- What methodological possibilities exist for increasing the amounts of data available from field surveys that are essential for groundtruthing the remote sensing analyses?

Our study detailed below continues the theme of the feasibility study mentioned above (Mustafa et al. (2012) and is addressed to the above questions with the aim of further developing the existing methods of satellite-based monitoring of Antarctic penguin colonies and of supplementing them with new surveying tools.

4 Test locations

Four test locations were selected for this project. For all four of these locations ground counts of the current penguin populations were available. Three locations were in the maritime Antarctic on King George Island (South Shetland Island). The fourth location was the colony Cape Bird (McMurdo Sound) in continental East Antarctica (Figure 1).

Figure 1: Map of the test locations



Basis data: SCAR Antarctic Digital Database

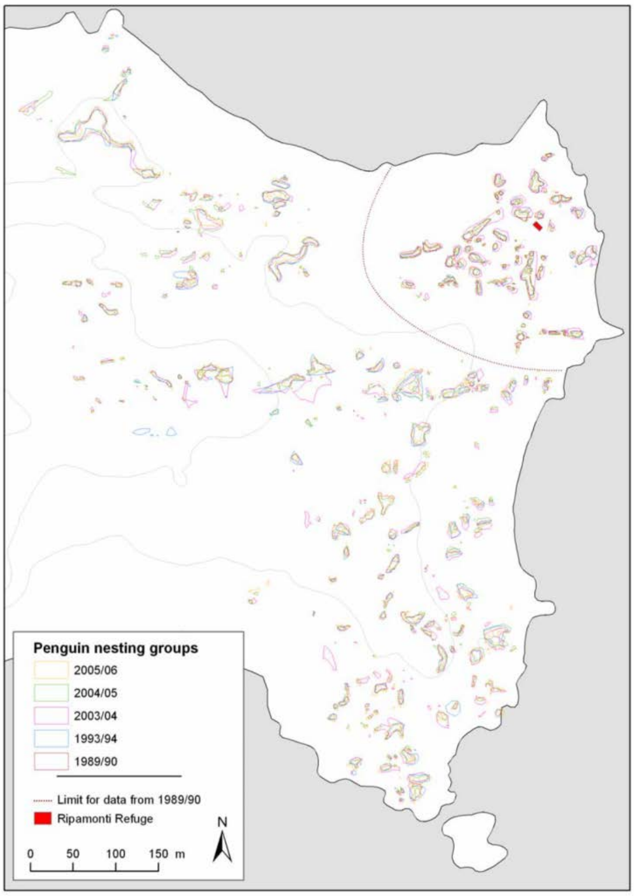
4.1 Ardley Island

Position: 62.2°S/ 58.9°W

Ardley Island lies in Maxwell Bay, in the south east of King George Island, and has an area of 1.1 km^2. It is ~400 m east of the Fildes Peninsula to which it is joined at low tide by a bar (an isthmus). The Fildes Peninsula itself is ~29 km^2 in extent and thus the largest ice-free area of King George Island. The Ardley Island penguins mostly breed on ridges that stand slightly higher than the surrounding area because the snow melts from these early in the spring. They also breed on steep crags further inland. The ground material near the beach and also far inland is a coarse gray-black gravel. The crags are dark in colour. Because of the abundant nutrients near the penguin colonies, the ground is covered by the green alga *Prasiola crispa*. Its colour makes it very noticeable. It tends to blow away, however, after long periods of dryness (and wind). In wet weather it becomes covered over because of guano-runoff and treading in by penguins. It is thus no longer visible in some areas, at least areas near colonies. All three *Pygoscelis* species of penguin breed here next to each other.

Detailed surveys of all penguin breeding colonies on Ardley Island have been carried out by the Polar and Bird Ecology group (Friedrich Schiller University, Jena). These took place in several breeding seasons 2003/04 - 2005/06 (Peter et al. 2008), and 2012/13 (Peter et al. 2013) to 2015/16 (Braun et al. 2017).

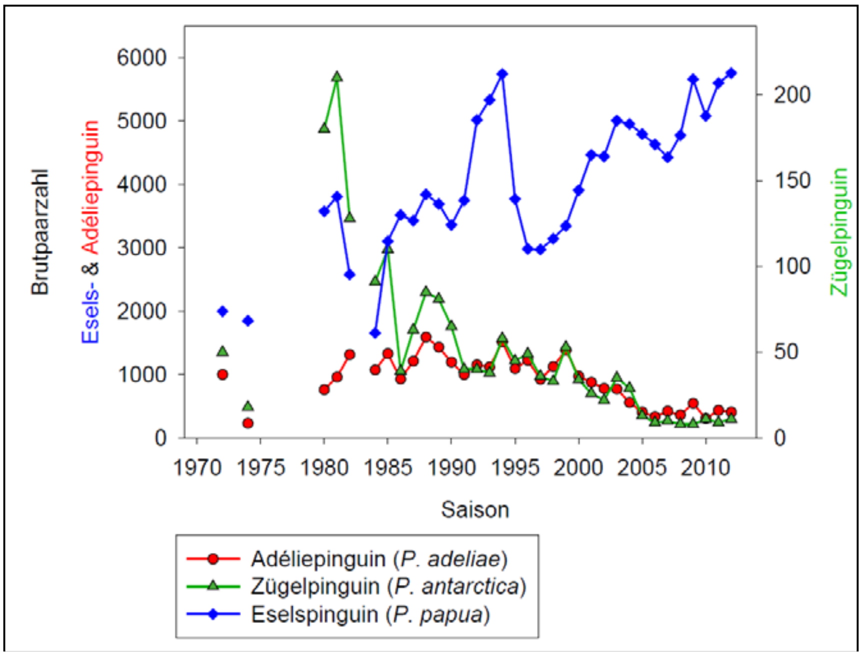
Figure 2: Change in the spatial extent of penguin nest groups on Ardley Island during five different seasons between 1989 and 2006



Peter et al. 2008

The same research group has counted the penguins since the 1970s (Figure 3). These counts have shown a clear rise in the numbers of breeding gentoo penguins (*Pygoscelis papua*) but a considerable fall in the numbers of chinstraps (*P. antarctica*) and Adélies (*P. adeliae*) until ˜10 years ago when they stabilized at low numbers (Peter et al. 2013 and Braun et al. 2017).

Figure 3: Change in breeding pair numbers on Ardley Island



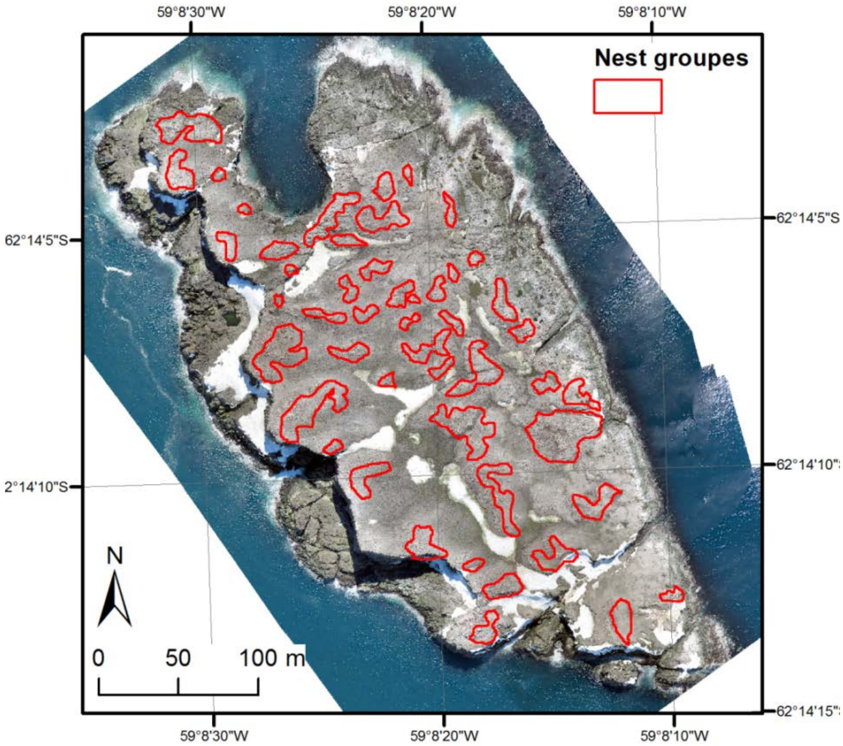
Peter et al. 2013

4.2 Withem Island

Position: 62.2°S/ 59.1°W

Withem Island extends for ~200 x 500 m and lies off the northwest coast of Nelson Island (South Shetland Island). There was, until now, little certain information on the chinstrap penguin colony found there. In February 1987 it was “covered with penguins” (Shuford & Spear 1988). Furthermore, data (Kopp et al. 2010) from the Polar and Bird Ecology group (Friedrich Schiller University, Jena) indicated that this island is an important foraging area for the skuas breeding on the Fildes Peninsula. The clearest evidence of a large penguin population, however, is from publically available satellite photographs. These show that penguins use practically the whole island for breeding (Figure 4). Until the current investigation, however, there was no data on the number of breeding pairs or the species composition.

Figure 4: Chinstrap penguin nest groups on Withem Island (UAV orthomosaic from 29-Dec-2013)



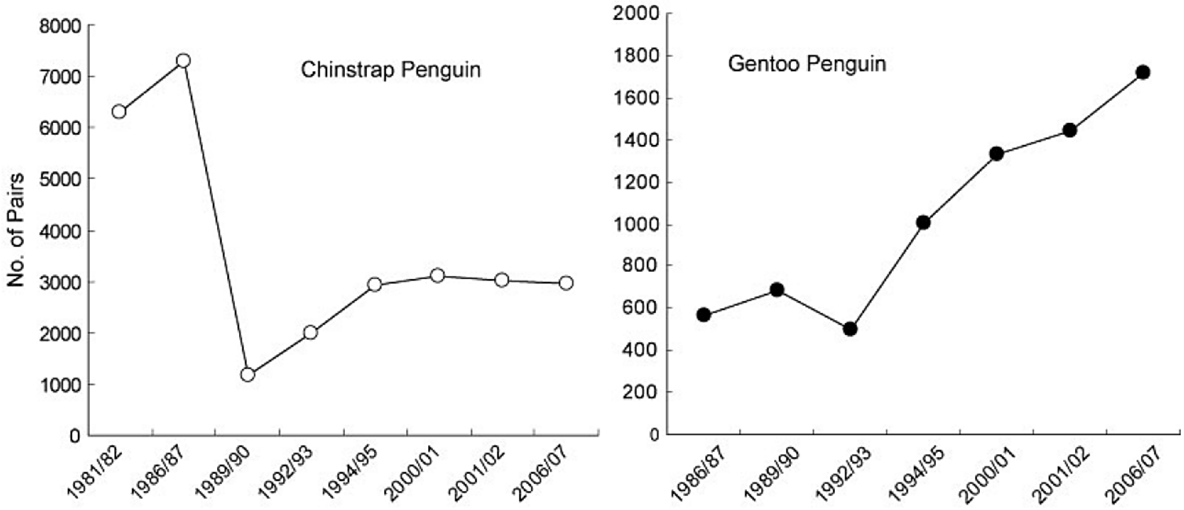
4.3 Narebski Point

Position: 62.2°S/ 58.7°W

The Narebski Point colony is on the south coast of the Barton peninsula (King George Island, South Shetland Islands). In 2009, the area was designated as Antarctic Specially Protected Area (ASPA) No. 171. The justification for this designation specifically mentioned the area's potential as a reference location for monitoring the effects of climate change and the direct effects of human activity (ATCM 2009).

The geological basis of the Barton peninsula consists predominantly of volcaniclastic material of the Sejong formation. This is covered, in parts, by mafic to andesitic lavas. The formation is interpenetrated by dark (mafic) volcanic dykes, particularly on the south coast. One of these dykes produces the highly rugged relief of Narebski Point (Kim et al. 2002).

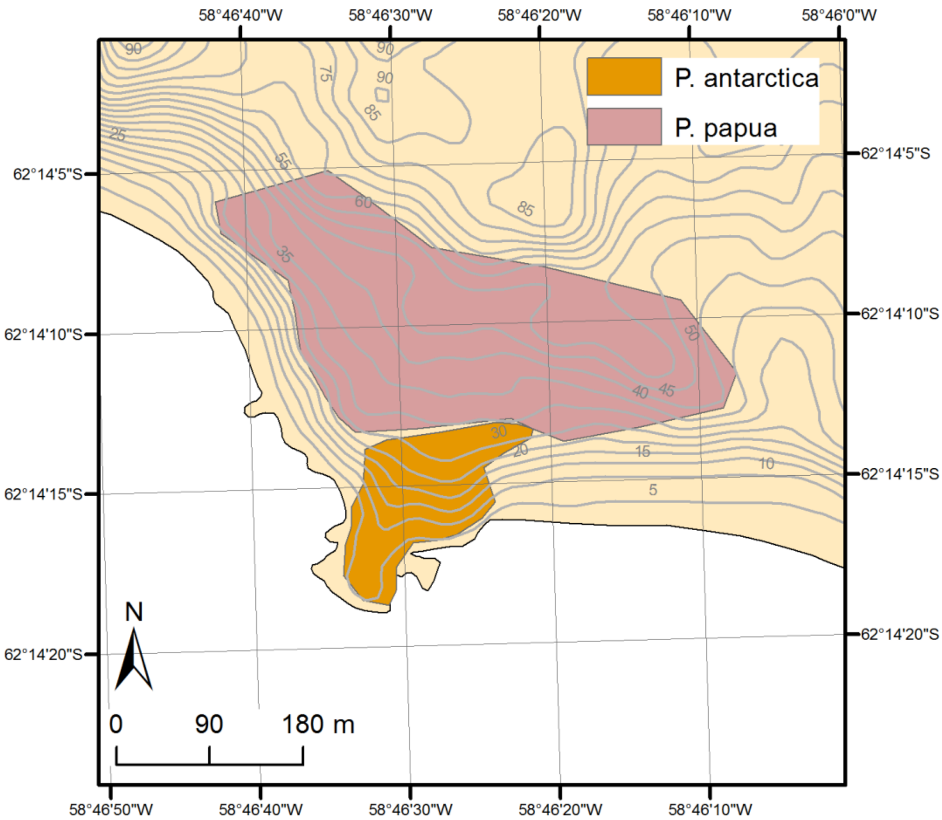
Figure 5: Development of the breeding pair numbers of chinstrap (left) and gentoo penguins (right) at Narebski Point



ATCM 2009

In the past, counts of this colony were carried out predominantly by scientists from the Korean research station King Sejong (Kim 2002; MEV 2007). These figures indicate that the numbers of chinstrap penguins have now stabilised at ~3,000 breeding pairs after a sudden collapse at the end of the 1980s. Over the same period, in contrast, the number of gentoo penguins has increased considerably. The numbers of this species have almost tripled, reaching ~1,800 breeding pairs in the 2006/07 season.

Figure 6: Spatial distribution of gentoo (*P. papua*) and chinstrap (*P. antarctica*) penguins at Narebski Point

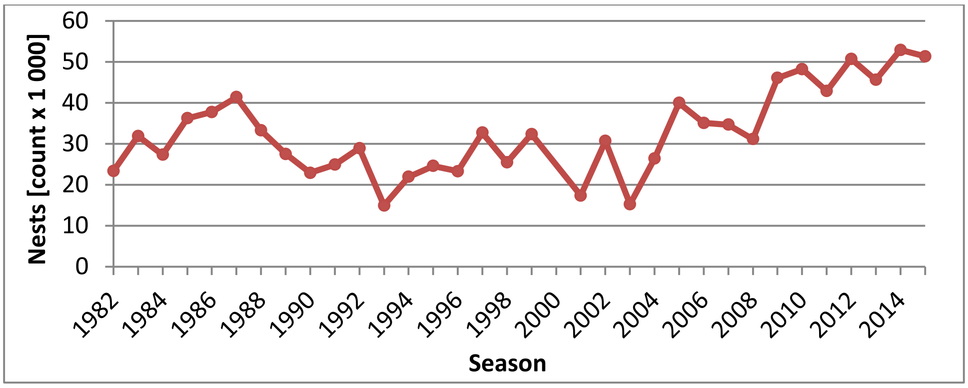


4.4 Cape Bird

Position: 77.2°S/ 166.4°E

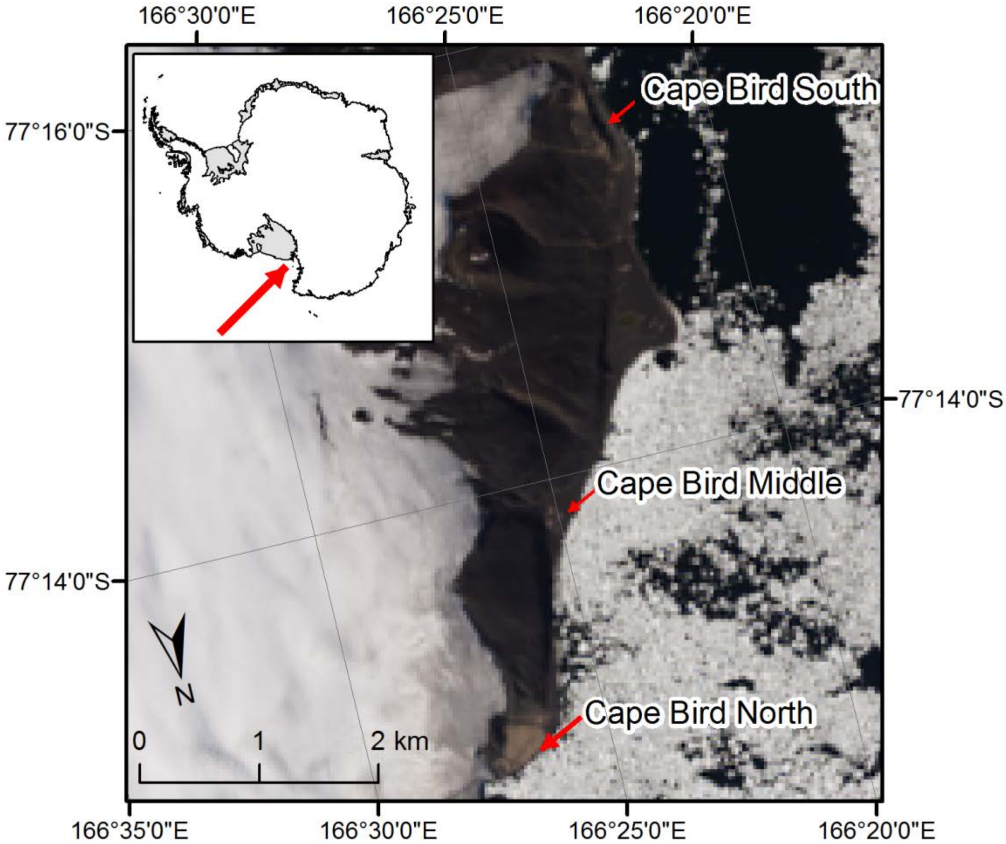
Cape Bird is an ice-free coastal area on the north coast of Ross Island in McMurdo Sound (Ross Sea, East Antarctica (Figure 8). The test location comprises the northern Adélie colony known as Cape Bird North. The area has an arid continental climate and is marked by summer temperatures below freezing. Data from the colony have been obtained from survey flights and the analysis of aerial photographs by the Landcare Research Organisation of New Zealand (Landcare Research 2016). From 1990 onwards there were frequent strong annual fluctuations. Since 2003, however, the number of breeding pairs has tended to increase.

Figure 7: Breeding pair numbers of Adélie pinguins at Cape Bird Noth



Census data: Landcare Research 2016

Figure 8: Position of the Adélie penguin colony on Cape Bird



Landsat-image: USGS/NASA

5 Platforms that are suitable for satellite-based monitoring

5.1 Testing suitable satellite platforms

In detecting penguins the properties required of the satellite data depend on the specific aims of the project. Each aim demands data with different properties. In order to detect all the penguin colonies in the Antarctic the satellite data required must have two preeminent qualities. First, because huge amounts of data are needed, the data must be acquirable at a reasonable price. And second, it should cover the entire area. For detection, therefore, the best data are provided by intermediate resolution Landsat 7 (ETM+) images (Mustafa et al. 2012; Fretwell et al. 2012; Schwaller et al. 2013). When, in contrast, the aim is accurately determine colony sizes or to detect small-scale changes, the satellite data must have a very high resolution in space and in time. For this aim, the research of Mustafa et al. (2012), Lynch et al. (2012) and Lynch & LaRue (2014) showed that high resolution (submeter) images such as Quickbird and Worldview 2 give the best results.

The following section describes and updates the availability and applicability of satellite images for this project and compares them to those in the preparatory study (Mustafa et al. 2012). An overview of all of the suitable satellites is given in Table 1.

Table 1: Overview of the recent available high resolution satellites which acquire images from Antarctica as well as medium resolution Landsat satellites for comparison purposes (status in August 2016)

Sensor	Ground sample distance at nadir [m]		Coverage [km]	Launch [year]	Provider
	Pan	Multispectral			
Worldview 3 (VNIR)	0.31	1.24 / 3.7	10.5 x 10.5	2014	DigitalGlobe
Worldview 3 (SWIR)		7.5	10.5 x 10.5	2014	DigitalGlobe
Worldview 2	0.46	1.84	16 x 16	2009	DigitalGlobe
GeoEye 1	0.41	1.65	15 x 15	2008	DigitalGlobe
Quickbird*	0.6	2.4	17 x 17	2002	DigitalGlobe
Pléiades	0.7	2.7	20 x 20	2011/12	AstriumGeo
Ikonos*	1	4	11 x 11	1999	DigitalGlobe
Landsat 7 (ETM+)*	15	30	185 x 185	1999	USGS
Landsat 8 (OLI)	15	30	185 x 185	2013	USGS

* since 2015 an acquisition of new images for Antarctica is not possible

5.1.1 Intermediate resolution sensors – Landsat 8

Landsat 8 images covering the whole of the Antarctic have been taken since the end of 2013. These images are available free via the USGS. The Landsat 8 satellite is the successor to Landsat 7. It replaces its predecessor for Antarctica because Landsat 7 is not imaging the Antarctic anymore. The properties of the ESA satellite Sentinel 2 also allow it to produce suitable data. However, this satellite did not take images of the whole Antarctic during the project period.

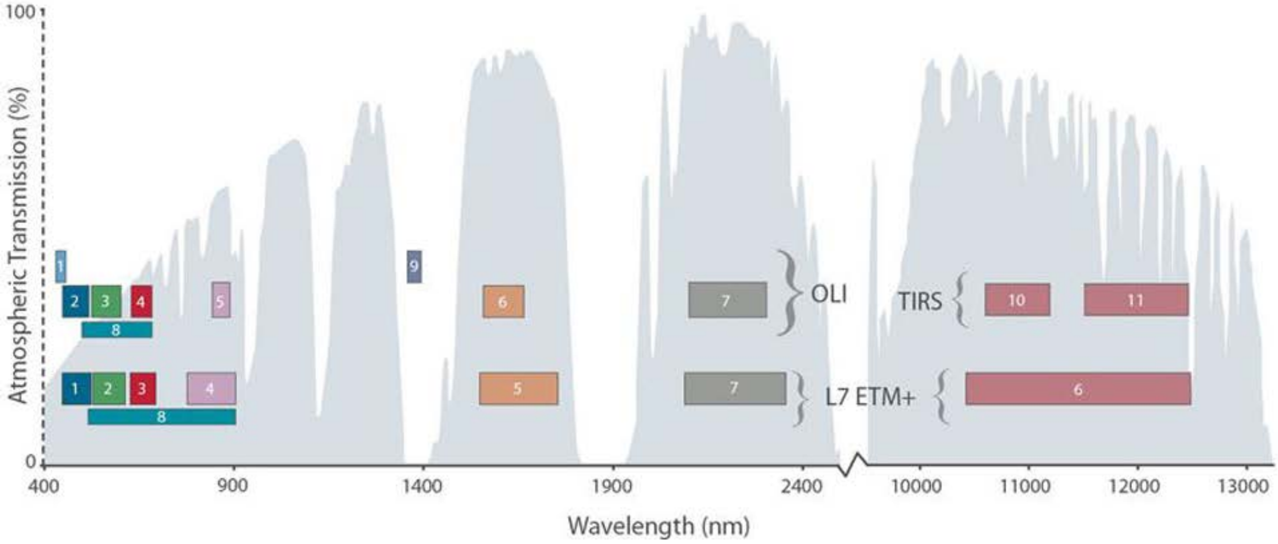
5.1.1.1 Spatial resolution

The spatial resolution of the Operational Land Imager (OLI) Sensors of Landsat 8 is 15 m in the panchromatic channel (Pan-channel) as it was in Landsat 7. Likewise, it is 30 m for the visible spectrum channels, near infrared (NIR) and short wave infrared (SWIR). In the thermal infrared (TIR) the Thermal Infrared Sensors (TIRS) now give a resolution of 100 m instead of the 60m from Landsat 7 (Knight & Kvaran 2014).

5.1.1.2 Spectral resolution

Landsat 8 covers two spectral bands that were not covered by Landsat 7. Furthermore, Landsat 8 divides the thermal infrared between two channels. In addition, Landsat 8 covers two new channels "Coastal Aerosol" and "Cirrus" (bands 1 and 9, Figure 9). Coastal Aerosol is for imaging shallow coastal waters and tracking fine particles like dust and smoke whereas Cirrus is for detecting cirrus clouds. A further alteration affects the spectral range of the pan-channel. The pan-channel now covers only the visible spectrum (RGB) and not the visible and near infrared as in Landsat 7. This is important because only the channels covered by the pan-channel can be spectrally sharpened (pansharpening). Pansharpening involves merging into a single image the spectral characteristics of the multispectral channels and spatial information from the pan-channel. In consequence, the merged image possesses high spectral and spatial resolution (Vijayaraj et al. 2004). Because of the change in the pan-channel coverage, it is no longer possible to sharpen Landsat 8's NIR channel in order, for example, to calculate the NDVI (Normalized Differenced Vegetation Index) at a spatial resolution of 15 m.

Figure 9: Comparison of the spectral bands for Landsat 7 with those of the ETM+ sensor (below) and for Landsat 8 with those of the OLI and TIRS sensors (above)



USGS 2013

5.1.1.3 Suitability

As far as the spectral properties are concerned, the Landsat 8 data is just as suitable for detecting penguin colonies as was the Landsat 7 data. It's expected that the new bands available in Landsat 8, (Coastal Aerosol and Cirrus) provide no additional direct information for the questions addressed in this study. There is likewise no effect of the better spectral coverage and poorer spatial resolution of the thermal infrared. This is because this band is not used for detection because of its coarse spatial resolution. There could be, however, a decline in the ability to detect small colonies because, currently, it is no longer possible to pansharpen the near and short wave infrared bands.

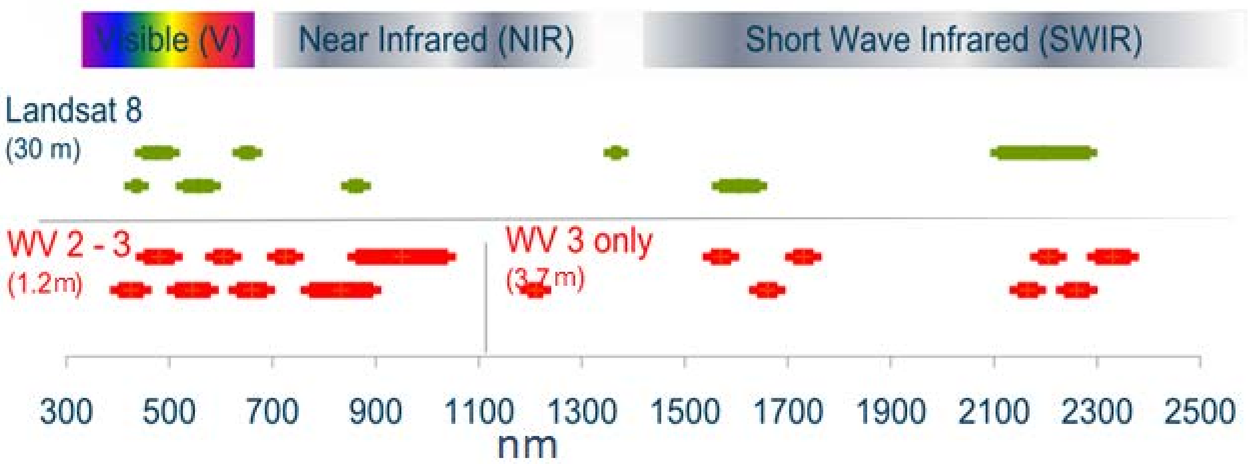
The spatial and temporal coverage of Landsat 8 is, however, clearly better than that of Landsat 7. Since 2003, Landsat 7 has suffered from a technical defect, the Scan Line Corrector Failure (NASA 2011) and since then has not been scanning correctly or completely. Landsat 8, so far, scans without any technical limitations.

5.1.2 High resolution sensors

A newer high-resolution satellite than Worldview 2 or Quickbird is Worldview 3, started in August 2014. This is unique in so far as has eight relatively high resolution SWIR bands (spatial resolution 3.7 m) in addition to eight high resolution VNIR bands in the visual spectrum and the near infrared (spatial resolution 1.24 m). These eight SWIR bands cover much the same region as does Landsat 8 (Figure 10). The disadvantages are, however, that the SWIR bands are at a lower resolution than the VNIR bands and cost more to acquire.

The spatial resolution is 0.31 m at nadir (vertically below the satellite) which is much higher than previous satellites. This high resolution nevertheless does not improve detection very much however as even such a resolution is insufficient for identifying individual birds or nests reliably. Guano covered areas are already well detected with the previous 0.5 m data. In addition, the 0.31 m resolution data is around 30 % more expensive than the 0.5 m resolution data (according to the E-geos 2016 price list of 20.3.2016).

Figure 10: Comparison of the spectral bands for Landsat 8, Worldview 2 and Worldview 3



modified from Marchisio (2014)

5.1.3 Hyperspectral data

No data from hyperspectral satellites was available for the test areas during the life time of the project. Start times that were planned for during the project were postponed to later dates. In consequence, it was not possible to include these data in our evaluation. In consequence the following old hyperspectral data should be examined for its utility.

There are several launch dates of hyperspectral satellites planned between now and 2020. However, there is little dependable information available on the exact status of these projects. An exception is the EnMAP (Environmental Mapping and Analysis Program) satellite with the HSI hyperspectral sensor. EnMap is in its final preparation phase. The launch is now planned, after several postponements, for 2018 (DLR 2016).

5.1.3.1 Current satellite platforms with hyperspectral sensors

To test the possibilities of using satellite-based hyperspectral data to detect penguins, we looked for archived images from experimental satellites with hyperspectral sensors that covered areas of the Antarctic containing penguin colonies. There are no images of the Antractic from the ESA satellite Proba 1 which carries the hyperspectral sensor CHRIS (Compact High Resolution Imaging Spectrometer) (Barnsley et al. 2004). There are individual images of the Antarctic from the NASA satellite Earth Observing 1 (EO-1) which carries the Hyperion hyperspectral sensor. However, these images are discontinuous and have been taken since 2001. The ground resolution of these images is 30 m but the swath width is relatively narrow at 7.5 km. Hyperion has 220 spectral bands each of 10 nm band width in regions 400-1000 nm (VNIR) and 900-2500 nm (SWIR) (Barry et al. 2002).

5.1.3.2 Analysis

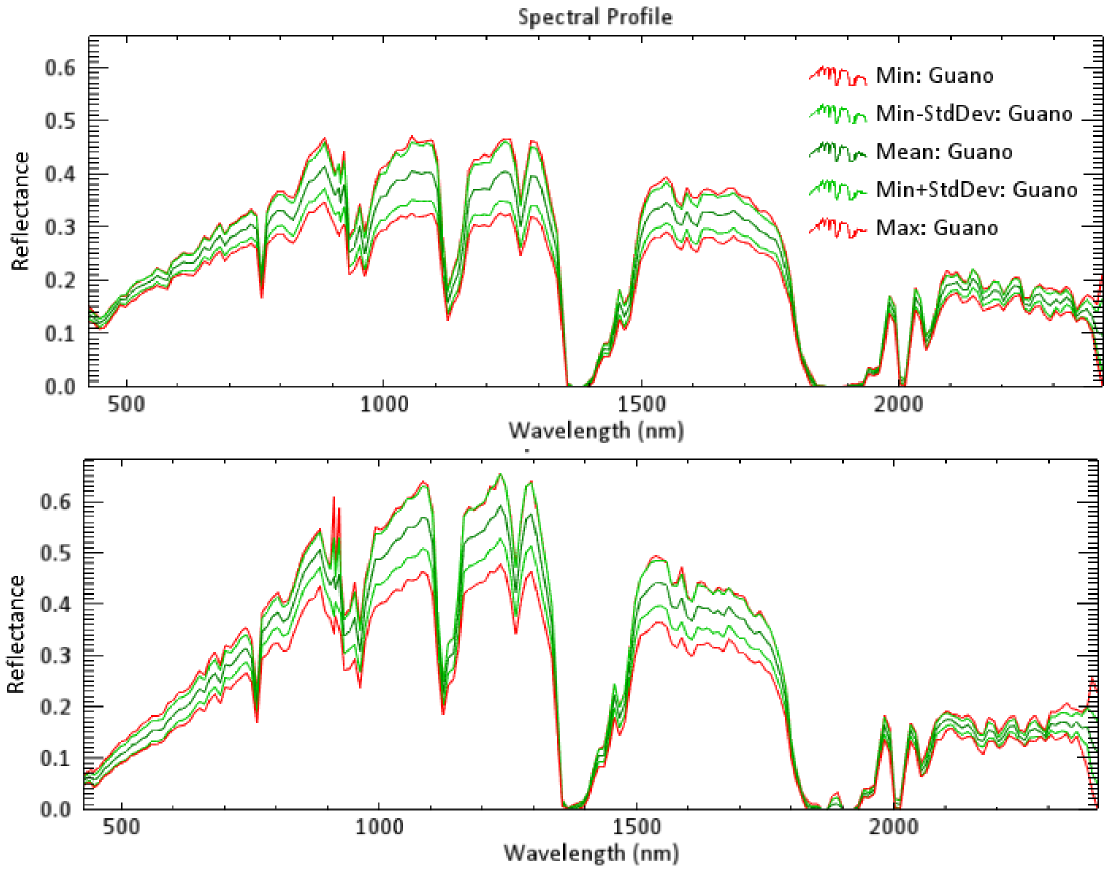
We were unable to find any suitable images of the test locations used in this study for evaluation. Therefore, we analysed EO 1 images of two other Adélie penguin colonies (Table 2). The images were atmosphere corrected in order to reduce the effects of the atmosphere on the various spectral ranges. Applying this preparatory step makes it possible to compare the spectral signature of guano in images taken at different places and different times. The ENVI Spectral Angle Mapper (SAM) was applied as the classification algorithm. This algorithm was specifically developed for the analysis of hyperspectral data. The spectral signature of guano

(Figure 11) was determined from test areas. This signature was then used to classify as guano covered or not. This method proved capable of detecting guano. However, a quantitative estimate was not possible because ground truth data was not available. In addition, we found it possible to classify test location 2 using the guano signature from location 1 and the reverse. It was not possible, nevertheless, to test whether species can be determined from the Hyperion images because the on-site measurements do not exist.

Table 2: Overview of the hyperspectral images selected

	Image from test site 1	Image from test site 2
Acquisition date	23-Oct-2010	30-Dec-2011
Geographic coordinates	74°54'14.70"S; 163°44'7.13"E	67°33'20.05"S; 62°19'35.56"E
Image ID	E01H0621132010357110KF	E01H1361072011364110KF

Figure 11: Comparison of the spectral signatures of guano from test location 1 (above) and 2 (below)



5.2 Obtaining suitable satellite images

5.2.1 High resolution satellites

In this project, in order to detect small scale changes, we used the satellite data provided by DigitalGlobe. Since the fusion of DigitalGlobe with GeoEye in 2013, this data is offered together with images from the GeoEye 1 and Ikonos satellites. In comparison to with the data offered by Astrium the DigitalGlobe data has the following advantages:

- DigitalGlobe supports high resolution satellites such as Worldview 3 with 0.31 m. The Atrium operated Pléiades provides a maximum resolution of only 0.70 m (although it is sold on the basis of a 0.50 m ground resolution; Astrium GEO-Information Services 2012).
- It's possible to obtain coverage by several satellites (a satellite constellation) thus increasing the probability of obtaining suitable (i.e. cloud free) images.

The images ordered were the high resolution satellite images from the DigitalGlobe European partner e-GEOS. These images had been captured by several different satellites including GeoEye, Quickbird, Worldview 2 and Worldview 3. New images were ordered as the four channel bundle with four multispectral bands (blue, green, red and near infrared) and the pan channel. We did not select the eight band bundle with four additional spectral bands in the NIR region, because the satellite constellation would then have consisted of only two satellites. This would have substantially reduced the probability of obtaining successful images without, despite the 4 extra bands, greatly improving the detection of guano spreads (Mustafa et al. 2012). Images from the archive were purchased as the eight band bundle whenever possible. The cost of this option for archive images is only slightly more expensive and the 8 bands allow examples of species differentiation to be carried out. A total of 10 packets of high resolution images were successfully selected and acquired (Table 3). In consequence, it was possible to acquire high resolution satellite images of all the test sites although not always for ideal times because of the frequently occurring cloud cover. It was never possible, for example, in any season, to obtain images of Ardley Island for December.

Table 3: Aquired high resolution satellite images

Date of acquisition	Satellite	Coverd test location	Ground sample distance [cm]	Spectral bands [number]
06&07-Jan-2014	Worldview 2	Cape Bird	50	4
16-Jan-2014	Worldview 2	Ardley Is, Narebski Point	50	4
11-Oct-2014	Worldview 3	Ardley Is, Narebski Point	40	8
30-Nov-2014	Worldview 3	Ardley Is, Narebski Point	50	4
27-Dec-2014	Worldview 2	Cape Bird	50	4
20-Jan-2015	Worldview 2	Ardley Is	50	8
03-Feb-2015	Worldview 2	Ardley Is, Narebski Point	50	8
05-Dec-2015	Worldview 2	Cape Bird	50	4
02-Jan-2016	GeoEye	Ardley Is, Narebski Point	50	4
18-Jan-2016	GeoEye	Ardley Is, Narebski Point	50	4
12-Feb-2016	GeoEye	Ardley Is, Narebski Point	50	4

5.2.2 Medium resolution satellites

As well as the high resolution satellite images, we also acquired the free Landsat 8 images to use for the intra- and inter-seasonal analysis of the test locations. With these images, however, it is not possible to choose an acquisition data of the image in advance because Landsat 8 images every point in the Antarctic at fixed intervals. The frequency with which a point is imaged increases with the nearness of the point to the South Pole. Parts of the continental Antarctic such as Cape Bird are covered every 1-3 days. The test locations on the northerly Antarctic Peninsula, in contrast, are covered only every 2-7 days. Table 4 shows the dates for the images acquired for each of the test locations. No images were acquired for Ardley Island or Narebski Point because these colonies are too small to be detected with the 30 m resolution Landsat 8 images.

Table 4: Dates of the Landsat 8 images for the intra-seasonal investigation at Cape Bird

Date of acquisition 2013/14	Date of acquisition 2014/15	Date of acquisition 2015/16
29-Oct-2013	23-Sep-2014	12-Oct-2015
14-Nov-2013	14-Oct-2014	26-Oct-2015
30-Nov-2013	30-Oct-2014	11-Nov-2015
11-Dec-2013	15-Nov-2014	27-Nov-2015
03-Jan-2014	01-Dec-2014	13-Dec-2015
11-Feb-2014	17-Dec-2014	29-Dec-2015
13-Mar-2014	28-Dec-2014	14-Jan-2016
	22-Jan-2015	23-Jan-2016
	31-Jan-2015	01-Feb-2016
	16-Feb-2015	19-Feb-2016
	18-Mar-2015	22-Feb-2016

6 Trial and further development of various methods for analysing satellite images

In addition to the methods (Maximum Likelihood Classification, Ratio Approach and subpixel analysis) already investigated in the pilot study (Mustafa et al. 2012), and the methods (Landsat retrieval methods) developed and successfully applied by Schwaller et al. (2013) or Lynch & Schwaller (2014), in this project new classification procedures were tested as to their suitability for detecting areas covered in guano. To this end the methods were tested on both high-resolution and medium-resolution images. As test areas Cape Bird was chosen for continental Antarctica and Ardley Island for the maritime Antarctic. To be able to evaluate the accuracy of the classification objectively, the commission error, the omission error and the cappa coefficient of each classification were determined with the help of ground truth data. The commission error (the lower the better) represents the proportion of pixels erroneously assigned to a different class. The omission error (the lower the better) represents the percentage of unrecognised or missing pixels of a class, and the cappa coefficient (the higher the better) shows how closely the classification matches the ground truth data (Congalton & Green 2009). Therefore, a high commission error means that guano is classified in places where there is none. This would clearly be a significantly greater problem for automatic Antarctic-wide guano detection than a high omission error, which would mean that not all areas covered in guano would be found. In order to arrive at a better assessment of the accuracy of the classification investigated, it was also compared with the Maximum Likelihood Classification investigated in the pilot study, which was also used by Waluda et al. (2014), among others. Prior to classification, the grey scales (digital numbers) of the images were converted into Top of Atmosphere Reflectance and spectrally sharpened using the Nearest Neighbor Diffusion-Based Pan-Sharpening algorithm (Sun et al. 2014), in order to achieve a resolution of 50 cm for the images in the multispectral channels as well. All classifications were carried out using the ENVI image processing software.

6.1 Types of classification studied

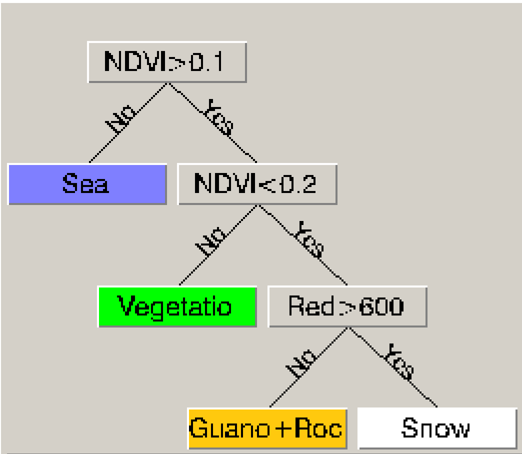
6.1.1 Cluster analysis (CA)

This study looks at two classification methods, the K-Means Classification and the ISODATA classification, both of which are based on a cluster analysis (*cf.* Everitt et al. 2011). In this analysis the pixels are classified only on the basis of statistical characteristics, without having to integrate training areas determined beforehand by the user. An iterative process is carried out, in which a previously determined number of classes is produced in the result (*cf.* Tou & Gonzalez 1977). The analyses showed that with this method it was not possible to separate guano from its surroundings. It was therefore not possible to determine the accuracy of the classification.

6.1.2 Decision Tree (DT)

In classification with decision trees, each pixel is assigned to a class in a multi-stage process through a series of decisions, mostly based on threshold values. In each decision, the pixels are assigned to one of two classes. From the new classes thus obtained, additional branches can then be created through further decisions, creating a tree structure. The advantage of the method is that with each decision other, or additional, input data can be used, such as digital terrain models, climate data and additional satellite images. Another advantage is this method's short processing time, compared with the other classification methods used. Figure 12 shows a simple decision tree, with which, with the help of threshold values in the NDVI and the red spectral channel, ocean, vegetation and snow can be distinguished from rock and guano. The attempts to distinguish between guano and rock using the available data were not satisfactory, and for this reason the accuracy of the classification was not analysed. Nevertheless, it can be helpful to use decision trees to make a preselection of the images to be classified (e.g. separation into ocean, vegetation, snow or just classifying areas that are located a particular distance from the coast), to be followed, in a second step, by a more time-consuming classification in the remaining class. This kind of method is used, for example, in a method developed by Burton-Johnson et al. (2016) for automatically distinguishing between rock, snow, clouds and sea.

Figure 12: Example of a simple decision tree with four result classes in the ENVI image processing software. With the help of the NDVI and the red channel, sea, vegetation and snow, for example, can be distinguished from guano and rocks



6.1.3 Neuronal networks (NN)

The structure of neuronal networks (NN) was derived conceptually from neuronal networks in the human brain. Thus, the artificial neuronal networks consist of a multitude of closely interlinked units (neurons). The advantage of NN in classification is that non-linear connections can be found (Rey & Wender 2010). In the practical application, for classification using NN only training areas are required in addition to the satellite data, as with the Maximum Likelihood Classification investigated in the pilot study.

6.1.4 Spectral Angle Mapper Classification (SAM)

Spectral Angle Mapper Classification (SAM) belongs to the spectral classification methods, in which the reference spectra are compared with the pixel values of the image using an n-dimensional angle. The advantage of this method is that it does not react sensitively to changes in lighting. Reference spectra are needed for the classification and these can either be obtained directly from the image by means of training areas or taken from external spectral libraries (Kruse et al. 1993). There are freely accessible spectral libraries at the U.S. Geological Survey, for example (see USGS 2016).

6.1.5 Adaptive Coherence Estimator Classification (ACE)

In a similar way to the SAM classification, the Adaptive Coherence Estimator Classification (ACE) is invariant to relative spectral changes such as differences in brightness (Kraut et al. 2005). With this method, in contrast to the Maximum Likelihood Classification, not all the pure spectral signatures of an object class (such as guano, snow or rock) that are present in the scene have to be known. Therefore, only the spectral signature obtained from a training area or from a spectral library is necessary for a classification. As with SAM, a threshold value also has to be set manually in the resulting image. This value subsequently determines whether or not a pixel belongs to the desired class. This often causes the following problem: if too low a threshold value is defined, the omission error is low, but the commission error is high. The opposite occurs if too high a threshold value is defined. In order to find the ideal threshold value, a Receiver Operating Characteristic Curve (ROC) (Bradley 1997) can be calculated, with which diverse threshold values can be compared with ground truth information.

6.2 High-resolution satellites

The various classification methods were tested on three high-resolution satellite images (Table 5). For maritime Antarctica two images of the Ardley Island research area were chosen, one in the middle and one at the end of the season. An image of the Cape Bird North research area was chosen for continental Antarctica.

Table 5: High-resolution satellite images for testing the different classification methods

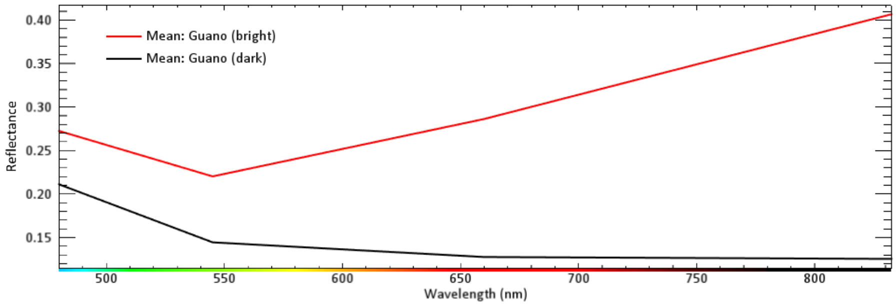
Research area	Image date	Sensor
Ardley Island	30-Nov-2014	Worldview 3
Ardley Island	20-Jan-2015	Worldview 2
Cape Bird	06-Jan-21014	Worldview 2

To compare the classifications in the best way possible, the same training areas or spectral signatures were used for all the methods. For the ACE classification, only a training area with light-coloured guano was chosen. With the other classifications, training areas of the surrounding object classes (dark guano, snow, sea, rock and vegetation) were additionally used. The ground truth for all images was the totality of the manually derived areas of guano. The false colour combination of the 4-3-2 (NIR-Red-Green) wavelengths, as well as ‘Photographic Stretch’ contrast stretching in ENVI, proved to be helpful in highlighting the guano especially clearly for manual interpretation, in particular so as to be able to distinguish guano from rock. In defining the guano areas, the problem arose that the transition from the guano-covered area to the surrounding area, particularly late in the season, is gradual, so that the borderline is very subjective. For this reason, the classification accuracy established with this ground truth data was only used as a measurement for comparing the classifications with one another, and not necessarily to indicate the absolute accuracy of the guano detection. For the image of Ardley Island of 30-Nov-2014 there was also data available from mapping of the nest groups carried out on the ground using GPS at the time when the image was obtained (28.-30-Nov-2014) (see section 0).

6.2.1 Classes of guano

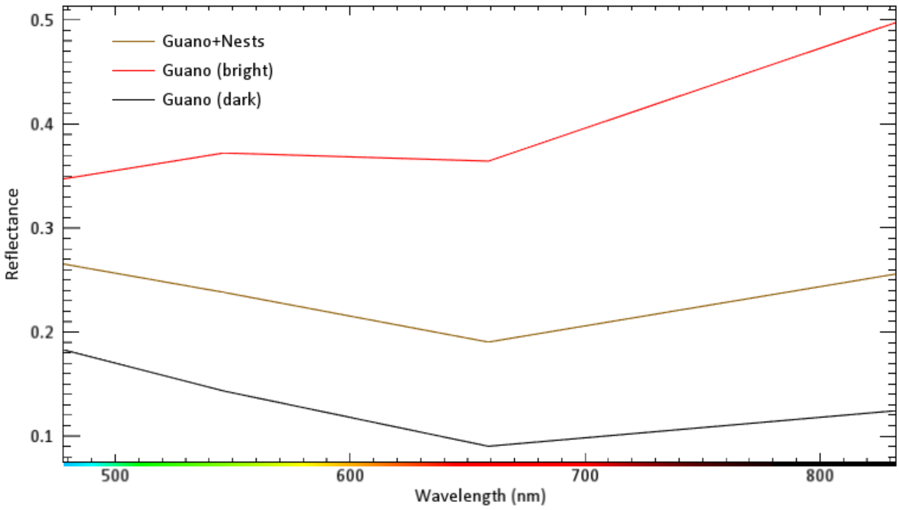
The analysis showed that there are several classes of guano in the satellite images. It was possible to distinguish between light and dark guano. Light guano shows strong reflection in red and near infrared, while the dark guano reflects only very little or not at all in these wavelengths (Figure 13 and Figure 14).

Figure 13: The spectral profile of light and dark guano from two areas of Ardley Island used for the classifications



Under optimum conditions it is also possible, in the case of light-coloured guano in particular, to differentiate between guano with nests and guano without nests. In the image the two types can be distinguished by their texture. While the guano-covered nesting groups are not at all homogeneous, the nest-free areas look very homogeneous, although this can only be recognised on even ground. On Cape Bird this is almost always the case, in contrast to overwhelmingly rocky Ardley Island. On average, the guano areas with nest groups appear spectrally somewhat darker than the light guano (Figure 14).

Figure 14: The spectral profiles of light (with and without nest groups) and dark guano on Cape Bird used for the classifications



The different classes of guano are relevant to the classifications, because the light guano stands out well against the surrounding area due to its high NIR reflection, while the dark guano in the spectral range studied is barely distinguishable from the surrounding rock.

6.2.2 Maritime Antarctica - Ardley Island

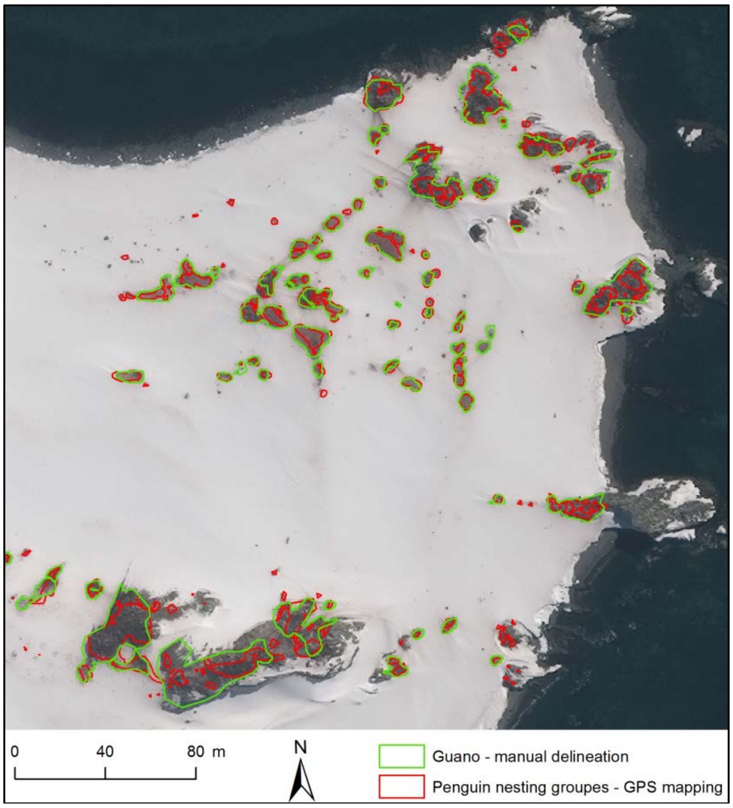
For Ardley Island it was possible to compare the classifications of all the guano in the Worldview 3 image of 30-Nov-2014 with the nest groups mapped on the ground at the time that the image was taken (section 0 and Table 6). It is noticeable that all the classification methods fail to detect the nest groups completely, although the training areas are derived from an area with nest groups. The spectral signature of the guano training area used is shown in

Figure 13. If we look at the results in detail (Figure 15), two things become clear. Firstly, the areas with nest groups are – as expected – significantly smaller than the areas of guano (approx. 50 %). Secondly, not all nest groups (approx. 17 %) in the image studied are recognisably covered with guano and therefore identifiable as such. It is therefore not possible to identify exactly the nest groups in the Worldview 3 image of Ardley Island of 30-Nov-2014.

Table 6: Accuracy of the classifications of the Worldview 3 image of Ardley Island (30-Nov-2014) in relation to nest groups mapped on the ground

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
manual delineation	48.32	17.77	0.621
ACE	63.65	19.07	0.482
ML	58.12	8.94	0.557
NN	83.03	61.28	0.205
SAM	79.41	81.04	0.175

Figure 15: Comparison between the manual delimitation of the guano (green) and the GPS mapping (red) based on a section of a Worldview 3 image of north-eastern Ardley Island. Both the image and the GPS mapping were produced on 30-Nov-2014



Satellite image ©DigitalGlobe

If the guano classifications relating to the manually delimited guano areas are compared with each other (Table 7), it can be seen that the Maximum Likelihood (ML) and the Adaptive Coherence Estimator (ACE) classifications provide the best results, and the ML classification with a cappa coefficient is significantly more accurate still. The results in Figure 16 show clearly that the classification with neuronal networks (NN) and the Spectral Angle Mapper (SAM) classification have a huge classification error in the beach area on the one hand, and on the other hand they fail to recognise more than 50 % of the guano-covered areas as such. The results of the Worldview 2 image from Ardley Island of 20-Jan-2015, which was late in the season and therefore virtually snow-free, are similar, except that this time the ACE classification is marginally more accurate (Table 8).

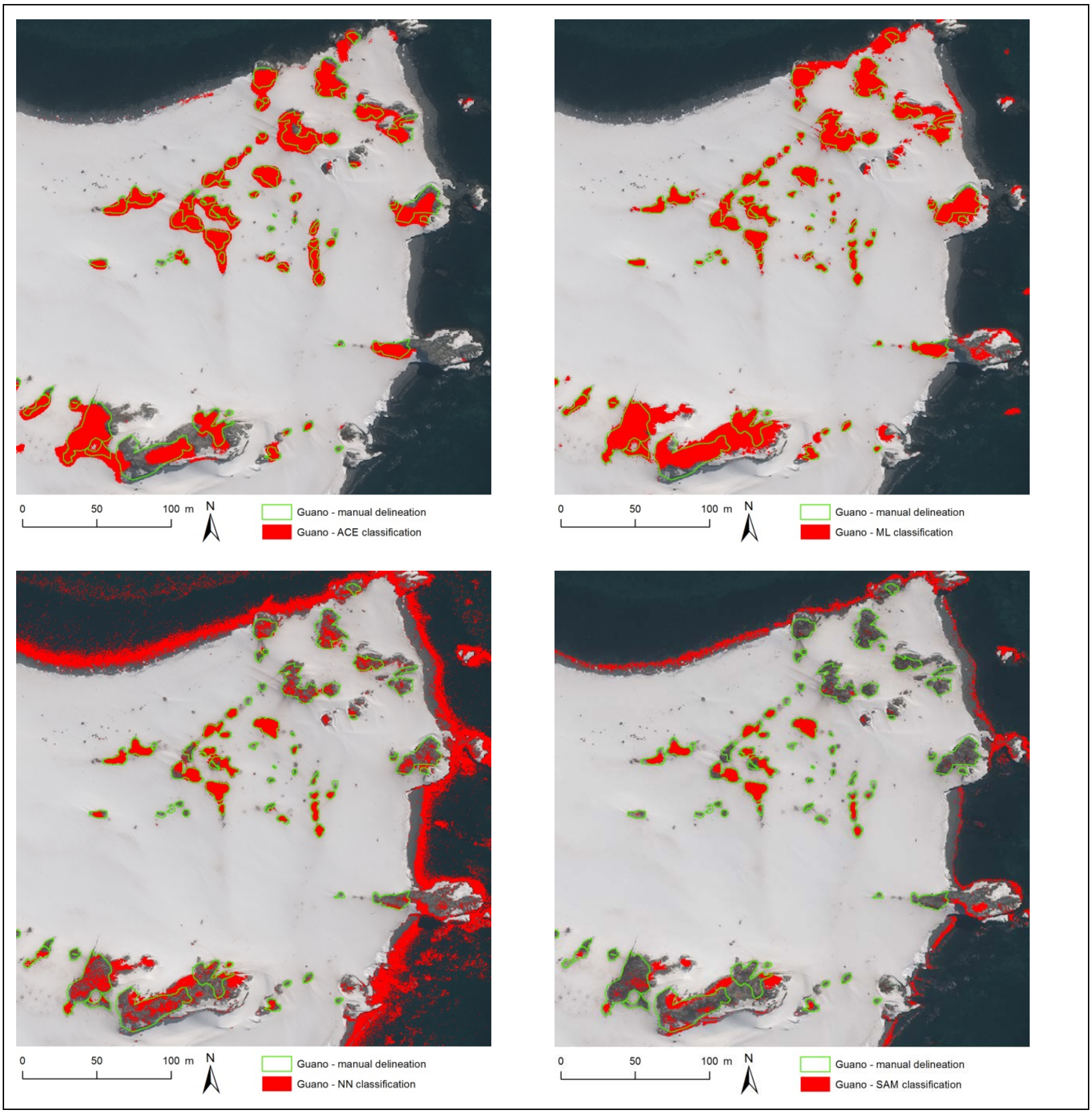
Table 7: Accuracy of the classifications of the Worldview 3 image from Ardley Island of 30-Nov-2014 in relation to the manually delimited areas of guano

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
ACE	42.76	22.89	0.638
ML	31.57	9.99	0.765
NN	72.33	61.81	0.283
SAM	66.40	81.27	0.2151

Table 8: Accuracy of the classifications of the Worldview 2 image from Ardley Island of 20-Jan-2015 in relation to the manually delimited areas of guano

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
ACE	32.63	24.70	0.671
ML	45.09	18.04	0.603
NN	68.25	47.15	0.296
SAM	47.84	25.57	0.178

Figure 16: Comparison of the classification results of a section of north-eastern Ardley Island in a Worldview 3 image of 30-Nov-2014. All classifications are based on the same training areas



Satellite image ©DigitalGlobe

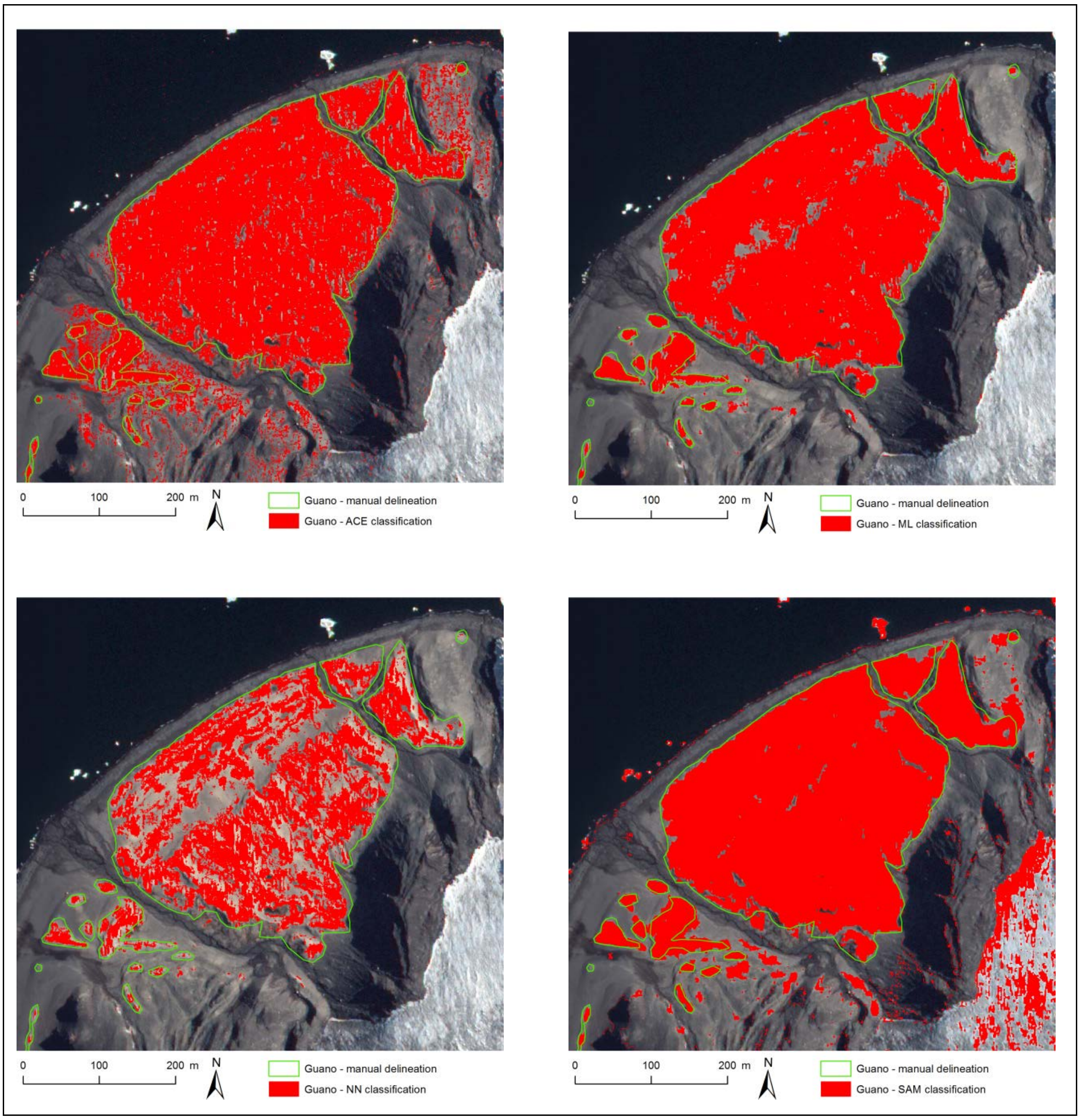
6.2.3 Continental Antarctica – Cape Bird

In order to validate the accuracy of the various classifications in colonies of continental Antarctica, these classifications were tested using an image of the Cape Bird North colony. As there is no ground truth data available for the nest groups of that colony, the classifications could only be compared with the manually delimited total guano-covered areas (Table 8). The spectral signature of the training area used for guano is shown in Figure 14 Results show that classifications are more accurate than those of Ardley Island. In this case the ACE and ML classification, as well as the SAM classification, achieve a relatively high cappa coefficient. A detailed examination of the classification results (Figure 17) clearly shows the differences between the various classification methods. The ACE classification erroneously identifies rock in particular as guano, while the SAM classification has problems distinguishing between guano and old glacial ice.

Table 9: Accuracy of the classifications of the Worldview 2 image from Cape Bird of 06.01.2014 in relation to the manually delimited areas of guano

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
ACE	11.45	14.97	0.7163
ML	1.46	16.03	0.8132
NN	0.49	50.53	0.4689
SAM	0.76	21.61	0.7268

Figure 17: Comparison of the classification results for the Cape Bird North colony in a Worldview 2 image of 06.01.21014. All classifications are based on the same training areas

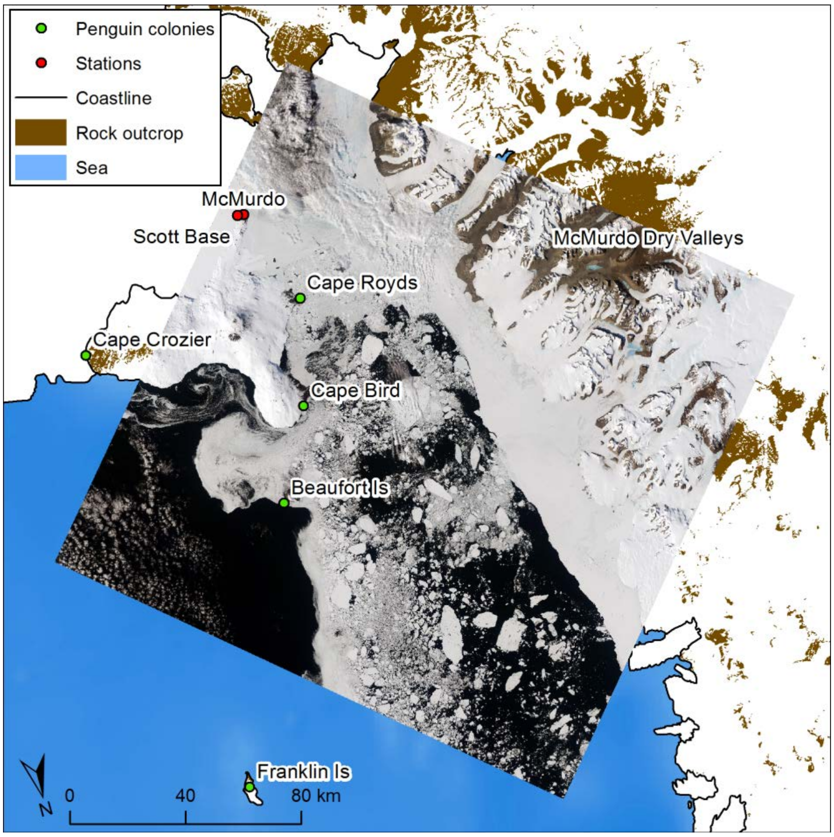


Satellite image ©DigitalGlobe

6.3 Landsat 8

In order to test the classifications in medium-resolution Landsat 8 (OLI) images with 30 m ground resolution and 7 spectral channels, one image each of continental and maritime Antarctic was selected. For continental Antarctica, a Landsat 8 image (Id = LC80571152015363LGN00) of 29-Dec-2015 was used, which covers the Cape Bird colonies (Figure 18). Because the maritime Antarctic research areas do not include any areas where the colonies are clearly recognisable with Landsat, an image (Id = LC82151042013344LGN00) of the northern Antarctic Peninsula taken on 10-Dec-2013 was acquired, on which the colonies of Brown Bluff and Hope Bay are located. Because the main purpose of the Landsat images is the automatic detection of penguin colonies, only those methods were tested that can be effectively automated, that is to say methods for which a spectral signature of guano is sufficient as a training class. These are the SAM and the ACE classifications. The SAM classification has been successfully tested by Fretwell et al. (2015) using Landsat 7 images of the Antarctic Peninsula.

Figure 18: Survey map shows the location of the Landsat 8 image of 29.12.2015 used, with the colonies that can be recognised on it

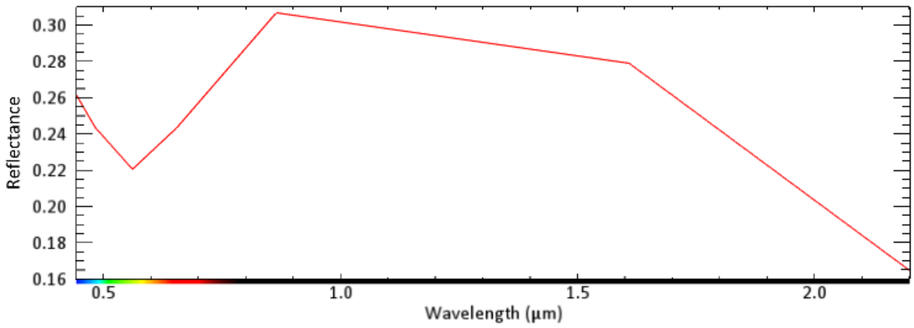


Basic data SCAR Antarctic Digital Database, Landsat image USGS/NASA

6.3.1 Continental Antarctica – Cape Bird

To test the ACE and SAM classifications, an entire Landsat 8 scene was classified using both methods. The reference used for determining the accuracy of the classification was the manually delimited surface area of the five Adélie penguin colonies (Cape Bird North/Middle/South, Cape Royds and Beaufort Island), which are covered by the image. The better to distinguish guano from its surroundings, the channels 7-6-5 (SWIR1, SWIR2 and NIR) were used for the manual interpretation. The spectral signature for the classification (Figure 19) was taken from the centre of Cape Bird North (n = 14 Pixel), as there is a large expanse of guano there. Some tests and an analysis using the ROC Method (Bradley 1997) produced the threshold values 0.8 for ACE and 0.02 for the SAM classification.

Figure 19: Spectral profile of the guano on Cape Bird North used for the classification of SAM and ACE. This spectral profile was also used in the classification of Brown Bluff and Hope Bay

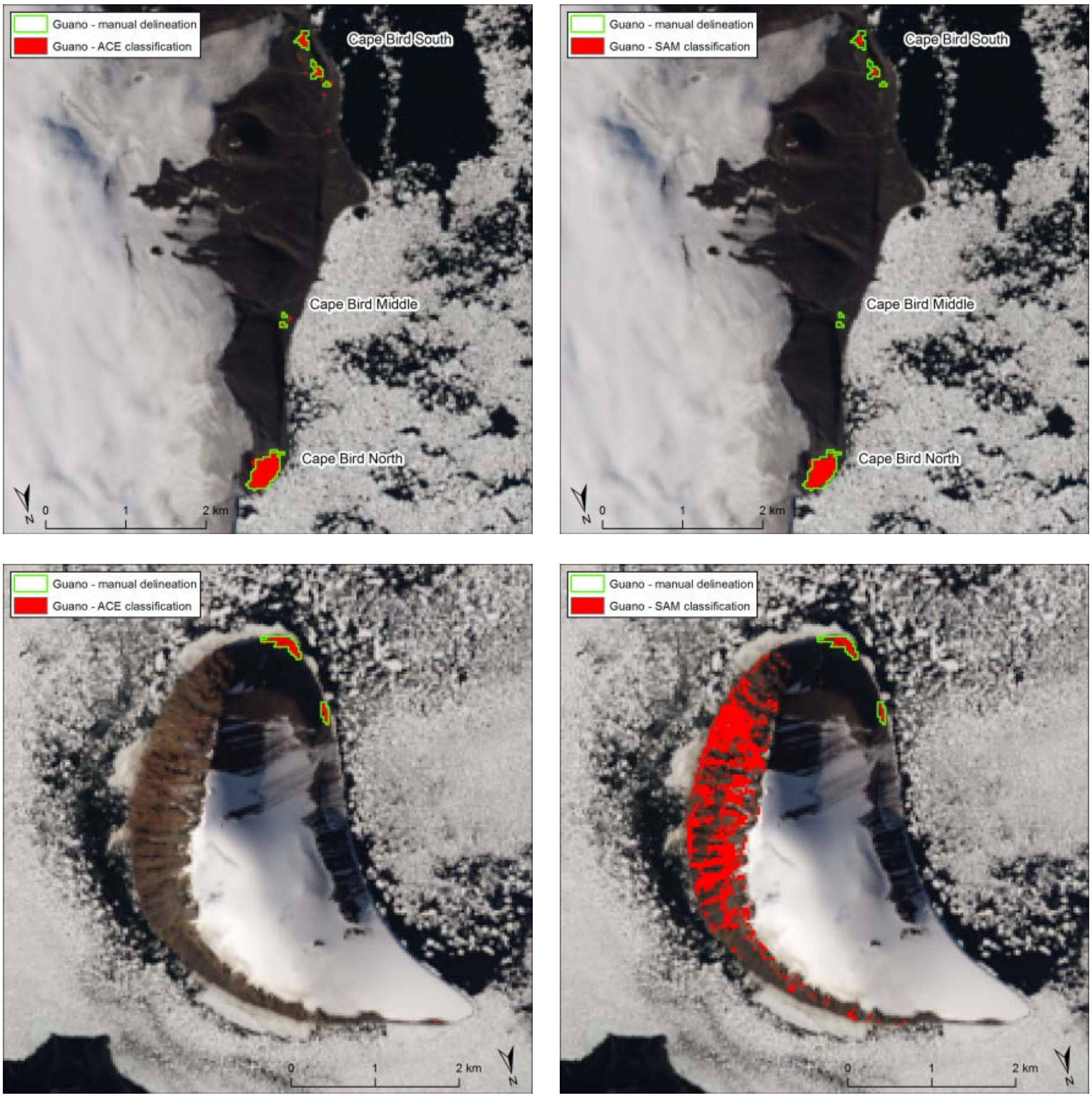


A comparison of the accuracy of the two classification methods is summarised in Table 10. This shows that the SAM classification is significantly less accurate than the ACE classification. As can be seen in Figure 20, both classifications produced similar results for Cape Bird, in contrast to the Beaufort Island colony, which is also classified in the image, where the SAM classification classified large areas of sunlit rocks as guano. In the Antarctic dry valleys region (McMurdo Dry Valleys), large areas were also classified as guano with the SAM classification, whereas with the ACE classification this occurred only rarely. When clouds were present in the scene, the visual analysis showed that both methods were equally susceptible to false classifications.

Table 10: Accuracy of the classifications of the Landsat 8 image of Cape Bird of 29-Dec-2015 in relation to the manually delimited areas of guano

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
ACE	16.33	13.38	0.85
SAM	53.85	32.39	0.547

Figure 20: Comparison of the classification results of Cape Bird (above) and Beaufort Island (below) in a Landsat 8 image of 29-Dec-2015. All classifications are based on the same training area



Landsat image USGS/NASA

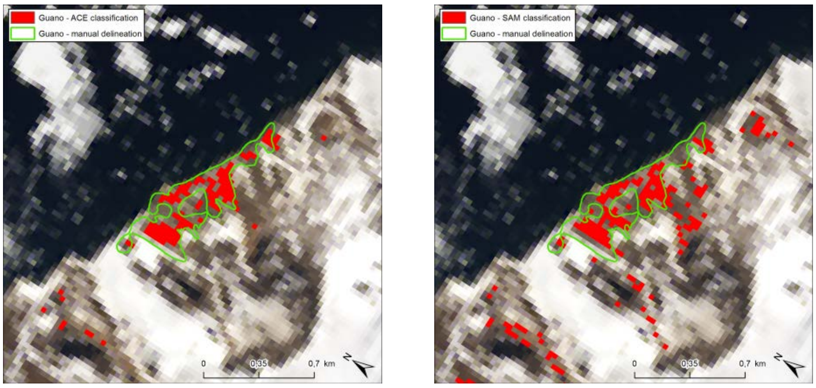
6.3.2 Maritime Antarctica - Brown Bluff and Hope Bay

The spectral signature from Cape Bird North was also used to classify the areas around the Brown Bluff and Hope Bay penguin colonies in a Landsat 8 image of 10-Dec-2013. The same threshold values – 0.8 for ACE and 0.02 for the SAM classification – were used for this. Because the guano was difficult to recognise visually in the image of Brown Bluff and Hope Bay (10-Dec-2013), the guano-covered areas were not manually delimited in the Landsat image itself, but in a high-resolution Google Earth image of 08-Jan-2012. This could also explain the relatively large classification errors of both methods (Table 11), as the ground truth data comes from a different time and a different imaging system. In the comparison, the ACE classification performs somewhat better, as this method shows lower commission errors (Figure 21) and as a result it defines fewer areas erroneously as guano.

Table 11: Accuracy of the classifications of a Landsat 8 image of Brown Bluff and Hope Bay of 29-Dec-2015 relating to the manually delimited areas of guano. The classification uses the guano signature from Cape Bird

Classification	Commission error [%]	Omission error [%]	Kappa coefficient
ACE	11.59	69.50	0.452
SAM	85.85	32.39	0.285

Figure 21: Comparison of the classification results from Brown Bluff in a Landsat 8 image of 29-Dec-2015. All classifications are based on the same training area from Cape Bird



Landsat image USGS/NASA

6.4 Conclusion

The analysis of the various methods for detecting penguin colonies using high-resolution images showed that the new methods tested offer no improvement on the previously trialled Maximum Likelihood Classification. The results of the Adaptive Coherence Estimator (ACE) classification in particular demonstrate similar accuracy. However, this method has the advantage that, unlike the Maximum Likelihood classification, it only requires one training area or one external spectral signature. Theoretically it would therefore be possible to use it for an automated classification. However, all the methods studied show major problems with the colony on Ardley Island, because of the island's very varied topography and widely scattered nests, which led to frequent false classifications in the results. In contrast, good results were achieved for the Cape Bird colony located in continental Antarctica. It should be possible to obtain a significant improvement in the analysis of high-resolution images through the use of object-oriented classifications. The use of such classifications for high-resolution images was studied in detail by Witharana & Lynch (2016) and achieved promising results.

With the ACE classification, better results were obtained with the medium-resolution Landsat 8 images of continental and maritime Antarctic regions. It shows fewer classification errors than the SAM classification that was also studied. It would be theoretically possible to carry out an automated classification of the whole of Antarctica with the two methods. It can be of great benefit to use the decision tree classification as a prelude to a classification, as this can considerably narrow down the areas to be classified (*cf.* Burton-Johnson et al. 2016) and thus minimise the risk of false classifications, for example when there are clouds.

Table 12: Overview of the suitability for guano detection of the methods studied in high-resolution images and fully automated guano detection in medium-resolution Landsat images (- unsuitable; 0 partially suitable, + suitable, ++ very suitable)

Classification method	High resolution images	Medium resolution images
ACE	0	++
ML	++	-
NN	-	-
SAM	+	+

7 Ground truthing count methods

Counts on the ground, as exact as possible (Ground Truth Data) are required for judging the predictive ability or the precision of information derived from satellite images. In this project we investigated and compared four different methods of obtaining such data.

7.1 Panoramic photography

To estimate the number of breeding pairs in a colony as quickly as possible panoramic images of the colony should be taken from an elevated position. The nests detectable in the image are then counted. Thereafter, the area covered in the panorama by specific, easily identifiable, groups of nests of typical density is estimated from a satellite image. This should give the average density of nests in the colony. The total area of the colony is then measured in the satellite image and the total number of nests in the colony estimated by the total area multiplied by the average nest density.

Table 13: Number of panoramic views taken in the research areas

Area	Panoramas [number]	Single images [total]
Ardley Island	13	177
Withem Island	10	70
Narebski Point	7	190

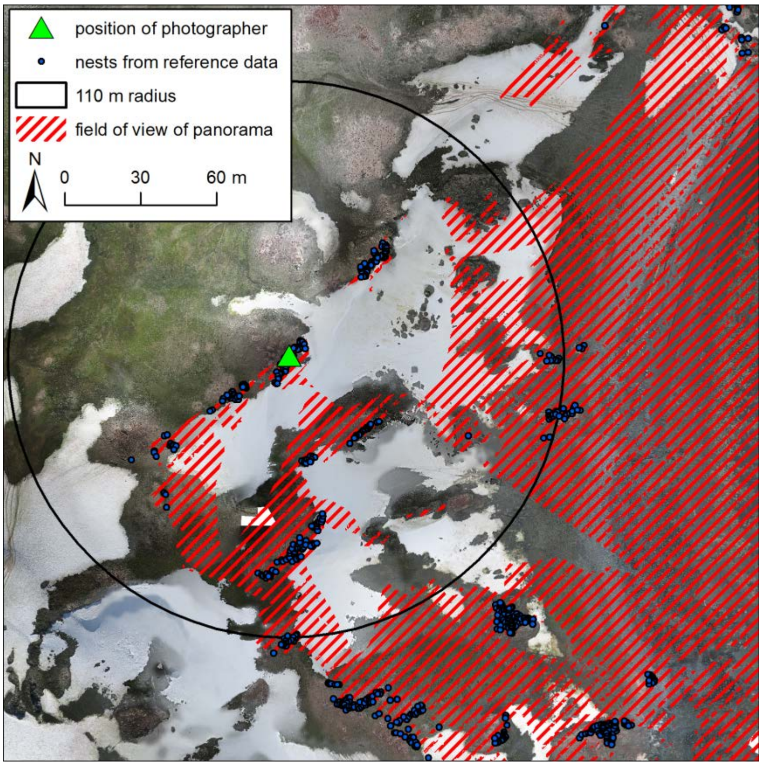
Figure 22: Examples of the panoramic views evaluated – top to bottom: Ardley Island (gentoo penguin nests), Withem Island (chinstrap penguin nests), Narebski Point (chinstrap penguin nests)

To evaluate the potential of this method, panoramas were taken during the 2013/14 season from 32 different positions (Table 13). These panoramas were of greatly different sizes. The smallest contained only 3 individual images but the largest contained 86. These individual overlapping images were fused together (stitched) using Microsoft Image Composite Editor. A panorama with the best view of the colonies was then selected for each study area (Figure 22) and the nests visible in it were counted. This process revealed that it was only possible to identify nests within a particular distance from where the photograph had been taken (Table 14). The images were taken at the same time as the UAV flights were made. This meant that it was possible to compare directly the number of nests counted in the panoramas with that obtained from the UAV flights. To do this, the nest groups seen in the panoramas had to be identified in the UAV mosaics. This was carried out using Viewshed Analysis (ArcGIS 10) starting from the point from which the photos had been taken (as determined by GPS). The base data for the Viewshed Analysis was formed from the high resolution DSMs produced by the UAV (Sect. 7.4). The visual result of a Viewshed Analysis of this type is given in Figure 23. It is then possible to compare the number of nests visible in the panoramas and that in the same field of view from the UAV flights (the reference data) (Table 14).

Table 14: Comparison of the counts from complete panoramas, those from UAV flights and the difference between them

Position	Nests from panoramas [count]	Nests from UAV flights [count]	Difference [%]	Max. distance [m]	Focal lenght (35mm equ.) [mm]
Ardley Island	238	265	10	110	46
Withem Island	137	164	16	40	25
Narebski Point	573	646	11	~100	135

Figure 23: Field of view (red stripes) for a 180° panorama of Ardley Island showing the reference nests visible in the panorama, produced with Viewshed Analysis



A problem in counting the nests in the panorama is the oblique view of the line of sight to some nest groups. Penguins therefore frequently obscure sight of those standing behind them (Figure 24). This is one of the factors leading to the differences between the number of nests counted and the reference data (cf. Table 14). Some nests are difficult to detect so that the penguins themselves have to be counted. However, this produces errors because the number of penguins cannot be equated with the number of nests. This is increasingly the case with increasing distance from the observer, increasing oblique view and increasing density of penguins (Figure 24). The distance for which nest counts are possible depends on the focal length of the camera lens. Examples are given in Table 14. On Narebski Point a further point added to the difficulties: Most of the chicks had already hatched and were no longer in the nest. Coverage of the colony was also problematic. It was possible to see large areas from a raised view point, but beyond a certain distance within these large areas nests could not be seen separately. It is possible to minimize this problem by taking several panoramas from different locations. This, however, demands considerably more time.

Figure 24: Detailed excerpts from the panoramas showing easily differentiated chinstrap nests Narebski Point (A) and gentoo penguins on Ardley Island (B), but also chinstrap penguins obscuring each other on Withem Island (C) and groups of chinstrap nests at a great distance (> 70 m; D)

7.2 GPS-based complete surveys

The most accurate measure of the population size of a penguin colony is achieved by direct counts carried out on the ground. The spatial arrangement of nests can also be obtained using a GPS supported survey (cf. Peter et al. 2008, Waluda et al. 2014). The disadvantages of ground counts, however, are the great investment in field work needed and the considerable disturbance to the birds. The GPS supported survey of all breeding pairs in the Ardley Island colony (about 7,000 breeding pairs) required two people for 2-3 days of work.

The Ardley Island penguin colony was surveyed three times in the framework of this study in the breeding seasons 2013/14, 2014/15, and 2015/16. The number of breeding pairs was assessed each time. The methodology used was that of the previous surveys of this colony (cf. Peter et al. 2008). That is, groups of penguin nests were recorded from a distance of 0.5 to 1 m using GPS field mapping device (Panasonic CF-P1/Novatel Smartantenna, GETAC PS535F/Trimble Juno SD). In addition, the number of nests being brooded at the time was recorded separately by species. The data were entered directly into shapefiles. Groups of nests at least 1 m from others were recorded separately.

Table 15: Number of breeding pairs in the Ardley Island penguin colony

Counts in November				Counts in December			
Date	*P. papua*	*P. adeliae*	*P. antarctica*	Date	*P. papua*	*P. adeliae*	*P. antarctica*
-	-	-	-	06. - 09-Dec-2013	6,187	429	14
28. - 30-Nov-2014	7,001	369	19	15. - 19-Dec-2014	6,464	512	16
-	-	-	-	04. - 07-Dec-2015	5,726	381	22

Surveys of the Ardley Island colony were usually carried out, for logistical reasons, from the beginning to the middle of December of each breeding season (Peter et al. 2013; Peter et al. 2008). This was also the case for the current investigation (Table 15). Nevertheless, an additional November count was made in the 2014/15 season. This was in order to make this date series of many years comparable with the count data from other colonies. The November date is closer to the Peak of Egg-laying date, which is defined as a standard for the CCAMLR Ecosystem Monitoring Program (CCAMLR 2004). November data is therefore of particular importance for comparing CEMP census data with other data collections. There are indeed some differences between the results of the November and the December 2014 surveys (Table 15). It is noticeable that there is a clear reduction (of 7.7 %) in the number of gentoo (*P. papua*) nests. Eventually, many birds abandoned their nests between the two counts. This trend is also seen in the data for determining the temporal pattern of breeding (Sect.11.2) which shows that about 10 to 15 % of the recorded nests were abandoned.

There is a clear increase in the number of Adélie penguin nests (plus 38.8 %). Comparison with the normal breeding timetable and field observations indicate that this results from attempts to reoccupy nests that had been abandoned during the bad weather phase in the second half of November.

It is thus clear that survey results are very dependent on the time of the survey, and the timing of the survey, in turn, is often dependent on logistic and weather-determined limitations.

Figure 25: Map of the Ardley Island penguin colony in December 2013

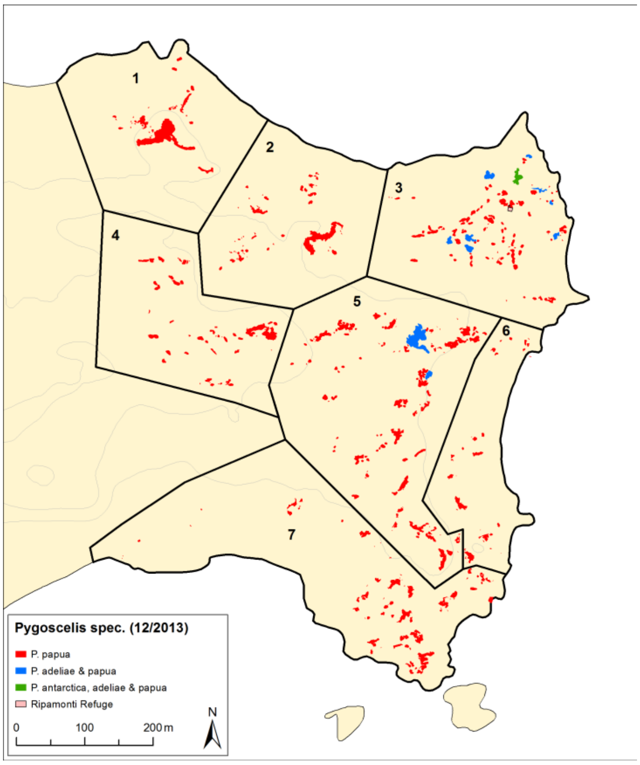


Figure 26: Map of the Ardley Island penguin colony in December 2014

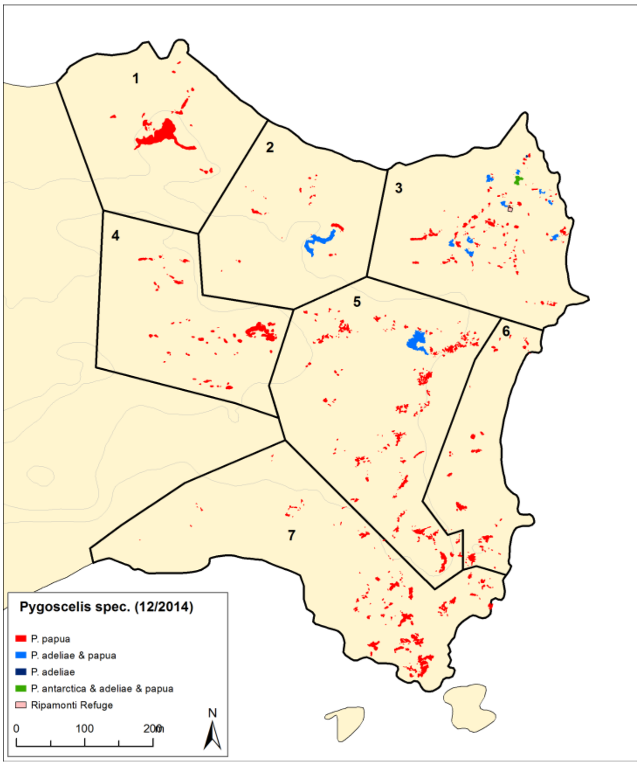
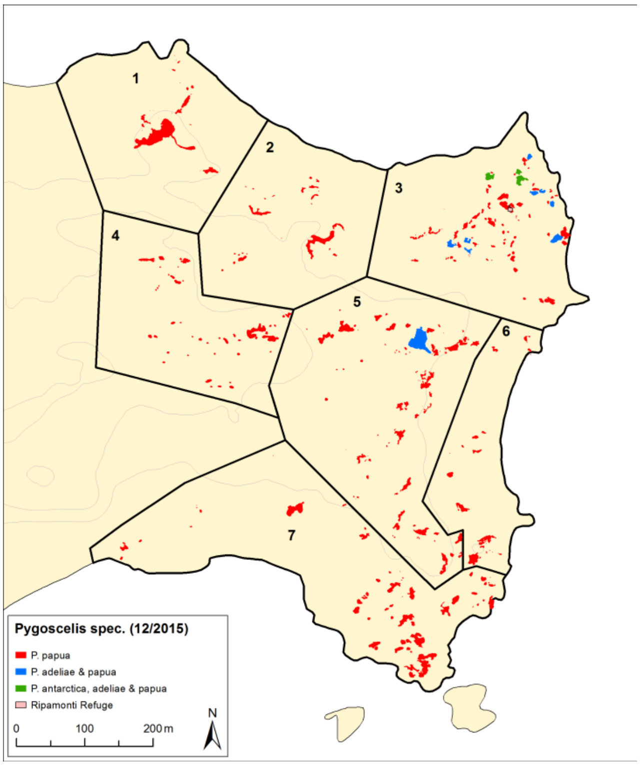


Figure 27: Map of the Ardley Island penguin colony in December 2015



7.3 GPS-based partial survey

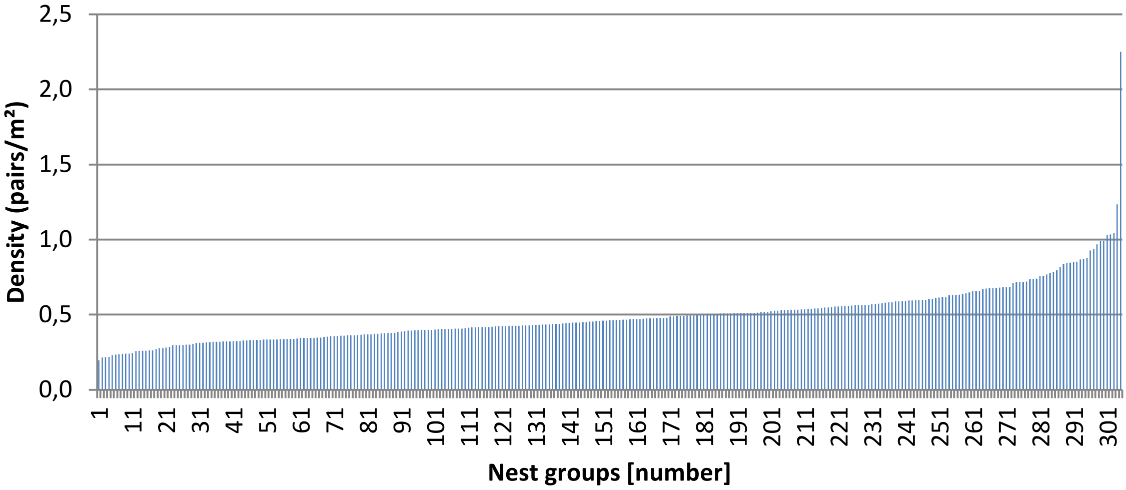
The difference between a partial and a complete survey is that in a partial survey only part of the colony is surveyed using GPS and the breeding pairs counted. The density of breeding pairs is then calculated from these data. To estimate the total number of breeding pairs for all nest groups it is then necessary to determine the area covered by all nest groups. This can be done with the help of satellite images that were, where possible, taken at a time near to that when the partial survey was carried out. The number of breeding pairs in the colony can then be determined from the density of breeding pairs determined on the ground in the partial survey and the total area of all nest groups determined from the satellite images. This method was used successfully by Lynch et al. (2012), among others, with high resolution satellite images.

There are two main sources of error with this method. One is the determination of breeding pair density in the partial survey. The other is the determination from satellite images of the area of the nest groups. Both of these sources of error can give rise to major imprecision in the estimations. To assess the size of the errors we tested the process using, as an example, the 2013/14 Ardley Island survey data and a high resolution Worldview 2 image of the same research areas and time.

7.3.1 Field evaluation of the density of breeding pairs

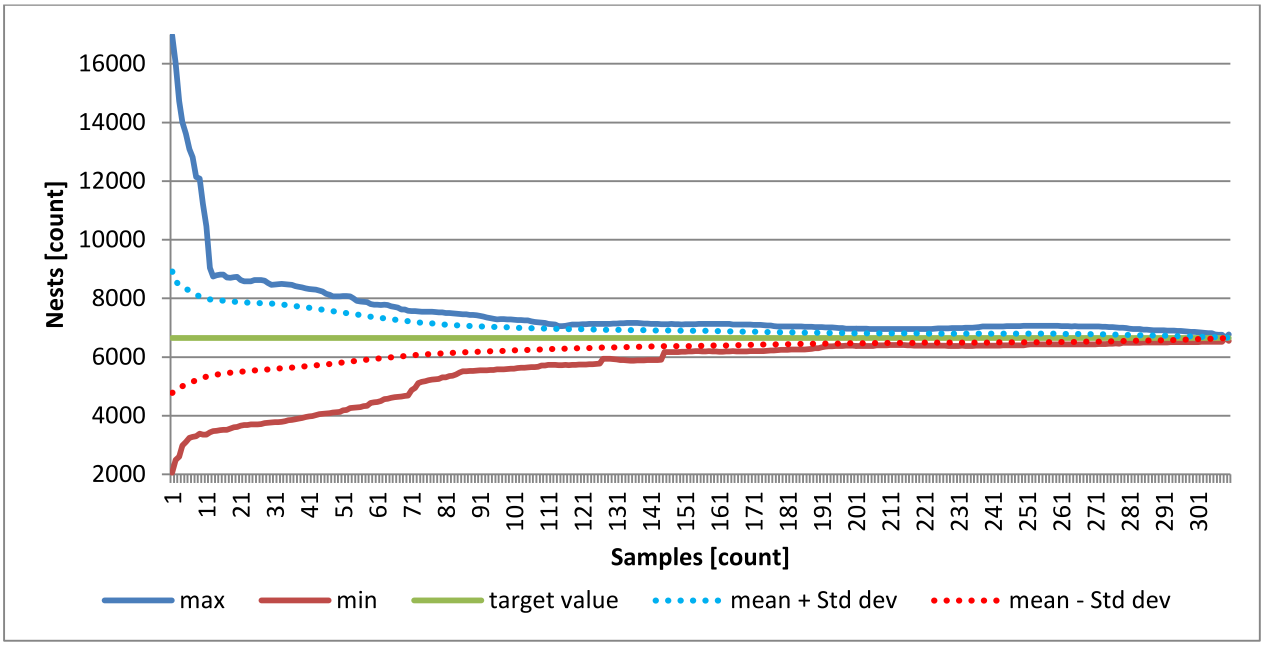
One of the difficulties in partial surveys is the variation in the number of breeding pairs per square meter or between groups of nests (Figure 28). This means that the sample selected (the groups of nests chosen for the partial survey) has a major effect on the density of nests finally calculated from it. To calculate the density for 2013/14 only groups of gentoo penguin nests with at least two breeding pairs were included. This limitation was applied because it was impracticable to determine the area of single nests. Another source of inexactitude was interobserver error because surveying was carried out by different people.

Figure 28: Density (nests/m²) of gentoo penguin nests calculated on the basis of the GPS-based survey in the 2013/14 season on Ardley Island. It is clear that the density of nests in the colony varies (minimum = 0.2, maximum = 2.2, average = 0.5, standard deviation 0.2)



We wrote a model in R (R-Core Team 2015) to determine how big the sample size has to be to determine accurately the real number of breeding pairs of 6,652 (Ardley Island 2013/14 season). All 310 nest groups were then tabulated manually in approximate order of their spatial distribution. That is, neighbouring nest groups tended to be closer together in the table than non-neighbouring groups. This takes into account the fact that a group of nests in the field is strongly spatially related. It is not at all a random sample of the colony. Using this script, 310 calculations were carried out. The first step was to calculate the total number of pairs based on the first group of nests in the list. In the second step, the number of pairs was calculated based on the first and second nest group in the list. In each subsequent step, the next nest group in the list was added to the nest groups used to calculate the total number of breeding pairs. With each step, the estimate of the number of breeding pairs gradually approached the known total. The model run finished when all 310 nest groups were included in the sample. In the second run of the model, the process started with the second nest group in the list. This start simulates the fieldworker starting at a different position. The process then proceeded as before. Repeating the process produced 310 model runs, each of 310 individual steps. The results recorded were the maximum and minimum estimate for the 310 sample sizes calculated from all runs of the model. The outcome shows how rapidly the greatest spread of the estimates declines with increasing sample size (Figure 29).

Figure 29: Minimum and maximum numbers of gentoo penguin breeding pairs in the Ardley colony calculated from 310 simulated samples. The plot shows the relationship between the population estimate statistics and the number of nest groups in the sample. Notice the degree to which the spread of the estimates declines with increasing numbers of nest groups in the sample.



These data were then used to calculate the maximum deviation from the real number of breeding pairs in relation to the size of the sample (Figure 30). In conclusion, the results indicated that the precision of the breeding pair density estimated from a partial survey of Ardley Island is strongly dependent on the sample size. This sample size is, in its turn, limited by the amount of work required (Table 16). For example, to be certain of obtaining 5 % precision, 281 nest groups have to be surveyed on the ground. This is ˜93 % of all the nest groups on Ardley Island. Whether this result is also valid for other colonies could not be determined. There are, however, large differences in breeding pair density (according to Woehler & Riddle (1998) 0.1-3.1 breeding pairs per square meter).

Figure 30: Maximum percentage deviation between the estimate of total breeding pairs (gentoo penguins) in relation to the number of nest groups included in the sample for the Ardley Island colony for the 2013/14 season

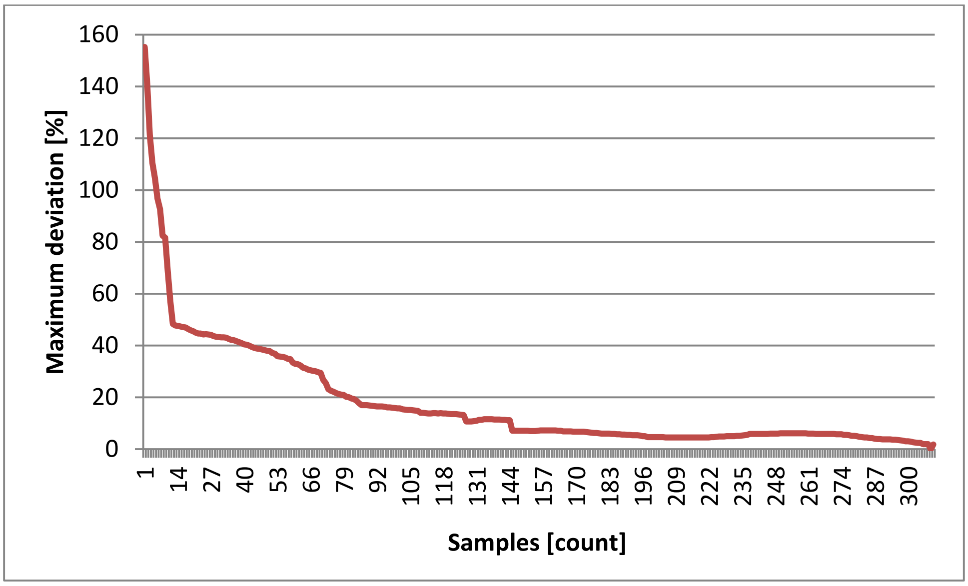


Table 16: The number of gentoo penguin nest groups that must be included in a sample to be certain of obtaining a given precision for the Ardley Island colony for the 2013/14 season

Lowest possible achieved accuracy [%]	Sample size of nest groups [count]	Share of the sample size from the total number of the nest groups [%]
50	14	5 %
25	58	19 %
10	146	48 %
5	281	93 %

7.4 UAV orthomosaics

A relatively new method (Goebel et al. 2015, Mustafa et al. 2014, Ratcliffe et al. 2015, Zmarz et al. 2015) for determining the abundance of penguin colonies is to use UAVs (Unmanned Aerial Vehicles). UAVs perform low level (15 - 300 m) flights over the colony, taking photographs of the ground. These aerial photographs are then stitched together, geo-referenced and calculated to an orthomosaic. The term 'orthomosaic' refers to the mosaic of individual aerial photographs stitched together and geo-referenced from which distortions caused by the terrain have been mathematically removed (orthorectified) using a digital surface model. Using a high resolution orthomosaic image (< 50 mm ground resolution) allows the nests of a colony to be counted.

The UAV we used was an octocopter (HiSystems, MK ARF Okto XL) that has 8 electric motors. It can carry a payload of 2.5 kg and is equipped with GPS (Figure 31). Depending on the payload and the weather conditions, the octocopter can stay airborne for 8-20 min and can reach altitudes of 3000 m above sea level. Practically, we found that flight times of up to 19 min, altitudes of up to 150 m above the ground and flight speeds of 22 km/h were possible because of the low outside temperatures and the strong winds that often prevailed.

Figure 31: The UAV MK ARF Okto XL (HiSystems) was used with a Sony A6000 and a thermal camera attached

The octocopter is equipped with software for independent flights. A specific flight path can be programmed before take off based on the map, timings for taking images included (Figure 32). This feature allows very economical survey flights with overlaps between images chosen exactly according to need. Independent flight mode also makes night flights possible, which is optimal for the thermal camera. It is possible to determine the real flight path flown because the drone records its position and other telemetric data in a log file many times a second. This file can be downloaded and analysed after the flight.

Figure 32: Example of a flight plan for surveying the eastern part of Ardley Island, an image is taken automatically at each point on the flight path (orange), the total flight time was around 12 min

For technical reasons, overflights can only be realized under specific weather conditions. They cannot be carried out during rain and the wind speed must be less than 30 km/h. Furthermore, it is of course only useful to carry out flights with optical sensors when visibility is good and when there is enough light. Given these limitations, flights were possible every 3.5 days on average during the 2013/14 season.

This method was used during the 2013/14 and 2014/15 season in the research areas of Ardley Island, Withem Island and Narebski Point. During 2014/15, however, bad weather prevented access to both Withem Island and Narebski Point. Overflights were made with sensors for several different spectral ranges (UV, RGB, NIR and thermal infrared), which will be discussed in the following sections.

7.4.1 RGB orthomosaics

The visual light (RGB) optical sensor Canon Powershot G15 compact camera was used in the 2013/14 season. In the following season the mirrorless Sony A6000 was used in addition. The

Sony A6000 has the advantage that the sensor has a greater resolution than the Powershot (24.3 instead of 12.1 megapixel). This makes it possible to take pictures with a greater ground resolution at a given altitude than with the Powershot, or to fly at a greater altitude reaching the same ground resolution. Both these cameras have the advantage over DSLR cameras that they are light and therefore permit a longer flight time. With these systems we took high resolution images (<50 mm ground resolution) of the colonies, created orthomosaics from them and, finally, from the mosaics, counted the nests. It is furthermore possible, using these images of the colonies, to produce 3D terrain models provided that the image overlaps are large enough. These models can then be used to orthorectify the satellite images with great precision.

Reduced resolution images of the mosaics produced and used in this study are available (Figure 33 to Figure 35) (The original full-resolution data sets can be downloaded freely from www.think-jena.de.).

Figure 33: UAV orthomosaic (10 mm ground resolution) of Ardley Island on 30-Dec-2015

Figure 34: UAV orthomosaic (25 mm ground resolution) of Withem Island (left) and its smaller neighbouring island (right) on 29-Dec-2013

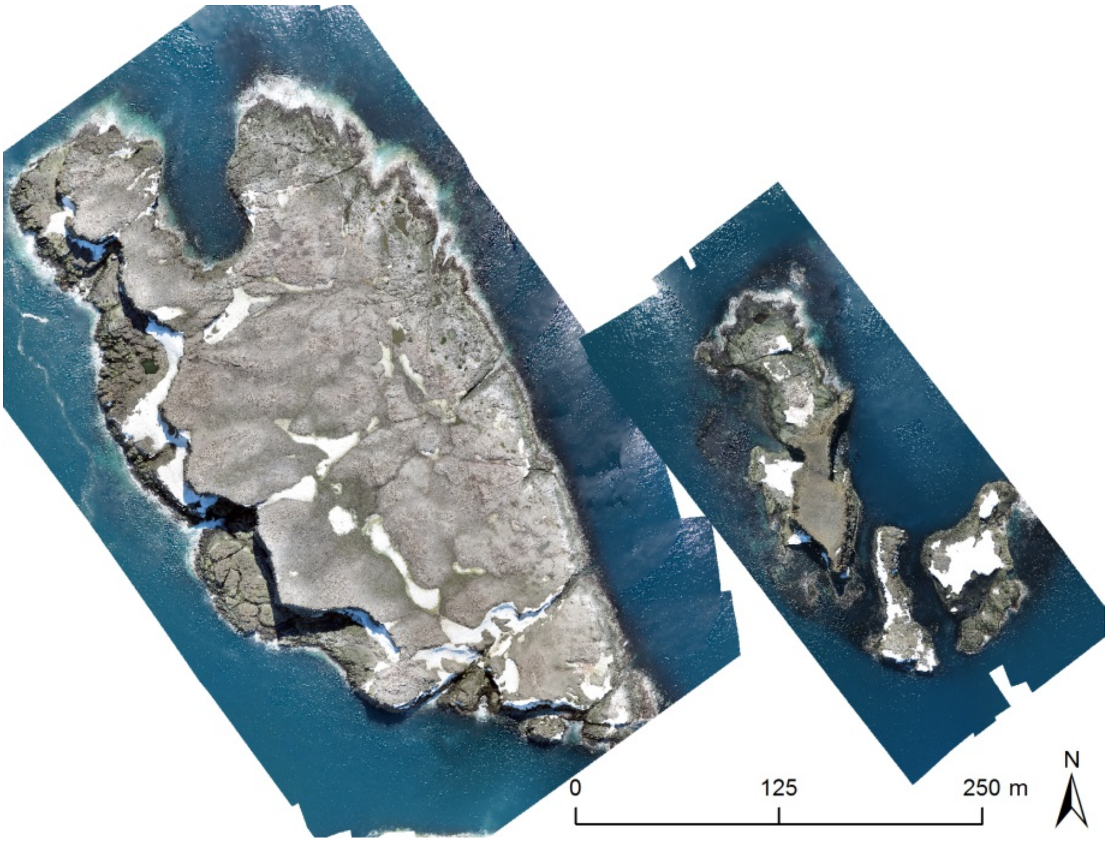


Figure 35: UAV orthomosaic (15 mm ground resolution) of Narebski Point on 03 and 04-Jan-2014

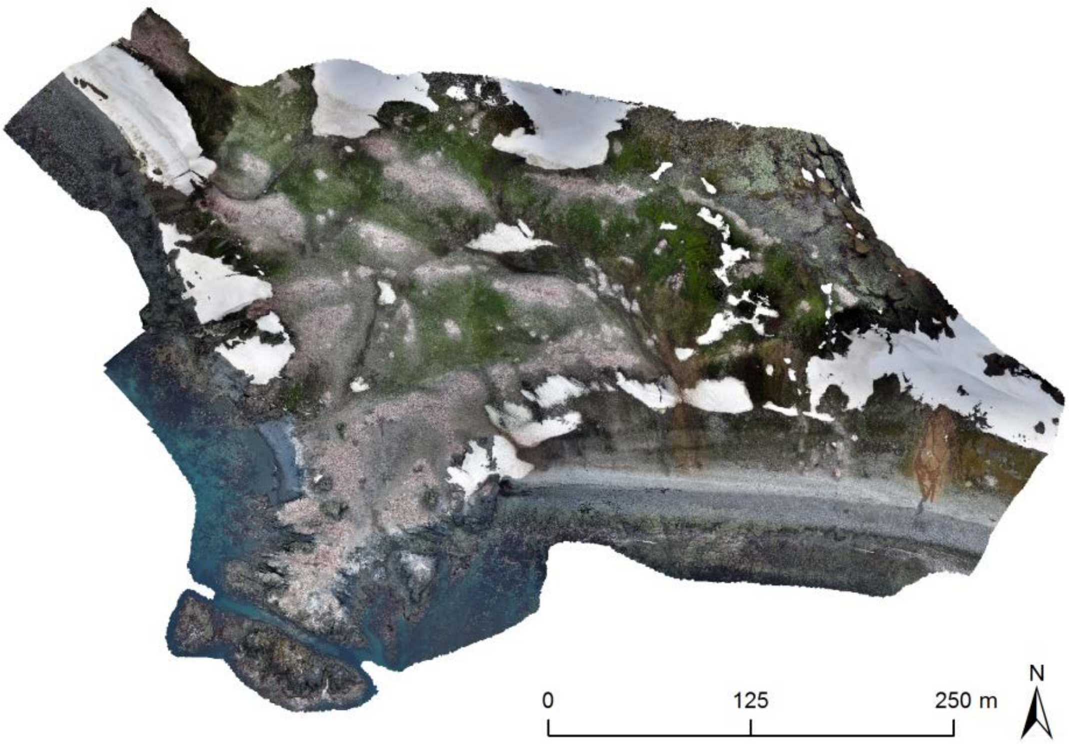


Table 17: Flight parameters of the UAV survey

	Mosaic area [km^2]	Number of flights	Ground resolution [mm]	Flying altitude over ground[m]	Number of single images
Narebski Point (2013/14)	0.23	5	30	100	318
Withem Island (2013/14)	0.15	2	30	100	122
Ardley Island (2013/14)	0.58	4	30	100	473
Ardley Island (2014/15)	0.46	8	15	50	1,373

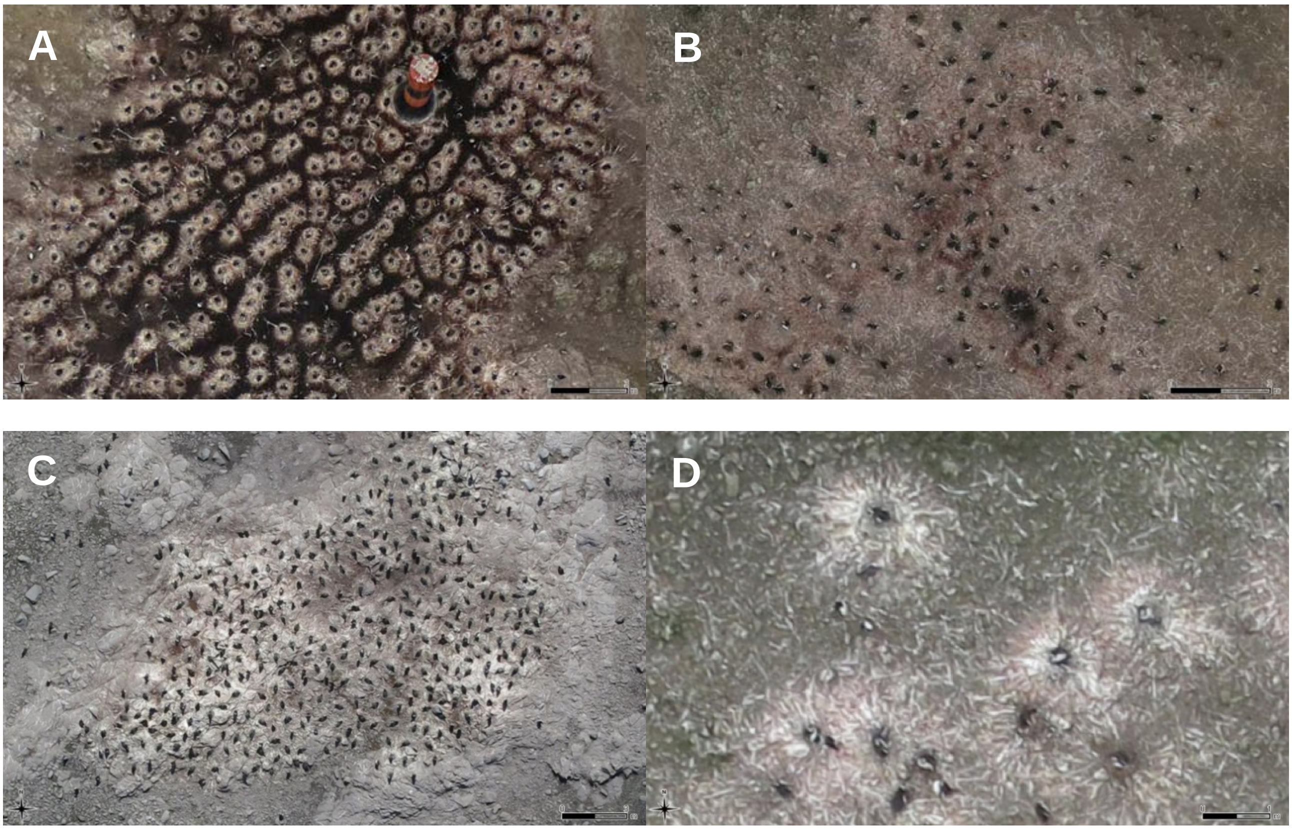
The flight parameters for the UAV survey of the penguin colonies vary (Table 17). The Ardley Island and Narebski Point mosaics for 2013/14 contain some gaps. These gaps originate in the topography of the sites. Therefore, the full survey figures given for comparison must be reduced by the number of nests not covered by the mosaic. Such omissions were avoided in the Ardley Island mosaic for the following season by optimizing the flight paths and increasing the frequency with which images are taken. Complete coverage was possible for the relatively flat region of Withem Island.

Easily identifiable are nests that are clearly separated from the surroundings and from each other (as in Figure 36, panel A). In most cases, however, the nests in the colonies are not so evident. Isolated nests are often recognizable by a star-like spread of guano with the nest standing at the center (Figure 36, panel D).

Sources of error in the counts are the non-breeding penguins moving among the nest groups. Avoiding including these in the counts was particularly hard when the nests were difficult to distinguish (Figure 36, panel B). In order to be able to exclude the non-breeders we were able to make use of the fact that penguin nests are not randomly close to each other. Instead, they are built more than “pecking distance” apart, around 0.5 m. Therefore, where two penguins are clearly standing closer than 0.5 m to each other in a group of nests and no nests can be conclusively identified, only one of the two individuals is counted as breeding.

The counts are difficult when the chicks are sufficiently developed to leave the nest and join créches. This was the case for some of the chinstrap penguins at Narebski Point. The nests not containing penguins were not included in the counts because in these cases it can be assumed that the nests are really unoccupied.

Figure 36: Examples of penguin nest groups in aerial photographs from UAVs; easily recognizable groups of gentoo penguin nests on Ardley Island (A), poorly recognizable groups of gentoo penguin nests on Narebski Point (B), easily recognizable groups of chinstrap penguin nests on Withem Island (C), star-shaped spreads of guano around gentoo penguin nests on Ardley (D)



The number of breeding pairs estimated by counting the UAV mosaic can be compared with that derived from the GPS based complete surveys carried out on the ground (Table 18). The deviation between the two methods lies between -1 and +11 %. In order to determine the different specific causes of these deviations we compared the results of the UAV survey in detail with the number of nests in individual groups of nests surveyed on the ground (Table 19). This comparison showed that the number of mis-classifications was higher than the absolute differences between methods. The greatest error factor was the occasional difficulty in discriminating between breeding and non-breeding individuals (Table 20). A large error factor can also be the building of new nests when there is a relatively long time interval between the ground and the UAV survey. Likewise an error factor is the number of nests abandoned during such time intervals. This latter error probably formed the largest portion of the “undetected” class. The undetected class also contained nests that could not be detected because of the topography (e.g. nests behind or below projecting cliffs). Discrimination between occupied nests and penguins without nests might be improved in the future by using sensors with greater resolution. Nests could also be more easily recognized if overflights were made at a lower altitude. This is scarcely practicable, however, because it would greatly extend the time needed to cover a large area and UAVs cannot stay airborne for long. Furthermore, overflights at or below 50 m altitude bear an increased risk to disturb the penguins (Rümmler et al. 2015) (see Sect. 7.4.4). It should also be noted that complex topography adversely affects the quality of the results. And, as it has been shown in other cases (Sect. 11.2), taking breeding cycle phenology into account is important for estimating the number of breeding pairs.

Table 18: Comparison of the time of the ground survey and that carried out by UAV

	Narebski Point (2013/14)	Withem Island (2013/14)	Ardley Island (2013/14)	Ardley Island (2014/15)
Ground survey	6 – 9 Dec 2014	-	8 – 10 Dec 2013	16 – 18 Dec 2014
UAV survey	3 – 4 Jan 2014	29 Dec 2013	17 Dec 2013	30 Dec 2014
Difference [days]	**25 – 29**	**-**	**7 – 9**	**12 – 14**

Table 19: Comparison of the results of the ground- and UAV surveys

	Narebski Point (2013/14)	Withem Island (2013/14)	Ardley Island (2013/14)	Ardley Island (2014/15)
Ground survey	5,524	-	6,630	6,992
Gaps in mosaic	1,223	0	431	0
Ground survey (without gaps)	4,301	-	6,199	6,992
UAV survey	4,784	1,0119	6,145	7,647
Difference	**+483 (+11 %)**	**-**	**-54 (-1 %)**	**+655 (+9 %)**

Table 20: Error analysis for the UAV survey results based on the detailed data for nest groups obtained from the ground survey

	Narebski Point (2013/14)	Ardley Island (2013/14)	Ardley Island (2014/15)
Falsly counted as breeding	+650	+468	+969
New nests	+117	-	+74
Falsly interpreted as not breeding	-168	-384	-10
Not detected	-126	-138	-378
Totaldifference	**+483**	**-54**	**+655**

7.4.2 UV and NIR orthomosaics

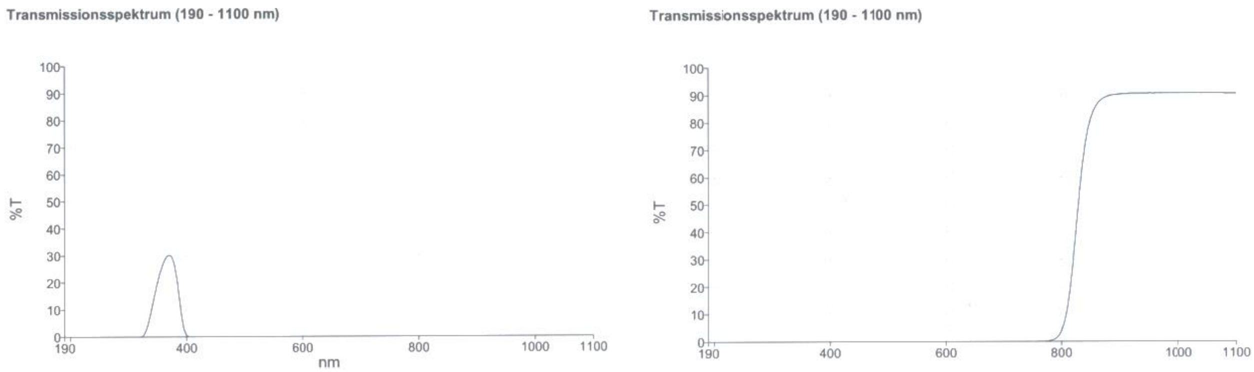
In the 2014/15 season, ultraviolet (UV) and near infrared (NIR) orthmosaics were created in addition to the RGB images. For this purpose the UV-IR cut filter of the Sony A6000 was removed and by the use of special filters it was able to take images in the UV, NIR or RGB ranges of the spectrum (Table 21).

Table 21: Overview of the spectral ranges exploited and the cameras used for these ranges

Sprectral range	Sensor	Wave lenght [nm]
UV	Sony A6000	310 - 390
RGB	Canon G15 and Sony A6000	420 – 700
NIR	Sony A6000	830 – 1 100
Thermal	ThermoImager 450	7.500 – 13.000

Because of the limited sensitivity of the sensors in the UV spectrum and the low transmission of the filter used, only about 20 % of the UV light reflected from the ground was available (Figure 37). To remedy this, the ISO values of the camera had to be increased from ISO 100 to ISO 2500. This leads to considerable noise in the images (Figure 38). Applying noise suppression to the image subsequently produced no increase in image quality.

Figure 37: Transmission curves (amount of light at different wavelengths) of the filters used for UV (left) and for NIR (right)



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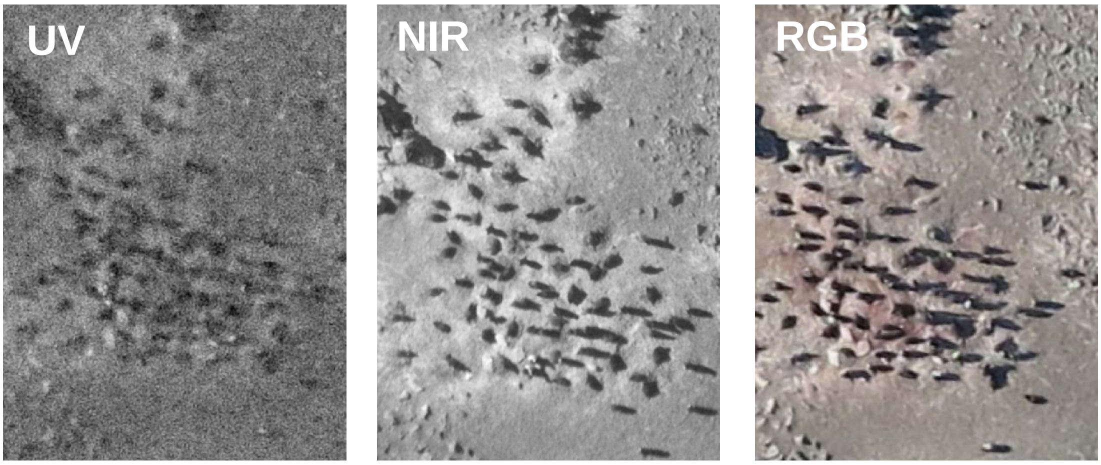
In contrast, the NIR filter used had a very much better transmission (90 %). The ISO value therefore only had to be increased from 100 to 250 to provide enough light for the images.

The interpretation of the mosaics showed that the UV images provided no improvement over the RGB images for the detection of breeding pairs. This was predominantly due to the great noise present in these images which prevented recognition of any additional detail.

In the NIR, in contrast, guano covered areas are easy to identify, caused by their strong reflection in the NIR region of the spectrum. However, the vegetation present also reflects strongly in the NIR and this can lead to confusion. This problem can be avoided by localizing the vegetation using the NDVI, so that Guano and Vegetation can be clearly differentiated. Another possibility involves using combined NIR, red and green channels in a false colour image. This combination clearly separates guano surfaces from their background. This is a great advantage of the NIR images over purely RGB images.

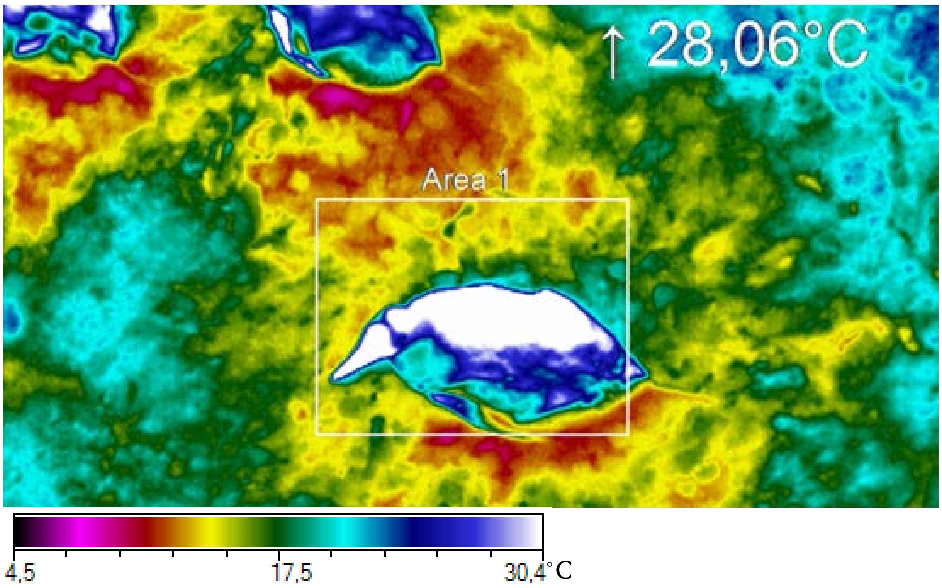
Figure 38: Details from an UAV mosaic of Ardley Island with 30 mm ground resolution showing a group of gentoo penguin nests on 08-Jan-2015 in the UV at ISO 2500, NIR at ISO 250 and, for comparison, in RGB mode at ISO 100.



7.4.3 Thermal infrared orthomosaics

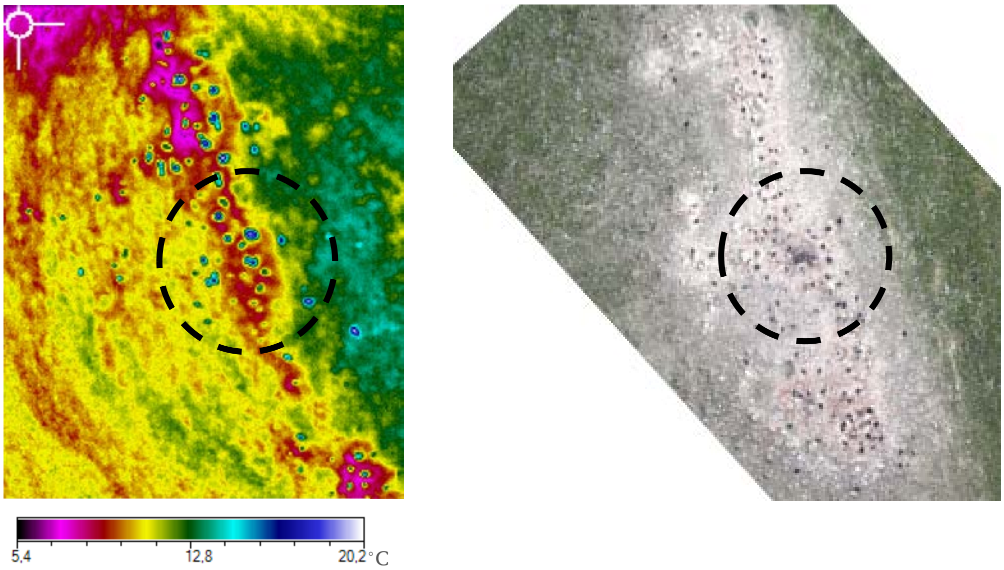
UAV flights carrying thermal sensors provided novel insights into the thermal signatures of the penguins and their guano. The higher temperature of the penguins clearly separates them from the lower temperatures of the background. This improves the certainty of identifying penguins, depending on the altitude of the flight. In addition, there is a similar clear temperature difference between the guano covered nests and their surroundings (Figure 39). This temperature difference is caused by the higher albedo of the guano.

Figure 39: Close up thermal image of a brooding penguin from an altitude of about 2 m; the immediate edge of the nest is clearly lower in temperature than the remaining area covered with guano. The average temperature of Area 1 (in the white rectangle) is 28.06 °C



The questions relevant to this study revolve around the detectability of nests. In fact, the thermal signature of nests in thermal images is clearly recognisable. The signature arises from the spatial combination of the high temperature of the penguin and the low temperature of the guano-covered nest area with the intermediate temperature of the surroundings (Figure 40).

Figure 40: Overflights with thermal (left) and RGB (right) senors of the same nest group on Narebski Point. The nest signatures show up against the cooler guano-covered area. Differentiation of the nests (green) from the penguins (blue) is potentially possible within the marked area (circle)



A temperature profile shows the low temperatures of nest structures (Figure 41) taken from a low altitude of 20 m. However, from the practicable altitude of 50 m, it was not possible to separate clearly the penguins on nests from those not on nests when using this method for the systematic analysis of large nest groups. Nevertheless, the thermal image allows the unambiguous recognition of penguins that are not standing or lying on the guano-covered areas.

Test flights with thermal and RGB sensors in parallel were carried out at successively higher altitudes from 20 to 70 m (in steps of 10 m) above the ground. These tests indicate a relationship between low altitudes and better recognition in the thermal image of structures such as nests. Nevertheless, it was only possible in a few cases to infer recognisable nest structures in images from altitudes of 20-40 m (Figure 41 and Figure 42). The normally circular guano deposits around nests are detectable in thermal images by their particularly low temperatures. The high albedo of the guano allows less warming of the guano-covered ground and stones than of guano-free areas. This forms a strong temperature contrast with the penguins.

Figure 41: Simultaneous thermal and RGB images from approximately 20 m above the ground; the temperature profile along the red line shows the temperature minimums of the circular guano deposits immediately next to the temperature maximums of the penguins (marked by black circles)

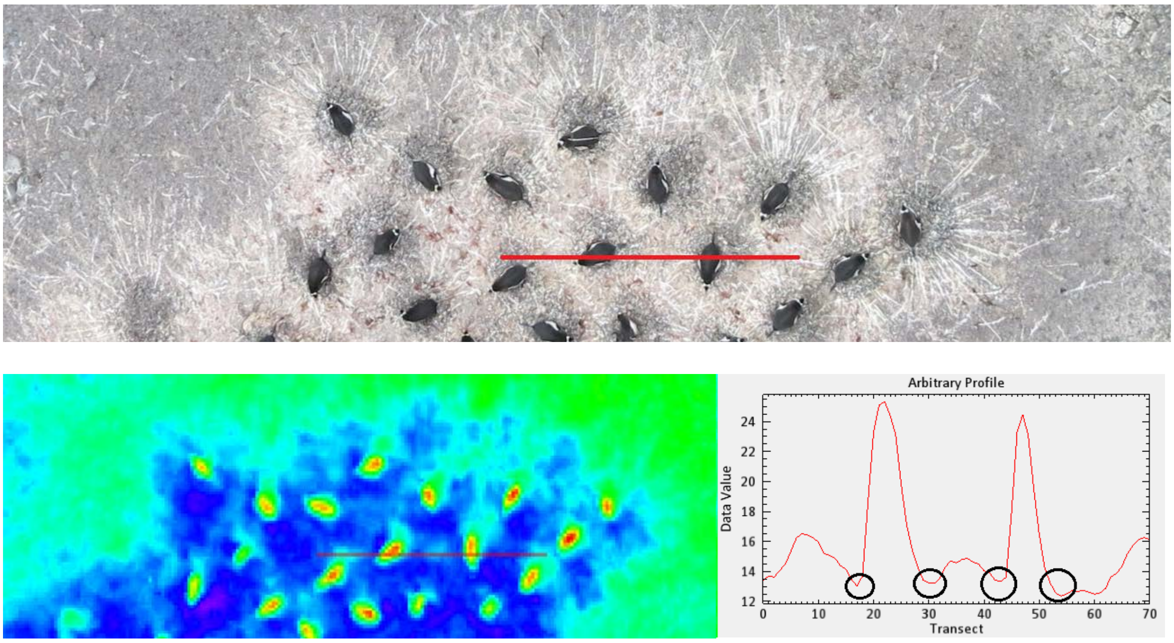
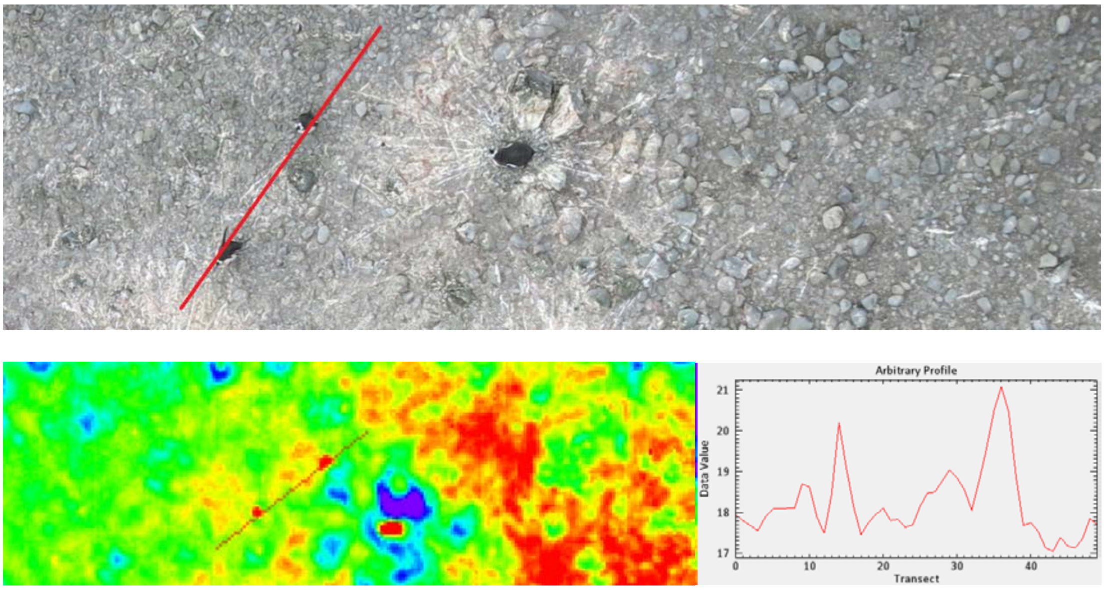


Figure 42: Simultaneous thermal and visible light images from approximately 20m above the ground; the temperature profile along the red line does not show temperature patterns common to the two penguins neither of which is on a nest.



In contrast to Figure 41, the temperature profile in Figure 42 for penguins not at a nest does not show distinct temperature minimums around the penguins.

The strong contrast of temperature between penguins and guano-covered surfaces offers the potential of automatic object-based classification with the aim of replacing manual counting of the mosaics. This is less likely to be possible in RGB images because the colour contrast between penguins and their surroundings is smaller than in thermal images. This would hinder the use of automatic classification in the visible light images. In the future it might be possible to improve the detectability of structures such as nests and standing penguins from the practicable hight of 50 m by using a thermal sensor of greater resolution.

Comprehensive survey flights of the whole penguin colony on Ardley Island have been carried out frequently with thermal and visual sensors in parallel at a flight height of 50 m. These parallel surveys demonstrated that this altitude represents the greatest height above the ground at which individual penguins can be detected in thermal images. Lower altitudes do not allow the entire colony to be surveyed on a single day. Low altitudes also produce fuzzy images caused by camera motion.

There are limitations to the comparability of thermal images and other images derived from UAV flights (Canon G15: 4000 x 3000 Pixel; Sony A6000: 6000 x 4000 Pixel). These limitations arise from the comparatively low geometric resolution (<10 %) of the thermal sensor of only 382x288 pixels (equivalent to 0.2 megapixel). At the height of 50 m above the ground, optimal for survey flights, the ground resolution of the thermal sensor is 0.157 m. There are local distortions in the mosaics of thermal images, even when it is possible to produce a complete mosaic of the survey locality. One of the causes of the distortions may be the limited geometric resolution of the individual images because this clearly reduces the number of tie points between the individual images.

Figure 43: Mosaic of 307 individual thermal images, flight altitude 50 m, date of survey 30-Dec-2104, north-east Ardley Island (top); detailed image of the area within the black rectangle of the top picture (bottom left); RGB image taken at the same time (bottom right)

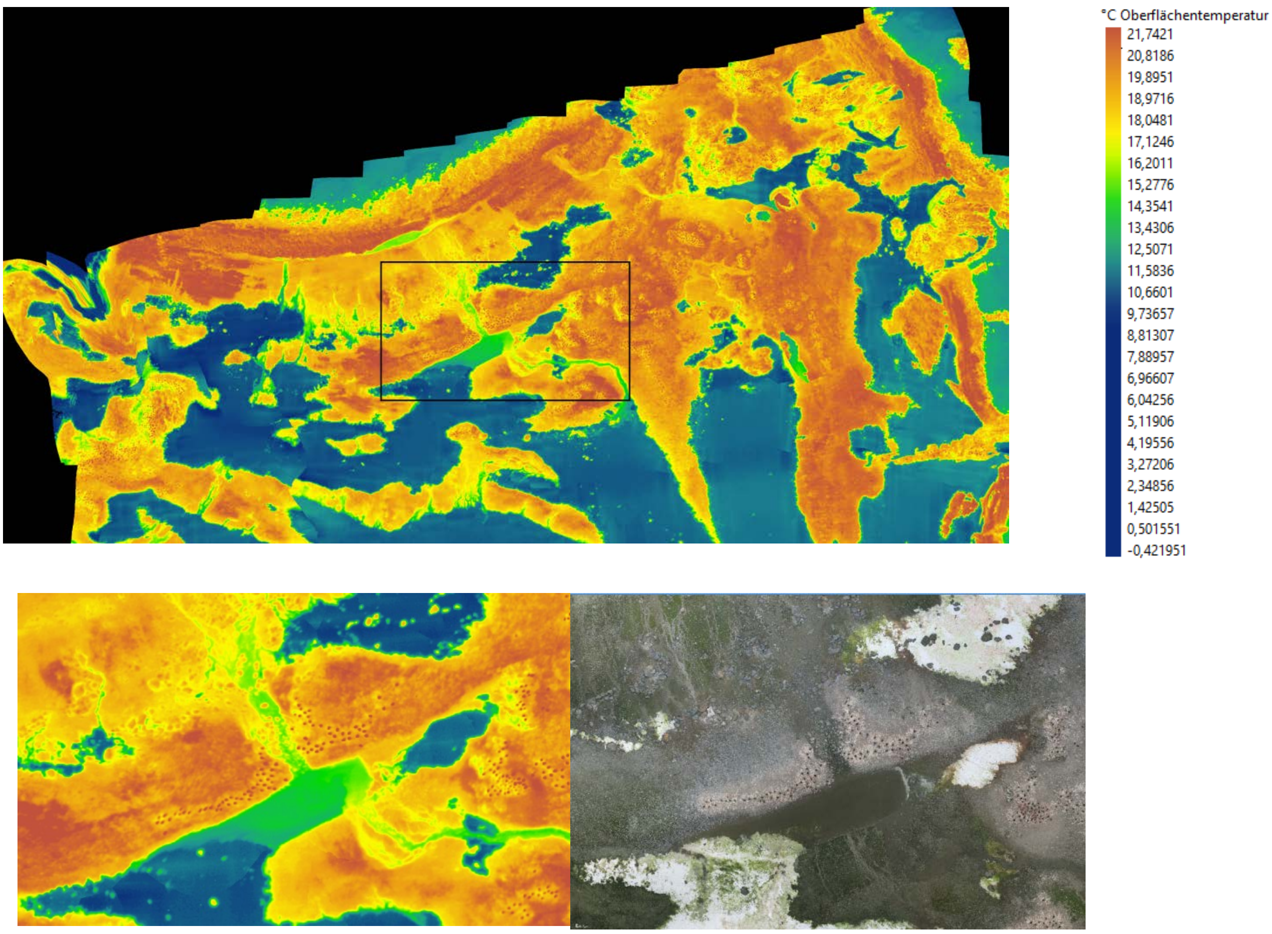
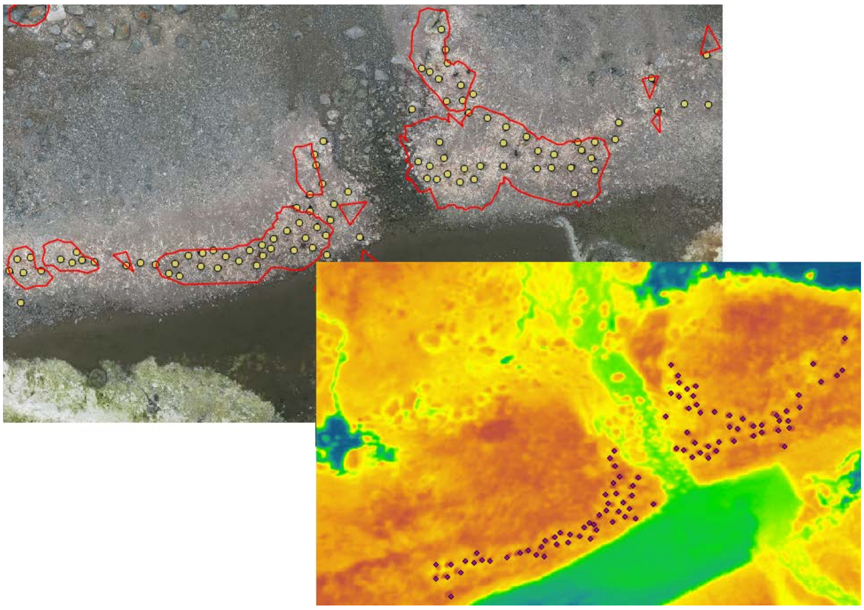


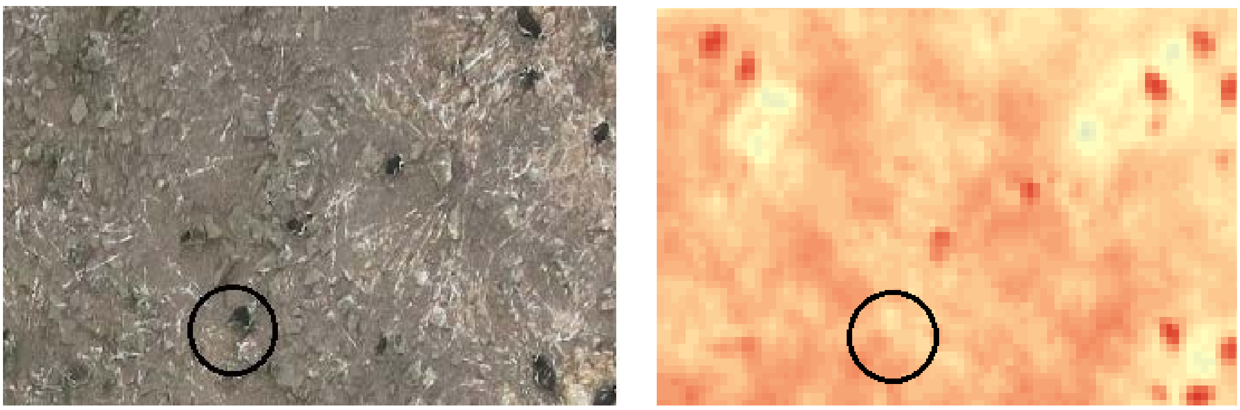
Figure 44: Comparison of penguin counts between simultaneous visual and thermal images (both details from mosaics), flight altitude 50 m, date of survey: 30-Dec-2014, north-east Ardley; red outlines indicate GPS-based ground survey



In comparative counts from the complete mosaics of simultaneous thermal and RGB images taken on 30-Dec-2014, the RGB image always produced higher results than the thermal image (Figure 43 and Figure 44). The underestimation of about 20-50 % from the thermal image results from their limited ability to detect vertically standing penguins. This limited ability may well result from the smaller surface area presented to the thermal sensor by standing penguins in relation to lying ones. In addition, the low geometric resolution of the thermal sensor makes the detection of nest groups against a heterogeneous background (e.g. rocks) difficult. Tests at lower altitudes indicate that there were no problems in detecting standing penguins or nest groups in rocky terrain. However, such low flights are not practicable because it is then not possible to cover all nest groups in an area by flights on a single occasion.

Considering both types of images obtained (thermal + RGB) showed itself to be a profitable approach to increasing the quality of the counts derived from UAV mosaics. In particular, it was possible to definitively exclude single large stones from the count that appear very similar to a penguin on the nest in RGB images by their absence of a heat signature in the thermal image. It was therefore possible, to a degree, to avoid misidentifications (Figure 45).

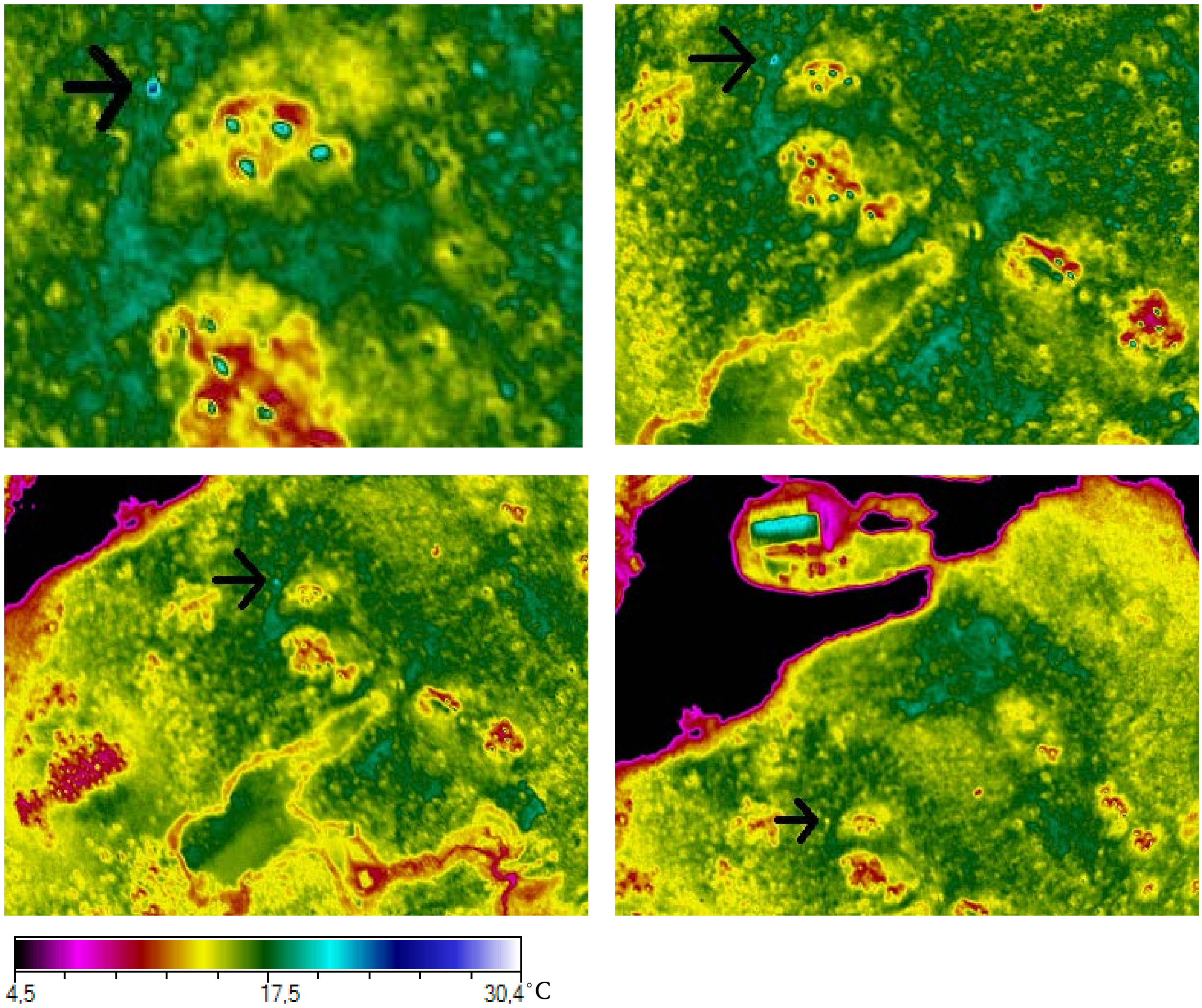
Figure 45: Verification of an RGB image against a thermal image. The black circles surround a stone



As well as being used to improve the counting method, flights with thermal sensors also served to develop methods for identifying penguins on and immediately nest to nest.

To further test overflights of penguin colonies with thermal sensors we carried out flights at different altitudes in order to determine the optimal altitude (Figure 46). It is not possible to transfer the flight parameters (height and image interval) used for the images taken in the visual range, because the thermal sensor has a markedly lower geometric resolution and a narrower lens angle (62°).
It is clear that individual penguins can be detected in thermal images taken at heights up to 50 m (Figure 46). It is also possible to determine whether a penguin is inside or outside of a guano-covered area. Flights at greater altitude (>50 m) would, of course, increase the area covered by individual images. However, at such heights, the detection of single penguins could no longer be guaranteed, particularly not against rocky backgrounds.

Figure 46: Thermal images from different heights (25 m top left, 50 m top right, 75 m bottom left, 100 m bottom right) using Ardley Island as an example; the black arrow indicates a penguin outside the guano-covered area

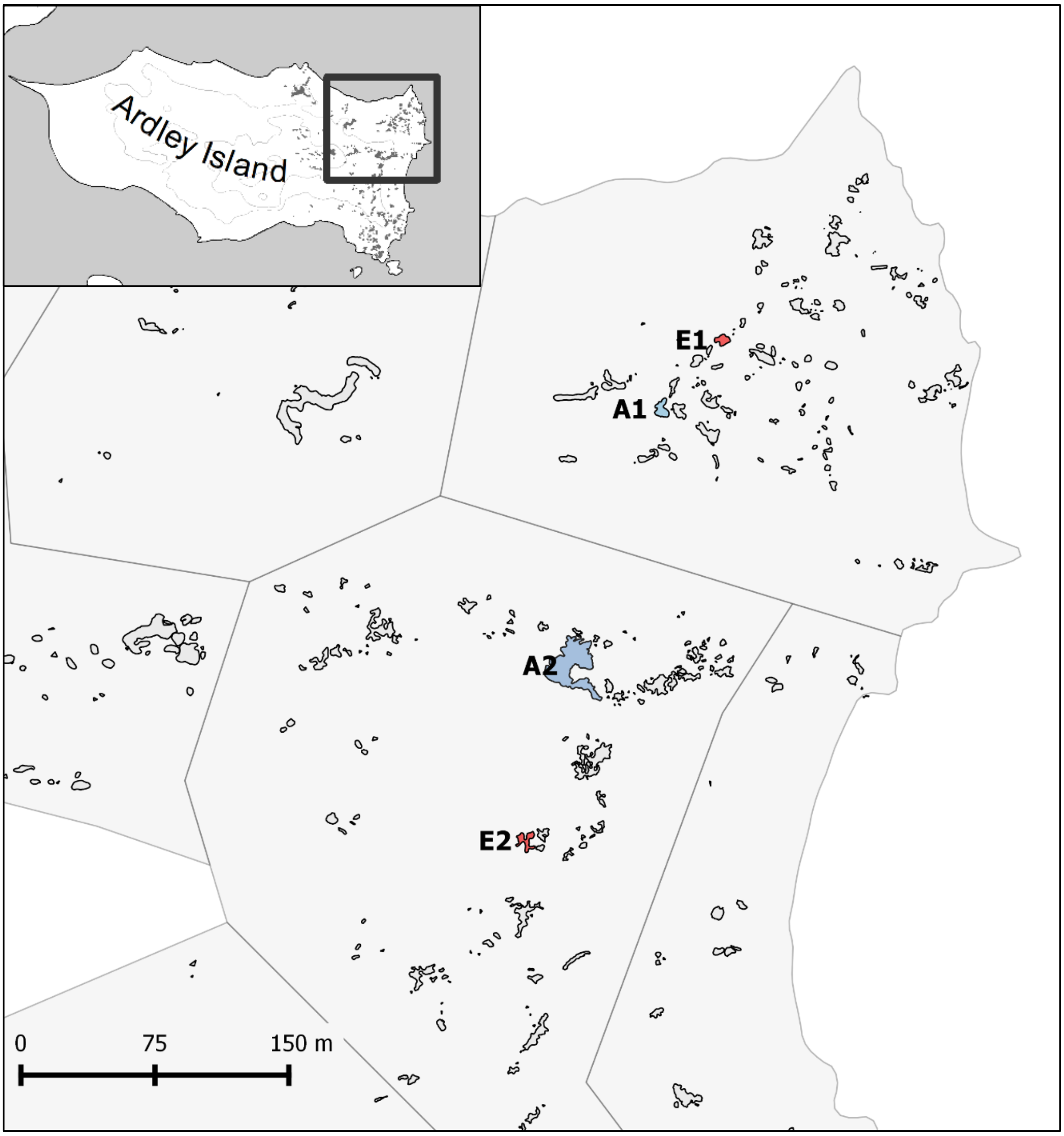


7.4.4 Disturbance experiments

7.4.4.1 Methods

During the 2014/15 season we investigated the effect of our drones on two locally occurring penguin species, the Adélie penguin (*Pygoscelis adelidae*) and the gentoo penguin (*Pygoscelis papua*). The experiments took place over nine days and they were all carried out on the Ardley Island penguin colony on two breeding groups of each species. One of each pair was near the coast, the other further away on a plateau (Figure 47). However, because of a heavy snow fall in December 2014, the second group of Adélie penguins almost completely disappeared so that no further investigations could take place on that group.

Figure 47: The location of the 4 breeding groups within the study area tested on Ardley Island; A1 & 2: Adélie penguins, E1 & 2: gentoo penguins



To determine the potential of drones to disturb the birds, we recorded videos of the individuals during UAV overflights. Behavioural changes were then identified and analysed using CowLog 2.0 software (Hänninen & Pastell 2009). The methods of behavioural analysis were based on the descriptions of Adélie penguins (Schuster 2010, Spurr 1975), gentoos (Van Zinderen Bakker et al. 1971) and for both species (Jouventin 1982). They will be examined in greater detail in the following sections.

The various patterns of behaviour can be divided into five categories: comfort behaviours and resting (which can be seen when the birds are undisturbed), and also vigilance, agonistic behaviour and escape behaviour, all of which are indicators of various types and intensities of disturbance. It is important to note that behavioural indicators of disturbance can occur in groups even when external disturbances are absent, caused by natural disquiet within the breeding group. In this study, we were unable to distinguish between natural disturbances caused by predators or disruption in the colony, and disturbances caused directly by the drones. All behavioural alternations were therefore included in the analysis irrespective of their cause.

Table 22: Summary of the behaviours described for Adélie and gentoo penguins in Jouventin (1982), Schuster (2010) and Van Zinderen Bakker et al. (1971).

COMFORT BEHAVIOURS	Adélie penguins	Gentoo penguins
	Comfort movements	Shaking movements
	Ruffle shake	Body shake shake
	Head shake	Headshake
		Tailwag
		Stretching movements
	Both-wing-stretch	Both-wing-stretch
	Yawn	Jaw stretch
		Body stretch
	Rapid wing flap	
	Cleaning	
	Head scratch	
	Shoulder/ Wing rub	
	Preening	
	Oil-preening	Oiling- Preening
	Nibble-preening	Nibbling-preening
		Body-nibbling
		Flipper-nibbling
	Maintenance	Breeding behaviour
	Nest maintenance	Nest building
	Egg maintenance	Egg laying
		Incubation
	Chick maintenance	Chick feeding
		Chick guarding
		Crèche stage
		Nest relief ceremonies
	Displays	Displays of pair-formation
	Ecstatic display	Ecstatic display (low/high intensity)
	Bowing	Bowing
	Mutual display	= Ecstatic display

RESTING BEHAVIOURS	Adélie penguins	Gentoo penguins
	Resting	Sleeping

VIGILANCE BEHAVIOURS	Adélie penguins	Gentoo penguins
	Vigilance	"Signs of nervousness" *(of individuals that moved away from the nest)*

AGONISTIC BEHAVIOURS	Adélie penguins	Gentoo penguins
	Agonistic behaviour	Threat behaviour
	Bill-to-axilla	low intensity
	Sideways stare, alternate stare	
	Point	
	Gape	high intensity
	Charge	
		Aggressive behaviour
	Tête-à-tête/bill-jousting	Tête-à-tête
	Peck	Pecking
	Full fighting	Attack and fighting

Table 22 shows a comparative overview of the diverse behaviours of the two species during the breeding period. In general, the two species have similar behavioural patterns although they are usually more pronounced and specialized in Adélies. On this point Jouventin (1982) writes "The Adélie penguin [...] has the richest repertoire of optical signals of all penguin species" (p. 19) and "In the Gentoo penguin [...] the »ecstatic« [...], »bowing« [...] and »mutual display« [...] are less elaborate and lack [...] specialized variants" (p.21).

Most of the behaviours described can be categorised in the group 'comfort behaviour'. These include comfort behaviour in the narrow sense: *stretching* and *shaking movements*. Both species show a whole body shaking movement, named *body shake* by Van Zinderen Bakker et al. (1971) and *ruffle shake* by Schuster (2010). Both these authors also describe identical head shaking (*headshake*). In the gentoo penguin Van Zinderen Bakker et al. (1971) describe an additional shaking behaviour, that of the tail (*tailwag*) that has never been mentioned for Adélies. The most distinctive stretching behaviour (*stretching movement*) in both species is the *both wing stretch (BWS)*. During this behaviour the penguin stretches itself as far as possible so that its wing tips almost meet behind its back. It is often followed by a *shaking movement*. Both species also demonstrate head stretching termed *jaw stretch* or *yawn*. Van Zinderen Bakker et al. (1971) mention in addition a behaviour that they call *body stretch* and describe as a combination of *BWS* and *jaw stretch.* In Adélies a behaviour termed *rapid wing flap* is frequently observed in which the wings are rapidly flapped forwards and backwards. This behaviour has not been described in gentoo penguins.

Comfort behaviour also includes grooming, which is the same in both species even though given different names by the different authors. Comfort behaviour also includes breeding and care behaviour, as well as maintenance behaviour, and these types include all behaviours associated with rearing progeny from nest building through incubation to care of chicks.

The final group of behaviours that can be assigned to comfort behaviour are *displays*. These comprise interactions between members of the breeding pair as well as, later in the season, those between parents and chicks. Both species have a specialised *ecstatic display* that can be observed in individuals at the nest and as one of the activities contributing to pair bond maintenance (*mutual display*). A further type of pair bonding behaviour is *bowing*, a form that occurs mainly when parents change places at the nest. Bowing is much more pronounced in gentoos than in Adélies.

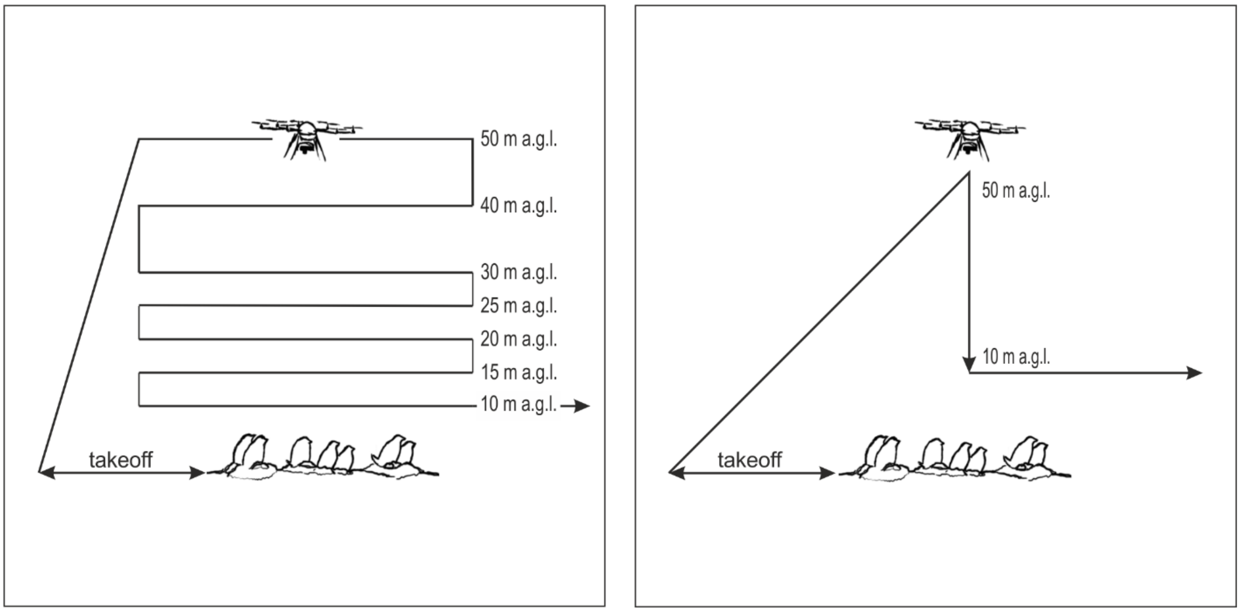
Some of these types of comfort behaviour also occur as displacement activities –movements that are irrelevant to or meaningless in a given situation – that arise in conflict situations (Jouventin 1982). Head shakes, in particular, are repeated frequently in stress situations even though they are physiologically unnecessary. The occurrence of such activities had to be ignored in this study because it is impossible unequivocally to identify displacement activity as such by observation.

Both species share only one form of resting behaviour and this is termed *resting* or *sleeping*. It is defined as "a lack of motion [and] a lack of observable attention to external stimuli" (Schuster 2010). In Adélie penguins, attention to external stimuli is easily differentiated from resting behaviour. When their eyes are open, a white ring around the eye can be clearly seen whereas, when the eye is closed or just a little open, this ring is much less obvious. Such clear differentiation is not possible in gentoos. In this species, the transition from sleep to resting with eyes open without paying particular attention to external stimuli, to vigilance is fluid and blurred. Because resting behaviour can be so clearly seen in Adélies, their vigilance behaviour is also clearly defined. Vigilance includes all kinds of attentive behaviour up to the point at which agonistic or defensive behaviour, or even escape behaviour, occurs. It is much more difficult to determine vigilance behaviour for gentoo penguins because it is not possible, in any particular case, to determine whether an individual with its eyes open is resting or is observing the surroundings. It is only possible to clearly determine behaviour types once behaviour indicating greater nervousness occurs. That is why it was necessary for the vigilance behaviour of gentoos to be divided into low and high vigilance. Low vigilance is defined by small movements of the head when there is no sign of nervousness such as rapid or sudden head movements, head movements of large amplitude, or neck stretching. These indications of nervousness fall into the category of high vigilance. The literature contains no descriptions of vigilance in gentoos with the exception of "signs of nervousness" in Van Zinderen Bakker et al. (1971): "When birds fled from their nests as I approached to inspect them, they would display what could only be interpreted as signs of nervousness. Looking back at the nest from a distance of twenty to thirty metres the birds held their flippers slightly extended and vibrated them and the body was also sometimes seen to tremble. The waving of an arm would be enough to make a bird in this state turn and run still further away" (page 256). However, this description refers to the situation when a bird has already fled from the nest. It is therefore not directly comparable with when we are carrying out our observations. We therefore had to define for ourselves what was vigilance behaviour based on our experience in the field.

The next stage in the behaviour of disturbed birds is composed of the various types of agonistic behaviour. These are the displays, threat gestures and attacks directed at other penguins or sources of disturbance. Adélie penguins show a clear pattern of agonistic behaviour in which each stage of increasing aggressivity occurs in a specific series. The series starts with the so called *bill-to-axilla* movement followed by *sideways stare*, *alternate stare*, *point, gape* and *charge.* In gentoos the behavioural types are less distinct and *bill-to-axilla* movement has not been noted. Van Zinderen Bakker et al. (1971) only distinguish *low intensity threats* and *high intensity threats.* If the threat gestures are ignored and the intruder comes closer, they are followed by aggressive behaviour: *têtê-à-têtê* (which some authors call *bill-jousting* because of the resemblance of the beak movements to fencing), *pecking* and, finally, *attack,* also known as *full fighting*. Both species have the same types of aggressive behaviour even though some of them are given somewhat different names by some authors. These behaviours are generally directed against another penguin, for example one from a neighbouring nest and can be taken as indicators of disturbance because the potential for conflict within the breeding group is increased by the appearance of the drone (or natural predators). This is also true if the aggression is not aimed directly at the drone.

The remaining group of behaviour types is defined as escape, that is, when the penguins leave their nests and flee from the drone, thereby risking exposing their eggs or chicks to cold or predators. Other behaviours described in the literature such as locomotion, copulation and foraging, were irrelevant to the study and were therefore not included in the analysis.

Figure 48: The flight schemes used in the investigation: horizontal mode (left), vertical mode (right)



The flights over the study groups were carried out in two different modes: horizontal and vertical (Figure 48). In horizontal mode the drone was flown along transects about 80 m long and at heights of 50, 40, 30, 25, 20, 15 and 10 m above the breeding group. The transects started with the highest altitude. The vertical mode also started at a height of 50 m which, however, was directly over the breeding group. The altitude was then gradually reduced so as to approach the birds. In both modes the take off point was 30-50 m away from the center of the breeding group. Horizontal flights lasted 2-5 minutes, vertical flights 1-2 minutes. Because of the ability of the drone to follow pre-programmed routes, it was possible to repeat the same flight path for all the tests. The flight speed was also pre-programmed but varied, nevertheless, because of the influence of different wind speeds. The horizontal and vertical mode tests were supplemented by tests with repeated horizontal habituation flights at an altitude of 10 m. Disturbance stimuli are not only of a visual nature but can also be acoustic. Therefore, the noise of the drone plays a role as well as its size (cf. chapter 7.4). According the manufactures (personal communication from HiSystems) our drone emits noise at a level of 70 dB at a distance of 5 m. Because of the propagation of the sound, the sound pressure falls by 6 dB at each doubling of the distance between source and recipient (Brown 2008). Thus, for example, a volume of 52 dB is expected at ground level when the drone is at a flight height of 40 m. In practice, however, the volume of the noise from the drone at a particular distance is not constant but depends strongly on environmental conditions and flight parameters. We were not able to measure the actual volume produced during the test flights. However, we measured the wind speed which can, at least, function as a proxy measure because it strongly influences the noise level of the drone. It was measured during the flights as a short-term average using a hand-held anemometer (Silva® ADC Wind). The statistical analyses were carried out as described in Rümmler et al. (2015) for Adélie and gentoo penguins.

7.4.4.2 Results

Adélie penguins

The analysis of the surveys on Adélie penguins demonstrated a significant influence of flight altitude on penguin behaviour. There was no influence, however, of the wind speed measured. The results fell into 3 categories for both the horizontal mode and vertical mode tests. The first group was of little disturbance before the drone took off, the intermediate group obtained for heights of above 15m for horizontal mode and above 20m for vertical mode, and the third group was of high disturbance below these altitudes. Above 20m no difference between the two flight modes could be found. Below vertical flights had a higher influence compared to horizontal flights. The habituation experiments indicated that there was no change in the disturbance levels when flights were repeated over short time intervals at low altitudes (for detailed results see Rümmler et al. 2015).

Gentoo penguins

The same statistical analysis method used for Adélie penguins was also employed for gentoo penguins, but given the presence of a second evaluable breeding group, the group number was added as another random factor to the model. Just like with Adélie penguins, no influence of wind velocity or the wind velocity-altitude interaction on horizontal ($p = 0.798$ and $p = 0.215$, respectively) or vertical ($p = 0.415$ and $p = 0.449$, respectively) flights could be demonstrated using binomial Generalized Linear Mixed Models (GLMM). Only the flight altitude influenced the interference level significantly ($p < 0.001$ for vertical and horizontal flights). As the other factors had no influence, the differences between the individual flight altitudes were tested using a univariate analysis of variance (ANOVA). No variance homogeneity was found for either horizontal or vertical flights (Levene test: horizontal: $L = 6.019$, $p < 0.001$, $N = 273$; vertical: $L = 40.611$, $p < 0.001$, $N = 194$). Not fulfilling the requirements of independence of the samples and variance homogeneity was accepted for the univariate ANOVA, and later a post-hoc test which was appropriate for heterogeneous variance was selected. The ANOVA found significant differences for the impact depending on the flight altitude in both horizontal ($F = 10.312$, $p < 0.001$, $N = 273$) and vertical ($F = 33.019$, $p < 0.001$, $N = 194$) flights.

For horizontal flights, the following correlations were found using a Tamhane-T2 post-hoc test (cf. Table 23): control phases without interference by the drone had the same disturbance level as high flight altitudes of 50 m and 40 m, but also 25 m differs significantly from the other altitudes. The lowest altitude (10 m) differs significantly from the control, the transfer (time between the drone taking off and reaching the first waypoint at 50 m) and the higher altitudes (40 and 50 m), but not from the other flight altitudes. The remaining mid-range altitudes showed no significant difference from the other altitudes or the transfer, only from the control.

Table 23: Results of pairwise comparisons (Tamhane-T2 post-hoc test) of the interference during different horizontal flying heights on gentoo penguins. The p-values are given in the upper right triangle of the matrix and the mean differences (column header minus row header) of the logit-transformed interference values in the lower left triangle. Significant differences are printed in bold.

	Control	Transfer	50 m	40 m	30 m	25 m	20 m	15 m	10 m
Control		**0.019**	1	0.833	**0.002**	0.235	**0.045**	**0.010**	**0.001**
Transfer	**-0.457**		1	1	0.364	0.898	0.394	0.226	**0.007**
50 m	-0.281	0.176		1	0.325	0.751	0.262	0.147	**0.004**
40 m	-0.403	0.053	-0.123		0.518	0.882	0.384	0.241	**0.006**
30 m	**-1.075**	-0.618	-0.794	-0.672		1	1	1	0.136
25 m	-1.414	-0.957	-1.133	-1.010	-0.339		1	1	0.811
20 m	**-1.725**	-1.268	-1.444	-1.321	-0.650	-0.311		1	0.982
15 m	**-1.552**	-1.096	-1.272	-1.149	-0.477	-0.138	0.172		0.811
10 m	**-2.924**	**-2.468**	**-2.644**	**-2.521**	-1.849	-1.511	-1.200	-1.372	

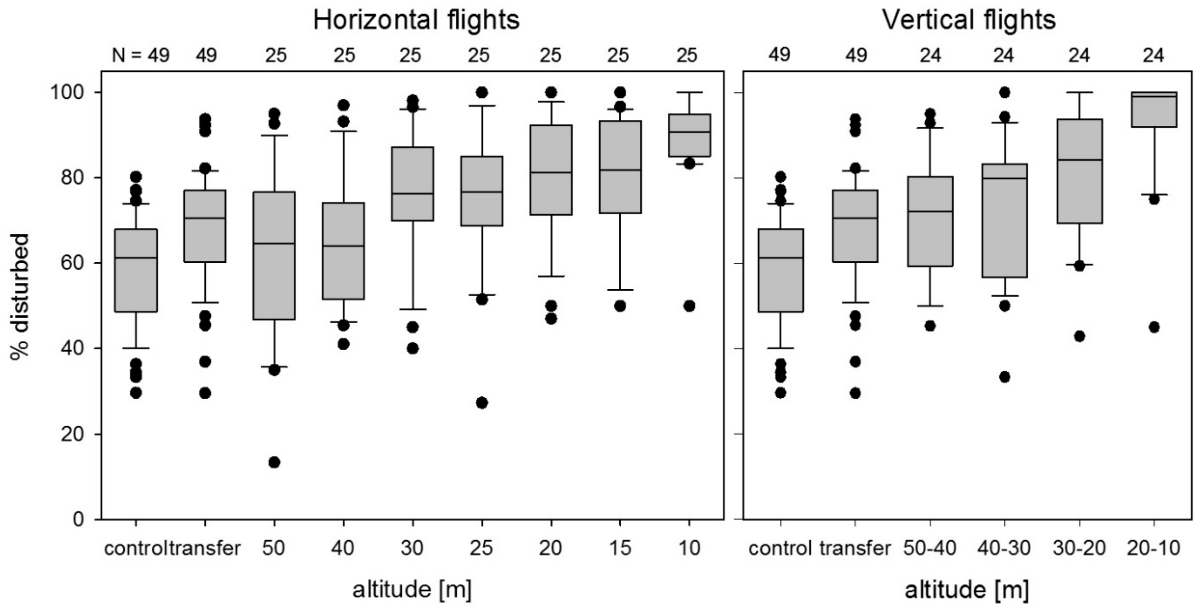
In vertical flight mode, the results are clearer (Table 24): the control phase was significantly different from all the other phases, except for 40-30 m (here appears extremely high value distribution) and showed a low level of disturbance. The 10 to-20 m class significantly distinguished itself clearly from all of the others with a high level of disturbance. The remaining altitudes and the transfer did not differ among themselves.

Table 24: Results of pairwise comparisons (Tamhane-T2 post-hoc test) of the interference during different vertical flying heights on gentoo penguins. The p-values are given in the upper right triangle of the matrix and the mean differences (column header minus row header) of the logit-transformed interference values in the lower left triangle. Significant differences are printed in bold.

	Control	Transfer	50 - 40 m	40 - 30 m	30 - 20 m	20 - 10 m
Control		**0.008**	**0.019**	0.153	**0.014**	**<0.001**
Transfer	**-0.457**		0.995	0.879	0.094	**<0.001**
50 - 40 m	**-0.665**	-0.208		0.998	0.228	**<0.001**
40 - 30 m	-1.072	-0.615	-0.407		0.840	**<0.001**
30 - 20 m	**-2.178**	-1.722	-1.513	-1.106		**0.021**
20 - 10 m	**-5.415**	**-4.959**	**-4.750**	**-4.344**	**-3.237**	

If the horizontal and vertical flights are compared to each other, similar results are found as for the Adélie penguins: there is no significant difference compared to all flight altitudes (Mann-Whitney U = 9.590, p = 0.054, N = 271) until the range under 20 m, when the vertical flight mode had a greater influence (Mann-Whitney U = 897.5, p = 0.001, N = 74).

Figure 49: Results of interference flights on gentoo penguins (horizontal flights left, vertical flights right). The percentage is shown of birds investigated with interference-indicating behaviour at a particular flying height of the drone, during both the control phase (control) and in the phase between start and reaching the first waypoint (transfer)



The analyses of the habituation experiments with gentoo penguins did not find any signs of habituation at an altitude of 10 m. During 3 test flights of eight repetitions each following at short intervals, no correlation between the repetition and interference level was found (Spearman rho = 0.340, p = 0.140, N = 24).

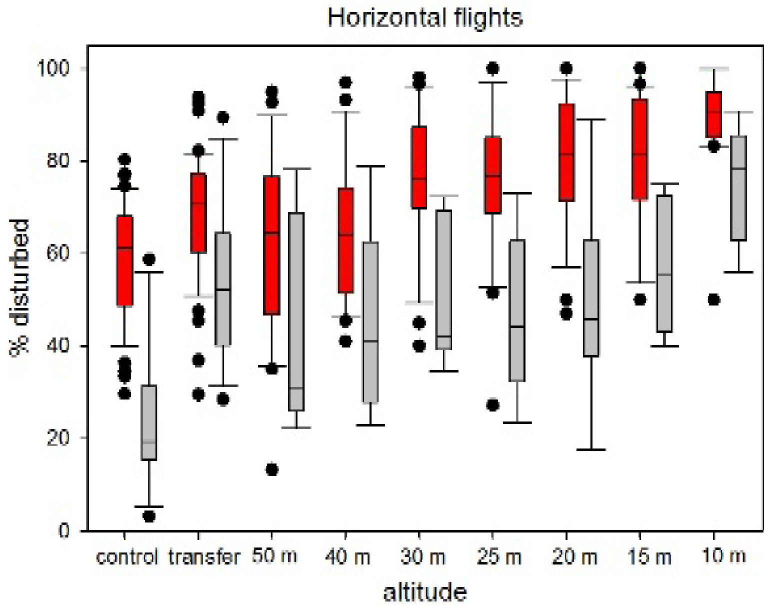
Comparison of both species

We observed a very similar pattern in the impact of the drone on both species. With vertical flights, three classes could be defined for the two species (low, medium and high interference), which are based on the same altitudes.

For horizontal flights, differences between the species were noted, even though the underlying pattern was similar. With Adélie penguins, a grouping of the disturbance levels into the three above-mentioned categories was evident. With gentoo penguins, the results were less distinct, and classification into such clear categories was not possible. Nevertheless, the disturbance level here was lowest for the control without drone and highest at low altitudes (see Figure 50).

One of the main differences between the species involved the absolute disturbance level. Even at rest, before the drone started up, it was significantly higher (Mann-Whitney-U = 552.0, $p < 0.001$, N = 61) among gentoo penguins (mean: 58.6 %, N = 49) than Adélie penguins (mean: 24.5 %, N = 12). This difference persisted during the transfer phase (gentoo penguins mean: 67.9 %, N = 49, Adélie penguins mean: 54.4 %, N = 18; Mann-Whitney U = 644.0, p = 0.004) and all subsequent altitudes (gentoo penguins mean: 77.1%, N = 271, Adélie penguins mean: 55.7 %, N = 99; Mann-Whitney U = 20894.0, $p < 0.001$, Figure 50).

Figure 50: Comparison of interference level among gentoo (red) and Adélie penguins (grey) during horizontal over flights



Regarding the relative changes in disturbance levels, the start (transfer groups) seems to have less impact among gentoo penguins, as the disturbance compared to control is less strongly increased and is overall one of the lowest level of all flight situations. In contrast, the disturbance during the transfer among Adélie penguins was one of the largest within the intermediate disturbance category.

7.4.4.1 Discussion

Our results show that the penguin species examined are noticeable affected by drones. All of the experiments revealed that even drones flying at heights of 50 m can still be noticed by the birds. This influence increases as the flight altitude decreases. For both species and flight directions, with the exception of horizontal flights over gentoo penguins, another stronger increase in disturbance below 20 m or 15 m flight altitude, respectively, was found. These results correlate well with observations made by Müller-Schwarze and Müller-Schwarze (1977), who conducted dummy trials with skuas and Adélie penguins and ascertained that reactions to the predator were evident from a flying altitude of the skua of 14 m. This could confirm the theory that the drone resembles a natural predator from the penguins' perspective and therefore would be considered a threat. When comparing the two penguin species, drone take off apparently has a greater influence on Adélie than gentoo penguins, although the basic level of disquiet among gentoo penguins is greater. The reaction to take off was less for gentoo penguins, although take off took place closer to gentoo (25-35 m) than to Adélie penguins (50 m). During low level over flights the disturbance level among gentoo penguins was higher. When contrasted to the control, however, the relative disturbance appears comparable. As only three brooding groups were analysed here, this comparison cannot be considered validated and further experiments are required to confirm these outcomes.

It was ascertained for both species that vertical flights below 20 m generated greater disturbance than horizontal flights. This is explicable as a predator diving directly towards a penguin poses a greater threat than one that is just flying over a brooding group. Nevertheless, some methodological causes should also be considered: for one thing, a vertically flying drone maintains the same horizontal distance from the separate individuals and just gets closer the whole time, while a horizontally flying drone is already moving away from the first individuals encountered, which can calm down, while it is approaching the birds at the other end of the group. As the analysis looks at the mean disturbance within the group, the birds that are already calming down reduce the disturbance level during the flyover. Second, vigilance regarding a vertical flight is easier to recognise for an observer as the penguin must raise its head (and beak), while no body movement may be required if the nest is favourably oriented to watch a drone during a horizontal flight. Personal observations in the field additionally suggest that the sound of the drone is louder during vertical movements than horizontal flight.

7.4.4.2 Conclusions

It must be noted that all conclusions drawn here are based on results from one drone model and are valid only for its characteristics, they cannot necessarily be easily transferred to other models.

To establish guidelines for the use of drones over penguin colonies, we can make the following statements based on our experiments. To prevent the penguins noticing the drone and thus completely excluding any disturbance, a flying height of 50 m is not sufficient. Further experiments are required to ascertain the exact altitude at which perception begins. To avoid increased disturbance, flight altitudes must never fall below 20 m. To prevent disturbance when the drone takes off, the distances we employed of about 30 m (gentoo penguins) and about 50 m (Adélie penguins) were not sufficient, with a stronger impact being noted on the Adélie penguins. Therefore we suggest a greater starting distance for Adélie penguins; for gentoo penguins the observed disturbance was less, which means a slight increase of the distance should be sufficient here.

7.5 Comparison of the methods

7.5.1 Quality

In terms of the quality of the results, the counting methods that performed best involved counting the nests directly. In particular, the GPS-supported full survey provided the most exact results, which allowed the nests to be identified correctly and the non-breeding penguins to be recognised.

With GPS-supported partial survey and panorama photography, the quality of the results depends primarily on whether a representative number of nests can be included for the density calculations, along with the specialist knowledge of the people doing the processing. This is particularly needed for colonies with a wide range of different nest group densities (e.g. Ardley Island).

UAV overflights with RGB sensors allowed clear identification of individual penguins and their nests, depending on the background. Problems are provoked by birds that are present near a nest group at the time the image is made (perhaps on guano-covered ground), but do not have a nest of their own. They are either non-breeding birds or individuals on the way to provide their partner or chick with food. The distinction is strongly dependent on micro-relief, the colour of the background and the level of development of the nests. The situation is similar for UV and NIR images, which do not provide any added benefit compared with the RGB images.

Breeding penguins are surprisingly clearly evident on thermal UAV images taken at a relatively low flight altitude (<30 m): The combination of a higher temperature radiation of the birds and lower temperature of their nests – compared with their environment – suggests that further development of this method (e.g. the availability of efficient UAV-adapted thermal cameras), possibly in combination with optical images, could be a promising way to clearly distinguish breeding and non-breeding birds.

7.5.2 Time requirement

Taking panorama photos of individual nest groups is the method that requires the least amount of time on site, if the site is clearly visible. It does not require preparation, and it is sufficient to photograph nest groups with a simple camera from a raised location and then count them later. This method is also relatively independent of weather conditions.

With a GPS-supported partial survey, the time required depends primarily on the homogeneity of the nest density. This parameter determines how many nest groups must be recorded to achieve sufficient accuracy.

More time is required for data collection and preparation for a flight with an UAV, though it makes no difference which sensor is used. The deployment must be planned and the equipment set up. Favourable weather conditions (especially wind conditions) are also a limiting factor. The flights themselves take relatively little time. For example, Withem Island with over 10,000 breeding pairs could be completely covered several times in less than 3 hours. The post-processing to produce the orthomosaics only takes a few hours. Manual counting takes the most time, but the procedure can be considerably accelerated due to the development of semiautomatic methods (cf. e.g. McNeill et al. (2011) for aerial images taken by plane).

Thus, the most time-consuming method is recording nest groups with a GPS-supported full survey. For the charting of Ardley Island, 2 people need 2-3 days. In addition, the survey must be planned and organised in precise detail in advance.

7.5.3 Disturbance potential

The least impact on the penguins is expected with the panoramaic photography method as it can be used to collect data soundlessly from a greater distance, if it is not necessary to go through the colony, which can be the case to a great extent with complex terrain structure.

The disturbance potential of UAV overflights is being thoroughly investigated given the newness of the technology. Experience has shown that a distinction must be made primarily between two moments of disturbance: the take off and landing procedures and the overflight. Results show that with the UAV model used here, overflights at 50 m trigger few reactions compared with lower flight altitudes (Rümmler et al. 2015). Reactions to the UAV, even attacks, by other bird species present (e.g. skuas) were not observed. In contrast to GPS-supported surveying and counting, these methods involve few areas of the colony being entered by people.

The GPS-supported full survey method has the highest impact potential among the methods tested, as every section of the colony must be entered at least once by the surveying personnel. The extent of disturbance for penguins nesting at the edge of the colony or nest group is assumed to be elevated given the short distance between the people and the nests (0.5 to 1 m). It also depends on the behaviour of the individual investigators. Rapid and for the birds unpredictable movements often risk driving adults from their nests. Such a situation is associated with major dangers like the presence of predators nearby (e.g. skuas) and cooling of eggs and chicks (wind, cold, wet). Partial surveying is subject to similar risks, but the disturbance potential depends strongly on the number of nest groups that have to be surveyed.

7.5.4 Susceptibility to weather

Methods that involve direct counting of birds or nests are less susceptible to weather conditions than imaging methods such as full and partial surveying. Panoramic photography is useless in fog, as the distant nests cannot be made out. Likewise, fog is a problem for UAV overflights. Flights are also hindered by strong winds (stronger than the cruising speed of the UAV) and precipitation.

7.5.5 Costs

As all survey methods have to be carried out on site, the costs of travelling to the research area are the same for all methods. There are differences between methods, however, in the time and labour investment needed and the cost of purchasing the technology required.

The lowest cost is associated with panorama photography, as it only requires a standard digital camera, a simple GPS (to determine where the panorama was shot) and a photographer. To estimate the breeding pair number of the entire colony, satellite images will have to be obtained as especially with large colonies or ones with complex relief only part of the area can be recorded directly with panorama photography. For the most exact results, high-resolution satellite images are also required, to determine the extent of the entire colony. The cost of high-resolution satellite images can rise to thousands of euros for a scene of 100 km^2.

For the methods involving UAV overflights, considerable one-off expense is involved in purchasing the technology: UAV, sensors and analysis software. The costs range widely, depending on how efficient the system needs to be. The efficiency in turn greatly affects the quality of the data obtained and the time investment required for processing and analysing the data. As no high-resolution satellite images are required, there may be fewer long-term costs than with panorama photography.

A similar situation applies to the GPS-supported surveys, although the initial purchasing cost of the recording equipment (GPS logger, field mapping device, software) is considerably lower. The major expense with this method is the personnel required for the fieldwork. For the preparation and analysis of data, considerably lower personnel and technical expense is involved than with the other methods.

7.5.6 Conclusion

All of the evaluation criteria are considered, it becomes clear that no method is superior to the others (see Table 25). Full surveying has the highest data quality, but also the greatest time investment, cost and disturbance potential. Panorama photography and partial surveying have the lowest data quality and the high resolution satellite images can be expensive, but these methods are quick to use and their disturbance potential is limited. The UAV overflights form an intermediate option, providing good data quality while taking relatively little time, for a low cost and low disturbance potential. Its only disadvantage is the high susceptibility to weather conditions.

Thus, which method to use ultimately depends entirely on the requirements of the user or on the local conditions, so all of the methods have their own advantages.

Table 25: Comparison of terrestrial methods to determine population size of penguin colonies (*Pygoscelis* sp.): * - low ; ** - medium; *** - high

Method	Data quality	Time requirement	Cost	Interference potential	Susceptibility to weather
Panorama photography	*	*	**	**	**
Full surveying on site	***	***	***	***	*
Partial surveying on site	*	*	**	**	*
UAV flight	**	**	*	*	***

8 Classifying the colour differences in penguin guano

Using remote sensing methods, it is currently possible to spot and survey seabird colonies, even when the individual animals cannot be identified (e.g. Fretwell et al. 2015; LaRue et al. 2014; Lynch & LaRue 2014). The widespread covering of guano on the ground can often be clearly distinguished from the surroundings due to its difference in colour even at medium resolution satellite images (Fretwell et al. 2015). There have already been successful attempts to define the distribution of different species among penguins in mixed colonies on satellite images (Lynch et al. 2012). However, these studies are just isolated cases so far. Particularly with completely unknown colonies, it is still very difficult to identify the species present from satellite images. As it is impossible to pick out single individuals reliably with the currently available ground resolution, interspecific differences in the clearly visible guano coloration could provide an important clue for species identification. The aim of this substudy was to ascertain whether there were differences in the guano coloration of a colony of one species over the course of the season or between different species (e.g. due to variations in diet). If that turns out to be the case, those differences could be used to characterise unknown colonies on satellite images based on the colour of the guano of a particular species.

The colour of penguin guano primarily depends on their diet. Earlier studies determined a penguin's diet from their excrement, through finding either undigested remains (Kooyman et al. 2004) or DNA residues (Jarman et al. 2013). They also noted a link between differences in diet and differences in guano coloration (Kooyman et al. 2004). But as far as we know, no study has yet explicitly attempted to link the different colours of guano to the diet.

If the guano coloration were solely dependent on the composition of the bird's diet, the food supply available at the time of examination would be decisive for classifying the guano colour differences. If several food sources are available, different species could utilise them to varying extents according to their ecological niche, which would lead to differences in colour. If in contrast only one food source is available, which both species rely on to the same extent, the guano of the different species would have the same colour. It is of course possible that different species could produce differently coloured guano with the same diet because of physiological differences. This cannot be assumed for closely related species like *Pygoscelis* penguins, but could be useful in comparisons with other bird groups (e.g. petrels, cormorants). When comparing with other bird families, there is the added element that fundamental differences in hunting style and morphology may make it very unlikely that they would go after the same food source. This possibility does not apply to the *Pygoscelis* penguins either. In this study, it was not possible to examine the availability of food sources at the time of investigation.

There are very few studies in general examining potential colour characteristics and inter- and intraspecific, spatial and phenological distinctions. The distinctive spectrum of guano against the background on satellite images has been used several times to detect seabird colonies (Fretwell et al. 2015; Fretwell & Trathan 2009; Mustafa et al. 2012; Schwaller et al. 2013b) and estimate their size (Fretwell et al. 2012; LaRue et al. 2014; Lynch et al. 2012; Lynch & Schwaller 2014; Naveen et al. 2012). In all of these cases, however, it was known in advance which species was/were present through range limits, habitat conditions or field studies. As far as we know, there is no successful study in which the species in seabird colonies pictured on a satellite image could be identified without one of those preconditions. That is why it is particularly interesting to ascertain whether there are clear interspecies differences in the colour spectrum of penguin guano which would enable the identification of the species in an unfamiliar colony (see Figure 54).

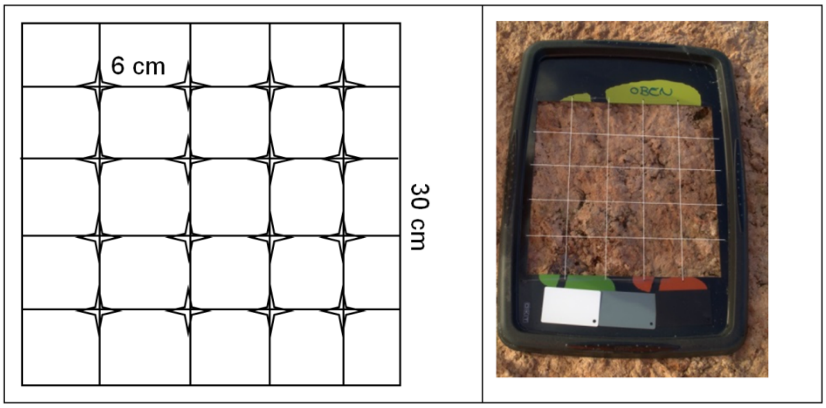
8.1 Methods

To classify colour differences of guano, it is necessary to first determine and classify the colour of guano on site or using remote sensing methods. The guano colour is identified on the ground with the help of Munsell colour charts (Munsell 1969) and photography like UAV and satellite images, as described below.

8.1.1 Munsell colour charts

The first step was to determine the colour of the guano using standardised Munsell colour charts in the 2014/15 season. A grid 0.3 x 0.3 m (corresponding to the area of one pixel of the highest resolution of a suitable satellite Worldview 3) was placed on four defined spots between the penguin nests. Subsequently, the colour at all 16 points of the grid pattern was defined with the Munsell colour charts (Figure 51), as only discontinuous measurements can be done with the colour charts. This colour determination was repeated several times during the course of the season. To exclude subjective influences on the colour determination, they were all done by the same two people. The test sites were placed near three gentoo and one Adélie penguin nest.

Figure 51: Outline of guano colour determination using colour charts (left) and example of grid pattern (right). Within a 0.3 x 0.3 m grid there were 16 sampling points (stars) at 60 mm intervals

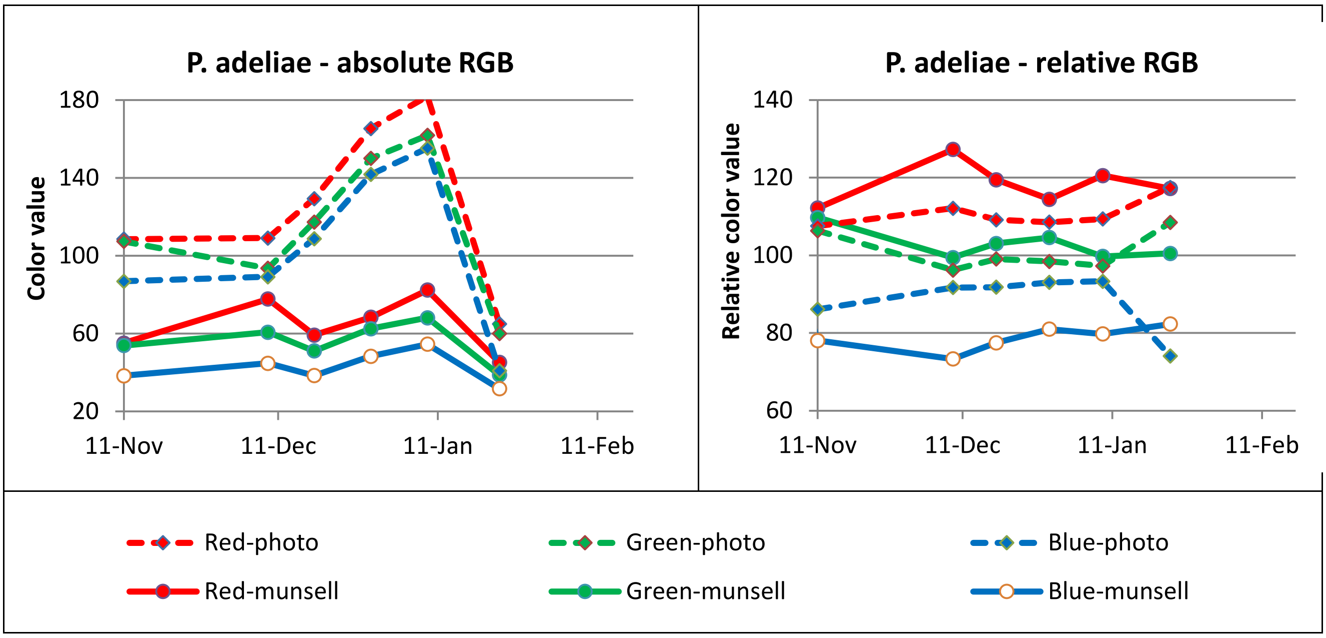


8.1.2 Photography on site

8.1.2.1 Suitability of photography on site

Taking photographs with a digital camera at the study site promises to be a more suitable method since determining colour with Munsell colour charts takes a huge amount of time, but first the comparability of values to the charts has to be investigated. To be able to compare the two methods, the 0.3 x 0.3 m grid was photographed with a digital camera (Canon PowerShot G15) in RAW format at the same test sites and at the same time as the colour chart determination. Black, white and grey cards were included in the photos to enable a later matching of brightness and colour, to make photos taken under different lighting conditions comparable. In addition, white balancing was done in all pictures according to the white card and uniform brightness levels set according to the grey card. In GIS the recordings were arranged in line with a reference image to make the position of the sampling points uniform so after resampling, the RGB values of the 16 points, comparable to the determination with the Munsell charts, could be read off.

Figure 52: Example of changes during the course of a season with the absolute RGB values (left) converted from Munsell values and read from the digital photos compared with the relative RGB values (right)



To restore the comparability of the Munsell codes with the RGB colour spaces of a digital photo, a translation matrix (Centore 2013) was used. This matrix translated the colour shades manually determined with colour charts into RGB values. Values missing in the Centore matrix were interpolated by linear regression. The translation into RGB values also enables a simpler presentation in diagrams and statistical analysis of the data.

When analysing the results of the manual colour determination (see Figure 52, left diagram), wide fluctuations become evident in the colour intensity of the red, green, and blue components, along with the brightness of the guano. They are affected by differences in moisture levels. Extremely wet guano ('mud') is darker than drier versions. The brightness is especially affected by the weather. Thus, for all sampling points, very low colour values were registered on 23/01/2015 because it was raining persistently and the ground was wet. To exclude the fluctuations in brightness, the absolute values were converted into relative colour values (cf. Sect.8.1.2.2), so the purely colour changes could be compared (see Figure 52, right diagram).

Comparison with the photographically derived RGB values showed that they were darker in general and the range of fluctuation was smaller (see Figure 52). The basic course of changes in brightness was similar to the Munsell values and thus primarily also reflects changes in the weather.

A decisive element in finding any distinctions is the relationship of the individual colour components to each other, as that remains unaffected by the variations in brightness caused by wetness. It revealed that, except for a few images, the red component was always most strongly pronounced, followed by green and then blue. This applied to both the Munsell and the photo results. It confirmed that despite the variation in brightness, colour determination using Munsell colour charts or digital photographs provided fundamentally comparable outcomes.

8.1.2.2 Use of photography on site

In the 2014/15 season, at the same four test sites where the examination with Munsell colour charts was done, the guano was photographed with a digital camera on a tripod at around 1 m height from the ground. As the subsequent processing involved laborious manual white balancing which was time-consuming, a new recording method was tried in the following season.

A special photobox was built (cf. Figure 53), which purpose was to enable a faster recording procedure and in turn would allow more test sites to be sampled. On the other hand, the photobox shaded the guano to be photographed from sunlight. The sample would be illuminated only with the camera's (Canon G15 digital camera) internal flash. This provided the benefit of a constant wavelength composition of the light source that would not be affected by changing environmental factors, like cloud cover or position of the sun. Likewise, individual white balancing was no longer required. This allowed the work on site and the post-processing to be done more efficiently.

Figure 53: Specially prepared photobox with mounted camera on site

In the first season (2014/15), the test sites were located at three gentoo and one Adélie penguin nest, whereas in the next season (2015/16) the new methodology allowed a total of 17 nest groups (13 gentoo penguin groups, three Adélie penguin nest groups and one mixed gentoo-Adélie penguin group) to be photographed at 10-day intervals. This produced 1109 photos at a total of eight investigation dates. Using a script for RawTherapee and IDL-ENVI, the mean of the red, blue and green channels was automatically determined for all photos of a species at the different timepoints.

To exclude moisture-induced fluctuations in the brightness of guano (see Sect. 8.1.2.1) and enable a detailed analysis to be done of the colour component distribution of guano from photographs, the colour values were standardised. The relative colour value F was then calculated according to (1)

$$F_X = \frac{X}{R+G+B} \times 300 \qquad (1)$$

with X representing each of the colour components considered (red, green or blue). Multiplication by 300 was done solely for reasons of clarity, so the results would be whole numbers and thus look more similar to the original 8-Bit gray values. As a result, the relative colour value could be analysed free of brightness fluctuations (see Figure 52).

8.1.3 UAV images

The spectral signature was determined from the UAV mosaics of the test sites surveyed in the 2014/15 season, for which the guano colour had been determined with Munsell colour charts. However, it was not possible to normalise the mosaics radiometrically, as they were composed of hundreds of differently illuminated individual images, so differences in the lighting and colour temperature could be offset. As with the satellite images, it is not always possible with the UAV images to find the exact position at which the ground photos were taken, which was due primarily to the radically changing surroundings of the test sites during the season. Another factor is the GPS accuracy of 2 – 4 m which makes the exact positioning of the test sites in the uav mosaic very difficult.

8.1.4 Satellite images

The spectral signature of the test sites was recorded from the available satellite images and the data was radiometrically corrected. To achieve this, the grey values were converted into reflectance values, an atmospheric correction was applied using Dark-Object-Subtraction (Chavez 1988) and, in a similar fashion as the ground images, the RGB values were transformed into relative colour values. Inaccuracies in the evaluation occurred because the precise positions of the test sites could not be established in the satellite images. This is due to the limited spatial resolution of the satellite images of 0.4 - 0.6 m per pixel in comparison with the 0.3 m long sides of the sample grid and the positional inaccuracy of the satellite images (approx. 3.5 m) plus the inadequate number of ground control points on Ardley Island. There are also no images from mid-December, which makes it difficult to compare the RGB results with the ground measurement data.

8.2 Results

To be able to compare the colour values of both species, the mean of the measurements at all test sites was generated. This means that for Adélie penguins, one nest group could be evaluated in the 2014/15 season and three in the 2015/16 season along with three nest groups for gentoo penguins in the 2014/15 season and 13 nest groups in the 2015/16 season.

As Figure 55 shows, the curves of the standardised colour values from Munsell and photographic determinations are the most similar. The exact values are not the same; the digital photos have almost without exception a higher red value than the blue component, while the curves run predominantly parallel.

Both species examined can only be distinguished at the beginning of the season. It is apparent that the relative red and green components of the Adélie penguin guano are almost the same at the beginning of the season, while the gentoo penguin guano has a clearly higher composition of red in the colour (Figure 54). This is consistent with observations from field workers who noted that at the beginning of the season, Adélie penguin excrement was often green. According to Heine & Speir (1989) this colouration occurs when the penguins have not been hunting for food in the sea for a long time. Sladen (1958) claims the green coloration is due to the penguins' gall pigments, while Myrcha & Tatur (1991) state that it is due to proteins, cholic acid and undigested algae cells (the diet of krill) in the guano. Later in the season this green coloration does not appear, so the red component is stronger. In the 2015/16 season, this green coloration was not observed, probably due to the later start of the fieldwork. Likewise, a slight increase in the relative red component of both species was evident at the end of the season.

In contrast to the simultaneously arranged Munsell and photographic colour determinations, the UAV images were taken on different days. For this reason, the shape of the curve can be influenced by short-term fluctuations. When analysing the relative colour values extracted from the UAV images, it is striking that at the beginning of the season the red and green components are almost equal for Adélie penguins and less pronounced but similar for the gentoo penguins. In the UAV images it is evident that at these sites the guano actually does appear greenish. Later in the season this strong green component fades. Another prominent aspect is the clear increase in the blue component in January, even surpassing the red component at times. In the UAV images this guano looks very dark, almost black.

From the satellite images it is striking that the relative red component is much larger than from the ground and UAV measurements. Details confirm that at the start of the season, the Adélie penguin guano has a relatively larger green component than the gentoo penguin guano. This distinction fades later in the season.

Figure 54: Model photos of penguin guano from Adélie (*P. adeliae*) and gentoo (*P. papua*) penguins from the same area at three different timepoints. The photos have been processed to make the colours clearly visible to the viewer

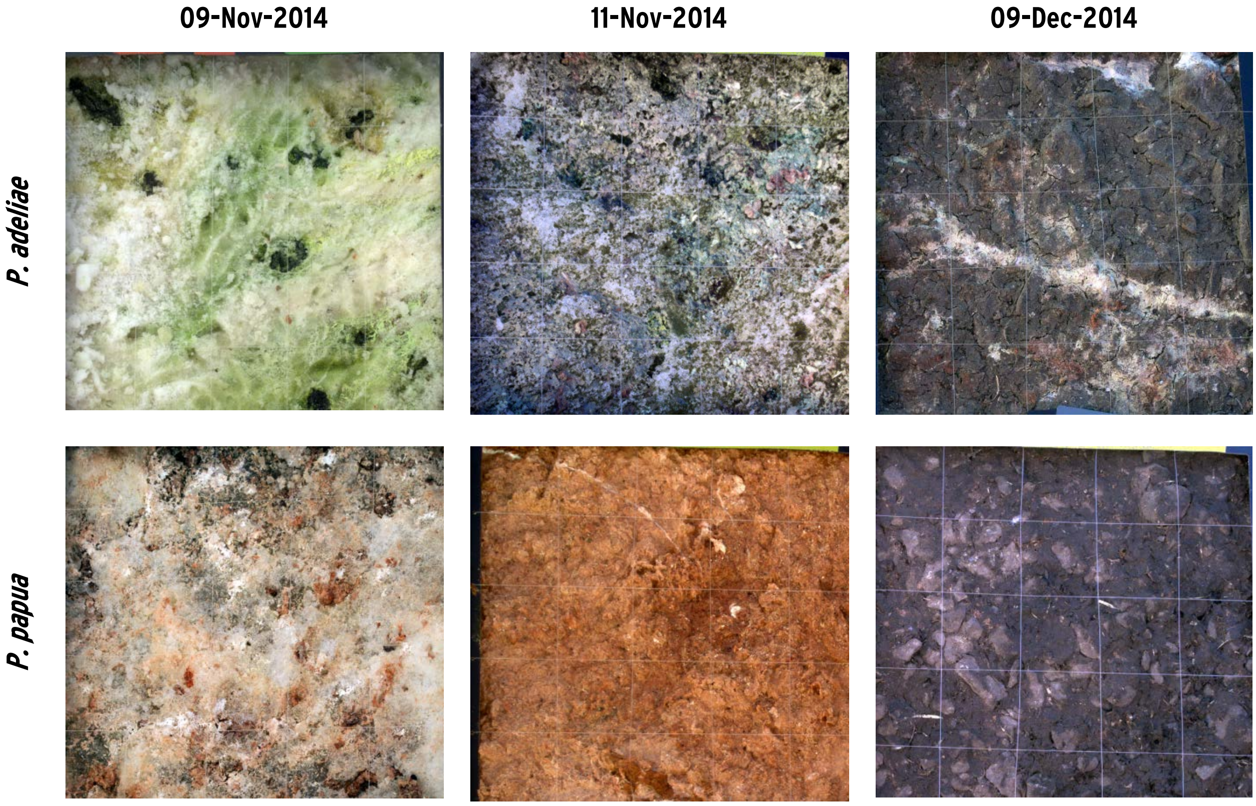
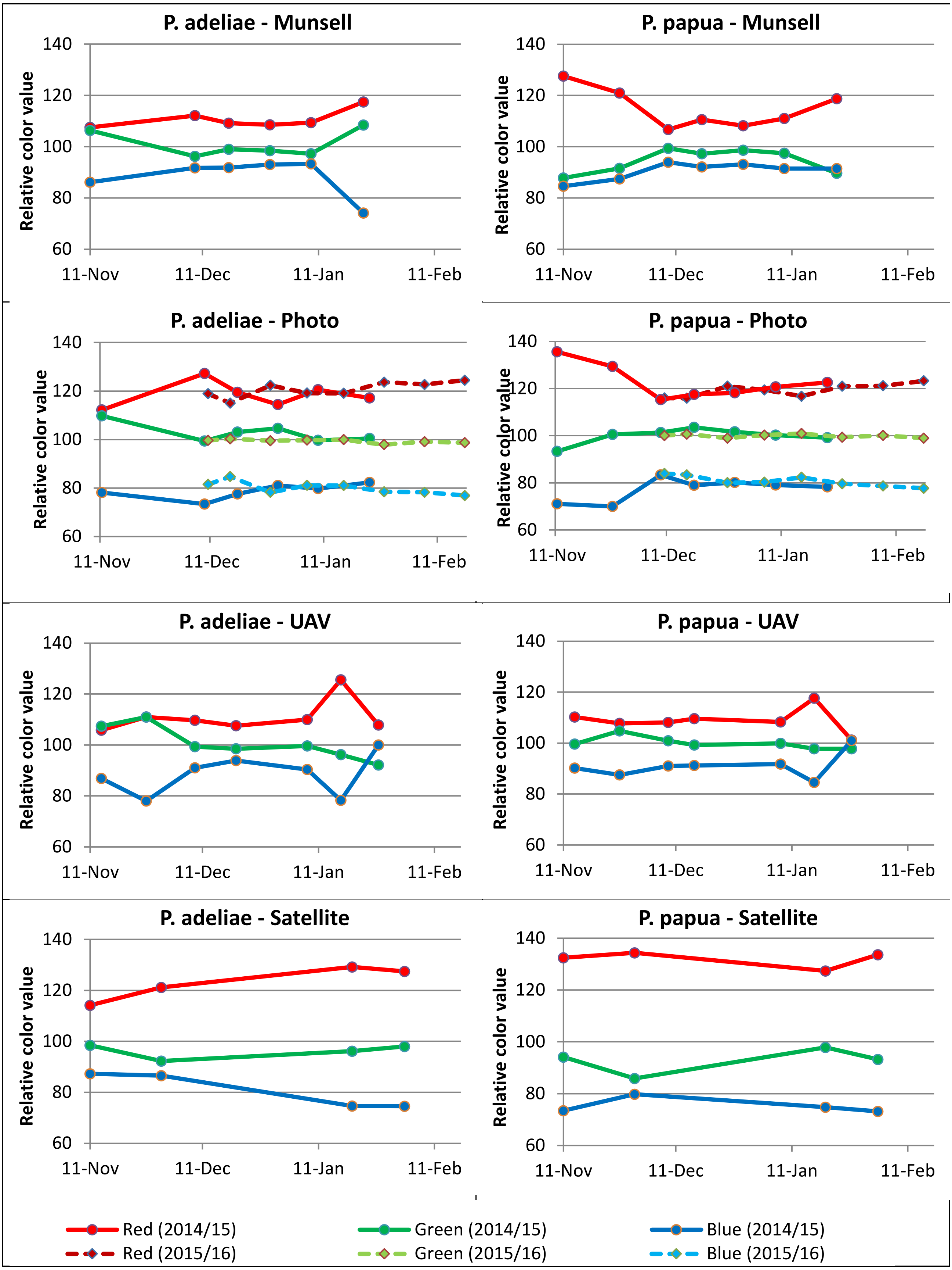


Figure 55: Comparison of the mean relative colour values of the four methods examined, all test sites separated into Adélie (*P. adeliae*) and gentoo (*P. papua*) penguins



8.3 Conclusion

When comparing the individual methods to each other, it firstly becomes evident that the ground photos allow the results of the Munsell color charts to be reproduced. A direct comparison with the UAV and satellite images is difficult as they differ both spatially and chronologically. Nevertheless, the general changes during the season are recognisable in both.

Of particular interest to this study was the question of whether colour differences exist between different species which could be recognised by photographic and remote sensing methods. This appears to be the case to a limited extent. All of the research methods could distinguish the guano colour at the test sites with Adélie penguins at the start of the season (beginning of November) from the test sites of the gentoo penguins. The difference is that the relative red and green components are equal (guano appears green in colour) or very similar. In the rest of the season in contrast, the red component predominates for all species. This is consistent with observations made by fieldworkers. The cause of this colour difference could be a change in the food supply available during the season, but this was not examined in this study. Only UAV images could confirm greenish guano from gentoo penguins at the end of November, although not as pronounced as that from the Adélie penguins. It is not known why this could not be observed with the other methods, but no standardised white balancing could be done with the UAV images, which may have affected the outcome.

9 Possibilities of distinguishing species

There are several theoretical possibilities to distinguish the three *Pygoscelis* species, which are explored below.

9.1 Distinguishing species by habitus

The three penguin species we are interested in are easy to distinguish by habitus with the naked eye on site. In particular, their distinctive colouring is helpful in identifying them (Figure 56).

Figure 56: On site images of gentoo (*P. papua*), chinstrap (*P. antarctica*) and Adélie (*P. adeliae*) penguins, each adults with chicks

9.1.1 Adults

Along with their distinctive habitus, the three *Pygoscelis* species differ in size. The gentoo is the largest with a size of 0.75–0.90 m standing up, while Adélie (0.7 m), and chinstrap (0.71–0.86 m), are smaller (Williams 1995). The body proportions are similar for all three species. Their distinctive colouring is the clearest characteristic from which the species can be identified with the naked eye in the field. They can often be observed from a great distance. The most prominent differences are the colouring of the beak and feet and the markings on their face and throat. All of these characteristics can only be viewed from the front or the side. The back of all three species is practically identical and uniformly black with the exception of the white patches on gentoo penguin's head which can be recognizable from certain perspectives. As the analysis of UAV images in the visual spectrum shows, this creates problems with species identification. As aerial images mostly show the back and top of the head of breeding penguins, all three species appear uniformly black in the normal nesting position. Even when standing upright, penguins are difficult to identify, because the feet are covered, the red beak of gentoo penguins looks black when viewed from above, and the faces are hardly visible.

The only reliable characteristic is the white, hourglass-shaped patch on the top of the head of gentoo penguins (the red arrows point to it in Figure 57). This allows for some of the individuals to be identified. A ground resolution of the mosaic of 20 mm is often not sufficient to recognise the patch. In addition, animals that are bending their heads down may also hide the patch. Therefore, individuals without a recognisable patch could be either a poorly photographed gentoo or another species of penguin. Once it can be ascertained that it is not a gentoo penguin, further classification into chinstrap or Adélie penguin is practically impossible with aerial images. Only very favourably positioned images reveal the white on the side of the head of a chinstrap penguin to distinguish it from an Adélie penguin. The characteristic stripe on the throat of the chinstrap penguin is too fine to ever be resolved on the aerial images taken.

9.1.2 Chicks

It is somewhat easier to differentiate the chicks of the three species examined. Small chicks still confined to the nest have few visible distinctive characteristics on aerial images. Identification is then generally derived from the parent bird present. Once they reach the créche stage, clear colour differences become visible. Even young gentoo chicks have a white belly. This allows reliable identification of a standing chick and distinction from the uniformly dark grey Adélie and uniformly light grey chinstrap penguin chicks. Chinstraps also develop a white belly at a later age. The light grey colour on their backs allows them to be distinguished from gentoo chicks under good lighting conditions. Rather large gentoo chicks whose heads have not yet moulted (missing crown patch) make it difficult to classify adult Adélie and chinstrap penguins and poorly reproduced gentoo penguins. If the ground resolution is adequate, the lack or presence of tail feathers can serve for identification. Under good lighting conditions and with good ground resolution, the differences in grey shades between Adélie and chinstrap chicks become evident. Another helpful aspect is the clear difference in timing of maturity of Adélie and chinstrap penguin chicks, because of the different breeding phenology.

Figure 57: RGB UAV aerial image with a ground resolution of 10 mm of adult penguins and chicks in nest groups. Blue: Adélie penguin; the chicks are uniformly grey and clearly different from the adults (not in frame), red: gentoo penguin; chicks (circled) resemble the adults (arrow), but are lacking the white crown patch and their backs are dark grey instead of black, green: chinstrap penguins; the chicks have already developed a white belly, the grey colour of their backs is lighter than that of the gentoo chicks. The presumed identification is tested against the nest position charted on the ground

9.1.3 Nest spacing and grouping

Other potential criteria for distinguishing species include spacing between nests, nest density and style of nest grouping. Earlier studies by other authors have already explored these possibilities. We noted that the method of measuring nest density varied. While some of the studies measured nest spacing (from edge to edge or centre to centre) and then calculated the density after assuming a regular distribution (Naveen et al. 2012), others measured the actual density over a number of nests lying within the measured nest groups area (Oelke 1975, Woehler & Riddle 1998, Quintana & Cirelli 2000). Another method used is point-stop counting (Kirkwood et al. 2007). Some studies measured only nest spacing and did not calculate density (e.g. chinstrap penguins in Volkman & Trivelpiece 1981). Given all these different methods, it is not surprising that a wide range of densities and spacing was found. Table 26 summarises the published nest densities and spacings for chinstrap, gentoo and Adélie penguins. We can conclude that no reliable classification of the individual species based on nest density or spacing can be created from these published data. While the range for one species across the studies is very large, nevertheless the smallest nest density (0.25 nests/m^2) and largest nest spacing are published for gentoo penguins (Tab. 26), and Adélie penguins tend to have the closest nest spacing. Furthermore, gentoo penguins tend more strongly than Adélies towards looser groupings of nests with comparably smaller nest groups, which is particularly evident on uneven ground. There the nest groups are often loosely spread on the raised areas.

Table 26: Survey of nest spacing and densities in the literature. Where known, for nest spacing a specification is given of whether it involves edge to edge or centre to centre measurements.

Species	Location	Mean nest spacing (cm)	Mean nest density (nests/m²)	Reference
Adélie penguins	Cape Crozier	79.5 – 108 (Ø 93.5; centre)	0.57 – 1.47 (Ø 0.89)	Oelke 1975
	Mawson	-	0.39 – 0.92 (Ø 0.67)	Woehler & Riddle 1998
	Admiralty Bay	43.2 (edge)		Volkman & Trivelpiece 1981
	Admiralty Bay	37.0 (probably edge)	1.13	Trivelpiece & Volkman 1979
	Wilkes Land	65 – 72 (not specified)	-	Penney (1968)
	WAP Region	66.9 – 84.0 (Ø 77.3; not specified)	-	Müller-Schwarze & Müller-Schwarze 1975
Gentoo penguins	Cierva Point	-	0.02 – 1.54 (Ø 0.25)	Quintana & Cirelli 2000
	South Georgia	100 (not specified)	-	Croxall & Prince 1980
	WAP Region	92.1 – 119.2 (Ø 103.4; not specified)	-	Müller-Schwarze & Müller-Schwarze 1975
	Admiralty Bay	74.3 (edge)	-	Volkman & Trivelpiece 1981
Chinstrap penguins	Admiralty Bay	59.9 (edge)	-	Volkman & Trivelpiece 1981
	Admiralty Bay	50.1 (probably edge)	-	Trivelpiece & Volkman 1979
	WAP Region	80.2 – 90.5 (Ø 86.4; not specified)	-	Müller-Schwarze & Müller-Schwarze 1975
	Deception Island	70 – 70.5 (centre)	2.34	Carrascal et al. 1995
	Deception Island	-	1.5	Naveen et al. 2012

9.2 Breeding biology and phenology of penguins

An indirect method of identifying species is based on the variations in breeding biology and phenology of the three *Pygoscelis* species, which are illustrated using the example of Ardley Island given below.

The seasonal timing when colonies become established on Ardley Island depends strongly on the ice conditions in the Maxwell Bay and the snow conditions on land and can vary widely from year to year (Mönke & Bick 1988; Peter et al. 1988; Zippel 1987). In Table 27, for example, the phenological data for establishing colonies, laying eggs and raising chicks are given for the 1984/85 season. Along with the annual variations, it is worthwhile noting that within a colony, great variations in the egg-laying timepoint in a season can be seen depending on the snow conditions, especially among gentoo penguins.

Table 27: Example of the breeding phenology of the *Pygoscelis* species on Ardley Island in the summer of 1984/85

	Adélie (*P. adeliae*)	Gentoo (*P. papua*)	Chinstrap (*P. antarctica*)
First return	17/28 Sep	15 Aug	27 Oct
Colony established	11 Oct	17 Oct	11 Nov
First egg found	29 Oct	25 Oct	15 Nov
50 clutches complete	5 Nov	15 Nov	23 Nov
100 clutches complete	11 Nov	23 Nov	Beginning Dec
First chick seen	3 Dec	Beginning Dec	21 Dec
50 chicks hatched	10 Dec	15 Dec	27 Dec
100 chicks hatched	16 Dec	End Dez	Mid Jan
Créche	3 Jan	Beginning Feb	20 Jan
First chick fledged	20 Jan	End Febr	13 Feb
100 chicks fledged	Beginning/Mid Feb	17 Feb	End Febr
Last adult in colony	17 Feb	-	-
Adult moulting begins	18 Jan	Beginning Feb	1 Feb
Young have left Ardley	Beginning/Mid Febr	End Feb	Mid March

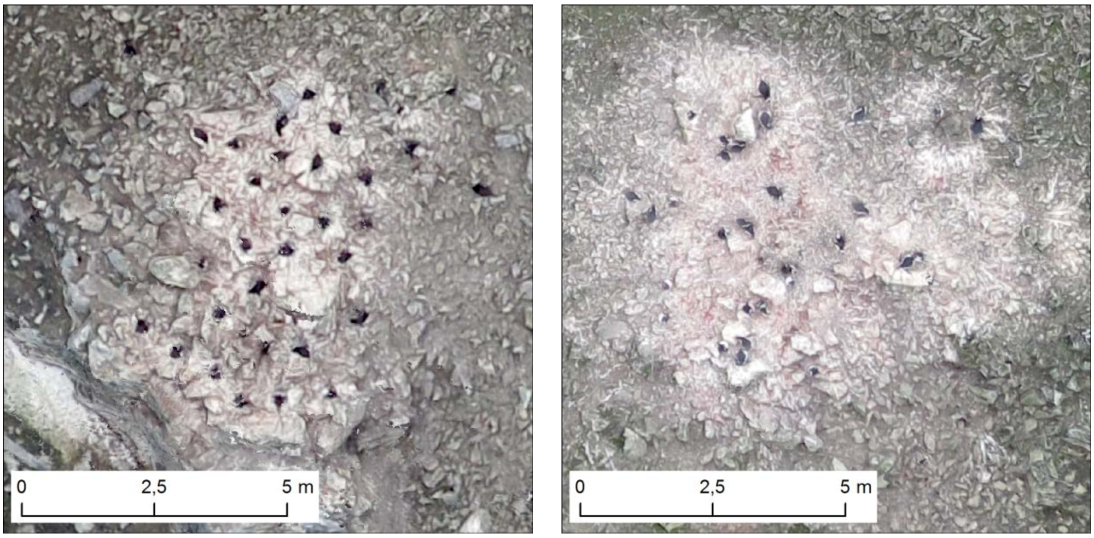
Peter et al. 1988

There is hardly any variation in the incubation periods between the three species: Adélie penguins 33 - 43 days (Trathan & Ballard 2013), chinstrap penguins 31 - 39 days and gentoo penguins approx. 35 days (Shirihai et al. 2002). Adélie penguin chicks fledge after 41 - 64 days; as a high-Antarctic species, their period for raising young is the shortest, followed by chinstrap penguins with 48 - 59 days. The longest nestling period is seen with the gentoo penguins, as their young first fledge after 62 - 82 days, and in extreme northern parts of their range this can extend to 85-117 days (Shirihai et al. 2002).

Especially the large differences in time between Adélie and gentoo penguins compared with chinstrap penguins can help distinguishing the species if the sampling date is favourable. The difference in the state of 50 % young hatched between gentoo penguins and chinstrap penguins is almost 2 weeks (Table 27). As the young are clearly recognisable on UAV images, this is a potential distinguishing characteristic.

This hypothesis was tested with an orthomosaic from a UAV flight above Narebski Point on 03/01/2014. It was possible to distinguish all 15 chinstrap penguin nest groups from the 80 gentoo penguin nest groups solely on the basis of the orthomosaic. The distinction was based on the fact that the adults were still breeding in the chinstrap penguin nest groups, producing a set nest structure, while in contrast the chicks had already left the gentoo penguin nest groups and the nest structure was beginning to break down (Figure 58). Validation was done with the KOPRI mapping data from the same season.

Figure 58: Comparison between a chinstrap penguin nest group (left) with adults that are still brooding and a gentoo penguin nest group (right), whose chicks have already hatched and the nests are partly abandoned (UAV orthomosaic with 15 mm resolution of Narebski Point, 03/01/2014)

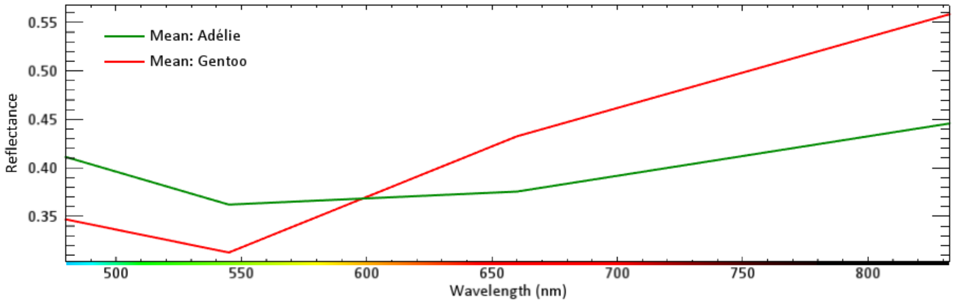


9.3 Guano colouring from satellite images

In chapter 0, it was ascertained that colour differences in the guano of Adélie and gentoo penguins could be evident at the beginning of the season. This study covered only a few, small test sites, however. Below we examine whether this distinction exists also in wider areas and will support species identification over a wide area.

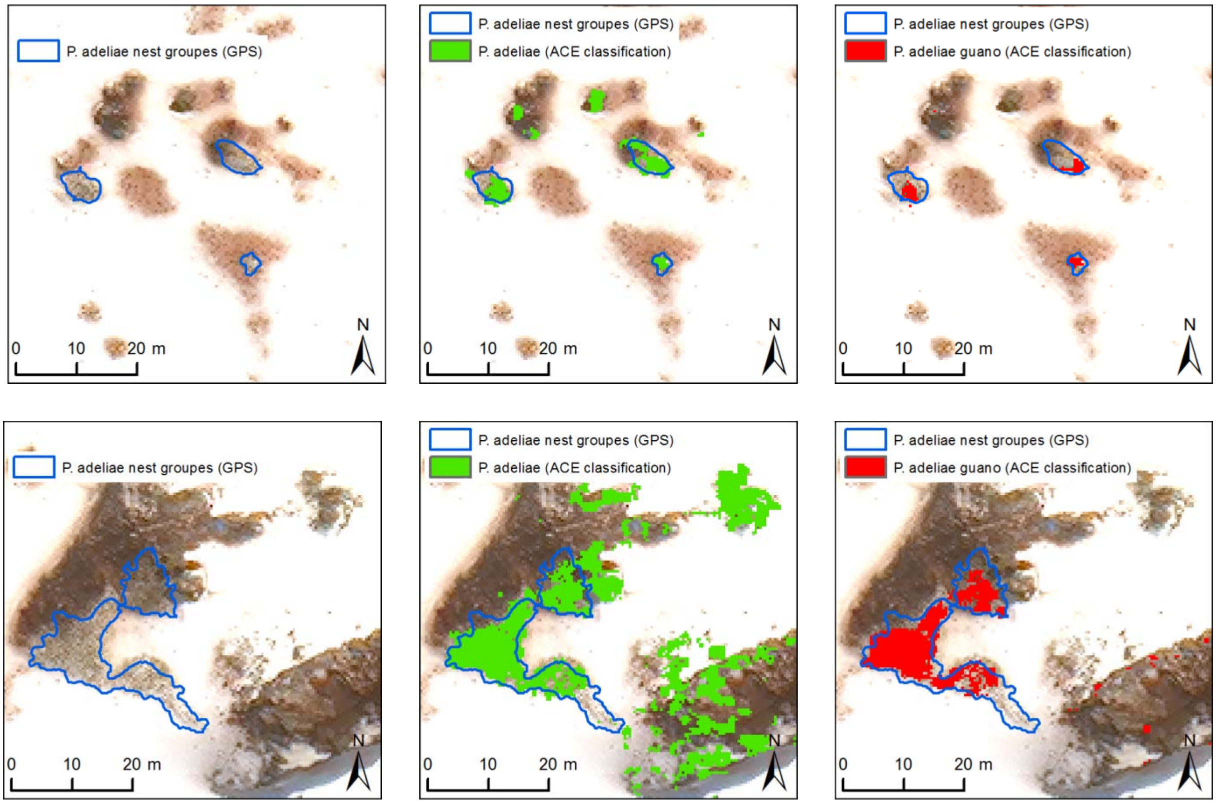
Using a Worldview 3 image of Ardley Island from 11/11/2014, we investigated whether Adélie penguin nest groups could be distinguished from gentoo nests and detected solely on the basis of their guano signature. Using GPS-mapped nest groups of both species, the nests were identified and their average spectral signature recorded. Adélie penguin guano has higher reflectance in the green spectral range (Figure 59). The two types of guano can also be distinguished visually by the green shade of the Adélie penguin guano compared with the orange gentoo penguin guano. This was also possible when only a small group of Adélie penguins was situated among a large gentoo penguin nest group. This phenomenon was only visible in the image from 11/11/2014, already in the image from 30/11/2014, it was no longer possible to distinguish the guano.

Figure 59: Comparison of mean spectral signature of Adélie and gentoo penguin guano, taken from a 6-channel Worldview 3 image (dated 11/11/2014) of Ardley Island and processed with ACE and SAM classification



To check whether the spectral difference in the two types of guano is classifiable, it was tested with SAM, ACE and ML classification methods (Figure 60). An optical analysis of the results showed that only ACE classification enables detection (for a threshold value >0.85) only of guano from Adélie penguins (*P. adeliae)* without a large risk of misclassifying it as guano from gentoo penguins (*P. papua)*. This distinction was only possible when the yellow and Red-Edge channels were added to the standard 4-channel satellite image (RGB and NIR), making it 6 channels in total.

Figure 60: Adélie penguin nest groups (*P. adeliae*) on Ardley Island in the middle of gentoo penguin nest groups (*P. papua*) on 11/11/2014 compared with GPS-mapping (left) and 4-channel (middle) and 6-channel Worldview 3 (right) images for 2 locations



Satellite image ©DigitalGlobe

10 Automation of satellite-supported detection of penguin colonies

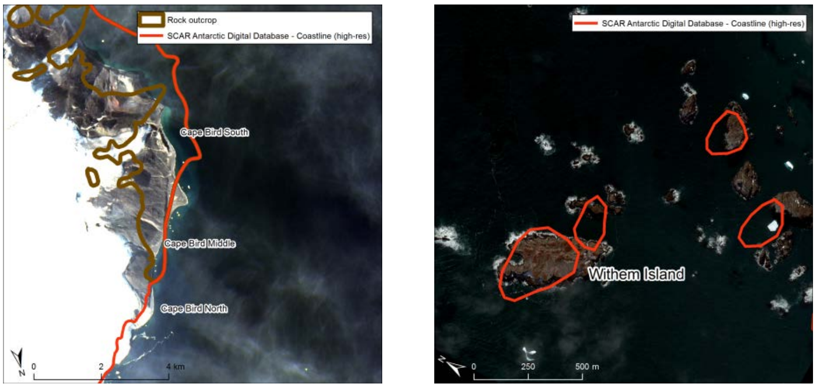
Since the study by Mustafa et al. (2013), which confirmed to a great extent the theoretical possibility of an automated analysis of satellite images for penguin monitoring, further research has been done on this question (*cf.* Lynch & LaRue 2014, Lynch & Schwaller 2014, Schwaller et al. 2013b). Various methods have now been developed and applied which make it possible to monitor rock-breeding penguin species throughout the Antarctic (see also sections 10.2 to 10.4).

10.1 Pre-processing of data from Landsat images for automated analysis

An important step in a fully automated detection of guano in extensive areas, such as the Antarctic coast, is the spatial and temporal selection of images.

One way of optimising the spatial selection, so that the smallest possible number of images would need to be obtained and analysed, could be to select only those images that cover areas where the penguin species being studied actually occur, instead of using images from the entire coast. Specifically for the *Pygoscelis* species, this would involve only the ice-free land areas. Fortunately, there is already a freely available data set for all ice-free land areas (rock outcrop) of Antarctica, which is provided by the SCAR Antarctic Digital Database (ADD). Because there are also ice-free areas far from the coast that the penguins cannot reach, the selection can be further limited to areas close to the coast (e.g. 10 km). A coastline layer, which is also provided by the SCAR Antarctic Digital Database, is suitable for this. If only Landsat images are obtained that cover ice-free areas near the coast, approximately 75 images are needed for the whole of Antarctica (including the Antarctic islands), whereas more than 250 images would be needed to cover the entire coast. However, this restriction to ice-free areas is problematic if the underlying data is not sufficiently precise or if new, previously unknown ice-free areas appear, for instance due to glacial retreat. For example, in the ADD data for rock outcrop and the coastline, a relatively larger and more variable misalignment was detected in relation to the Landsat images or the high-resolution DigitalGlobe images. Both of these data sets deviate by up to 1 km from the coastline or the rock outcrop that can be recognised in the satellite data (Figure 61). In these cases the shift is very variable and inconsistent, for example with no deviation for Ardley Island, but a deviation of 1 km for Cape Bird.

Figure 61: Shift in the coastline between the SCAR Antarctic Digital Database and a Landsat 8 image (01-Feb-2016) of Cape Bird (left) and a GeoEye image (12-Feb-2016) of Withem Island (right)



Coastal layer SCAR Antarctic Digital Database, image left NASA/USGS, image right ©DigitalGlobe

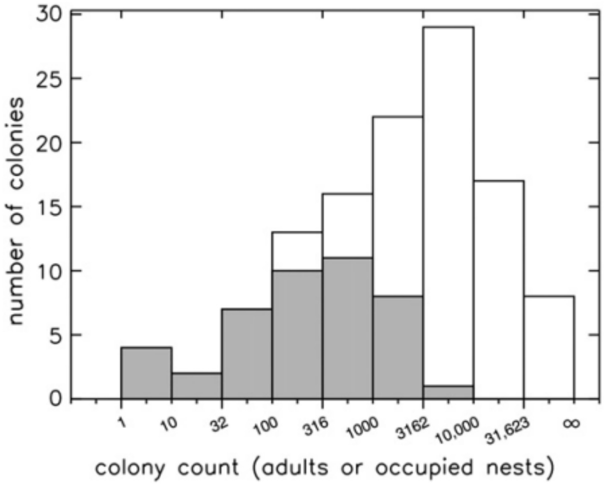
The temporal selection of the satellite images of a season can also be optimised. If the areas in which penguin colonies can occur are covered in snow or obscured by cloud, any penguin colonies present cannot be detected. Clouds can also lead to major misclassifications. Cloud identification in the data is therefore of great benefit for further processing. A possibility for checking cloud cover over ice-free land areas, but also for detecting ice-free land areas is a fully automatic method developed by Burton-Johnson et al. (2016) for Landsat 8. This method employs diverse thresholds and indices of Landsat 8-OLI and Landsat 8-TIRS data. External data for the coastline is also used, which does not originate from the image itself and in some areas shows a clear shift in relation to the Landsat 8 images (Figure 61). Among other things, this makes it impossible to detect Cape Bird using the ADD data, because it lies outside the coastline indicated in the data. A few small islands, for example near Withem Island, cannot be checked either, because they are not recorded in the ADD data.

10.2 Automatic detection of Adélie Penguin colonies of continental Antarctica with Landsat 7

Schwaller et al. (2013b) used automated classifications for detecting Adélie penguin colonies using Landsat 7 images for the whole of continental Antarctica. To this end, they developed a multi-stage procedure that can automatically identify guano-covered areas in various images. In the first stages, the images are converted into ground reflection values and the changes in brightness caused by topography variations are corrected. Subsequently, the guano is classified in the images thus prepared with the help of training areas. The method was applied to 195 overwhelmingly cloud-free Landsat 7 images with 30 m ground resolution, which had been taken between 1999 and 2003 as close as possible to the austral summer. In this process the Antarctic Peninsula was not considered, because other Pygoscelis species also breed there, which cannot be distinguished from one another using the methods available (Schwaller et al. 2013b).

The precision of the method was determined using 119 colonies from the eastern Antarctic, by comparing the colonies found there by Southwell & Emmerson (2013) with those found by Schwaller et al. (2013b). Figure 62 shows that the probability of detecting a colony greatly depends on the number of nests in that colony. For example, there was only a 23 % probability of Schwaller et al. (2013b) detecting a colony with a population of 100 - 315 breeding pairs, while the probability for colonies with 3,162 – 9,999 breeding pairs went up to 97 %.

Figure 62: Population sizes of 119 Adélie Penguin colonies. White bars show the colonies detected by Schwaller et al. (2013b) and grey bars show those that were undetected



Schwaller et al. 2013b

In the result 9,143 pixels were detected, probably belonging to *P. adeliae* colonies, which corresponds to a total area of 82,287 km^2. These 9,143 pixels were distributed over 187 different colonies, the sizes of which varied between 900 m^2 (1 Pixel) and 0.7875 km^2 (875 Pixel). It is assumed that six of these colonies, with a total area of 0.22 km^2, were previously unknown. In addition, a strong correlation was determined between the colony area measured and the number of breeding pairs (Schwaller et al. 2013b). If it is assumed on the basis of the strong correlation that the number of breeding pairs in the newly found colonies is just as high as in the equally large colony of Cape Hallet (235 pixels; 0.21 km^2), the breeding pair total, depending on the author, is estimated to be 56,153 pairs (Woehler & Croxall 1997) or 43,942 pairs (Ainley 2002). The data on the colonies detected was also published on the PANGEA data repository (Schwaller et al. 2013a).

10.3 Automatic detection of Adélie Penguin colonies in the whole of Antarctica with Landsat 7

Using the same algorithm as Schwaller et al. (2013b), Adélie Penguin colonies were also automatically detected by Lynch & Schwaller (2014), with the difference of additionally investigating the Antarctic Peninsula. The underlying data for this also consisted of Landsat 7 images from 1999 - 2003. In order to be able to include the Antarctic Peninsula in the investigation, in contrast to the study by Schwaller et al. (2013b) two different reference data sets were used, from which the necessary parameters for classifying the guano are derived. One data set for this purpose comprises the training areas of continental Antarctica and the other comprises the training areas of the Antarctic Peninsula. This had the advantage of making it possible to investigate each region using specially adapted classification parameters.

However, the guano of other penguin species and seabirds, among other factors, made classification on the Antarctic Peninsula more difficult. Another problem is the occurrence of a huge amount of smaller colonies on the Antarctic Peninsula which are hard to detect using only medium resolution Landsat images (Lynch & Schwaller 2014).

The results showed that on the Antarctic Peninsula alone, 143 areas were classified as potential Adélie penguin colonies. Among these are 17 previously unknown breeding areas with a total of 495 pixels (this correlates with estimated 229,129 breeding pairs).

10.4 Manual detection and determining abundance of Adélie Penguin colonies using high-resolution satellite data

The first comprehensive census of Adélie penguins was carried out by Lynch & LaRue (2014). It was not based on an automated analysis of satellite images, including up-to-date ground count data, but rather on a manual interpretation. It also shows, however, that a manual interpretation of a large number of high-resolution satellite images is possible. A drawback of using commercial, high-resolution satellite images for large areas is the high cost of the images.

In the results of the study the overall Adélie Penguin population is estimated at 3.79 million breeding pairs in 251 colonies. Of those, approximately 21 % breed on the Antarctic Peninsula. The breeding pair numbers of 41 colonies were determined for the first time, including the 17 colonies that were previously unknown (Lynch & LaRue 2014).

10.5 Conclusion

Methods have already been developed and successfully applied for using medium-resolution images (Landsat) for the automatic detection of guano-covered areas throughout Antarctica (Schwaller et al. 2013b, Lynch & Schwaller 2014). Furthermore, a method is available to automatically find clouds or ice-free land areas in Antarctica, which is important for pre-processing (Burton-Johnson et al. 2016). No method is known yet to detect guano automatically in a large amount of high-resolution satellite data from very diverse areas. There is a need for further research on this matter, which is why the topic is addressed in chapter 6, among others.

11 Study of intraseasonal variations in colony expansion and occupation, and the extent to which these can be detected

Many coastal areas of Antarctica have frequent cloud cover. This is true in particular for the South Shetland Islands. For this reason, it is rarely possible to take optical satellite images of the research area at the desired time. It is also often impossible to use other monitoring methods at the optimum times for logistical reasons or due to weather conditions. Detailed knowledge of intraseasonal variability of diverse measurement and target parameters could increase the informative value and transferability of data recorded at times in which conditions are sub-optimal. To this end, the Ardley Island penguin colony, or a part of it, was studied on the ground and from the air using various methods in the 2014/15 season. Figure 63 provides an overview of the investigation times of the individual methods for the 2014/15 season, as Figure 64 does for the 2015/16 season. Depending on the individual imaging method, the number of breeding pairs, the nest group area or phenomenological criteria are then investigated and, finally, the individual results are compared with one another.

Figure 63: Overview of times when satellite images were taken and of investigation times of the individual methods for intraseasonal work on the Ardley Island colony in the 2014/15 season

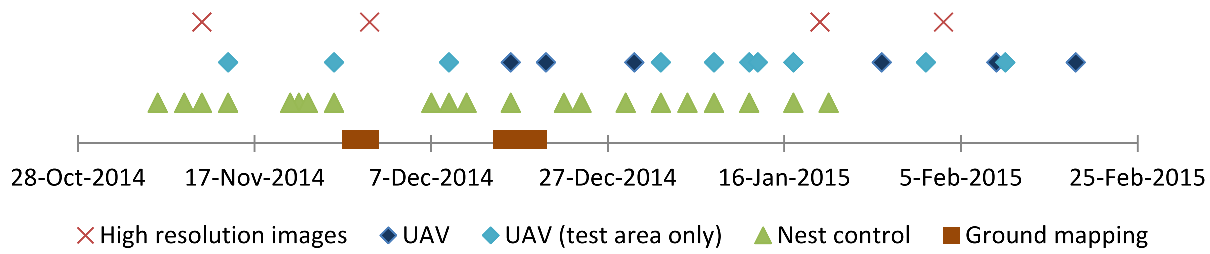
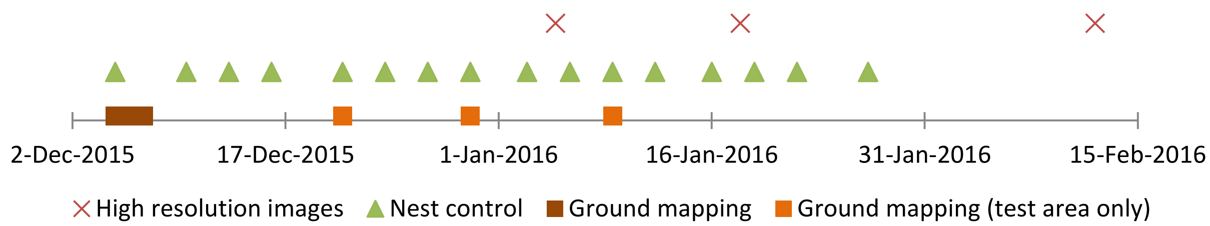


Figure 64: Overview of times when satellite images were taken and of investigation times of the individual methods for intraseasonal work on the Ardley Island colony in the 2015/16 season

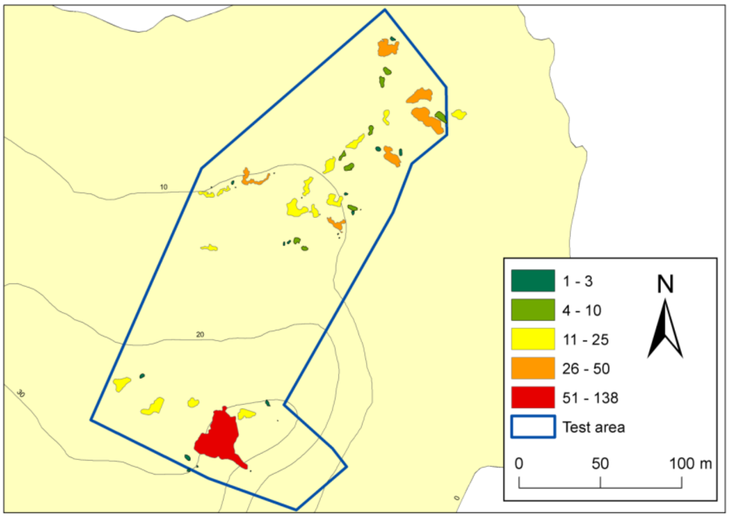


11.1 GPS-based partial mapping on Ardley Island

To investigate the intraseasonal changes, two complete GPS-based mapping surveys were carried out for the penguin colony on Ardley Island during the 2014/15 season (see section 0). Although this method is very precise for mapping the breeding pairs of a colony, it is also very time-consuming and labour-intensive, as well as being rather disturbing to the penguins. For a comprehensive mapping of Ardley Island, 2–3 people are needed for approximately three days. However, the two mapping exercises 2–3 weeks apart show that the choice of the time for mapping has a clear influence on the result. Between the two mapping exercises, the number of gentoo penguin breeding pairs mapped declined by 7.7 %, while the number of Adélie penguins increased by 38.8 %. The reason for this is the differing chronological sequence during breeding.

In order to achieve a higher temporal resolution of the course of events during the season, the active nest groups of a part of Ardley Island were ground mapped using GPS approximately every 10 days during the 2015/16 season (three times in total). Together with the comprehensive mapping, there is therefore mapping data available for four points in time (between 07-Dec-2015 and 09-Jan-2016). The aim was to obtain information about spatial dynamics in nest occupation within a breeding season and also to record changes in nest group areas.

Figure 65: Distribution of gentoo penguins on 07-Dec-2015. Nest groups are given different colours according to the number of breeding pairs



The test area was selected so as to reflect the topographical variety of the entire colony as well as possible. In this area 41 nest groups with a total of 678 nests of gentoo penguins were recorded (07-Dec-2015). The nest groups were divided into five size classes according to the number of nests (Figure 65). The four mapping events made it possible to follow the development in the number of nests. In addition, the data was compared with that obtained from the nest control.

Table 28: Development of the gentoo penguin nest groups in the area of the test zone for the 2015/16 season

Number of nests	Number of nest groups	07-Dec-2015	21-Dec-2015	30-Dec-2015	09-Jan-2016
1 - 3	13	29	23	22	21
4 - 10	12	81	67	68	65
11 - 25	9	179	166	169	168
26 - 50	6	231	207	219	182
> 50	1	158	128	135	91
∑	**41**	**678**	**591**	**613**	**527**

However, overall it can be seen that the size of the nest group areas remained very constant over the study period. In contrast, though, the number of nests and therefore also the density of the groups declined significantly (in total by 22 %). The nest groups with 1-10 nests were most affected by the decline (Table 28). A possible cause could be that these groups are usually

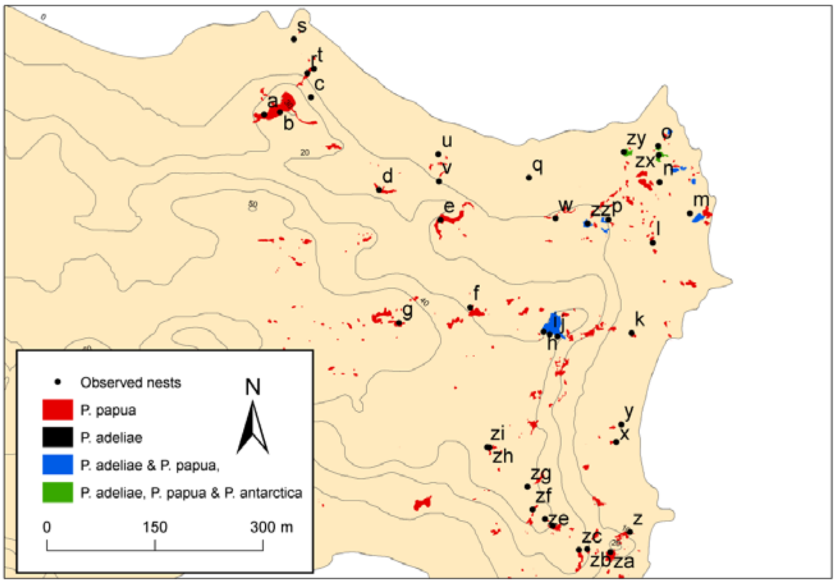
separated from larger groups and are therefore subject to greater pressure from predators. In the medium-sized groups with 11-25 nests, the fewest nests were abandoned during season. A higher rate of losses was recorded in the groups comprising 11-50 nests, though the losses were smaller than those suffered by the small groups.
These results were confirmed by the nest checks (see section 11.2), apart from one exception. Only in groups with over 50 nests significant differences were found between the partial mapping and the nest checks. In the nest checks hardly any abandoned nests were counted, whereas a relatively large number of such nests were detected in the partial mapping. This could be explained by the limited sample size in the partial mapping, as only one nest group with more than 50 nests was recorded.

11.2 Breeding phenology of penguins on Ardley Island

11.2.1 Method

During the seasons 2014/15 and 2015/16, the breeding behaviour of gentoo and Adélie penguins on Ardley Island was investigated thoroughly. The aim was to gain an overview of breeding progress and success over time. In addition, the times of significant breeding events were recorded (e.g. Peak of Egg-laying and Peak of Hatching). In the 2014/15 season at total of 103 gentoo penguin nests and 22 Adélie penguin nests were observed over an 87-day period (27-Oct-2014-21-Jan-2015). In the 2015/16 season the totals were 109 gentoo penguin nests and 40 Adélie penguin nests over a 54-day period (05-Dec-2015 - 27-Jan-2016). In order to ensure a comparison between the data of the two seasons, the same nest groups were considered in both seasons and the aim was to record data at three-day intervals.

Figure 66: Distribution of nests on Ardley Island that were checked regularly in order to record breeding progress.



In the selection of the nests, the representation of as many characteristics of the colony site within the test zone (e.g. distance from the coast, altitude, size of nest group) as possible was ensured (see Figure 66). The nest groups were marked with distinctive stones, which in most cases were still present the following season. In addition, the coordinates were recorded with the help of GPS devices.

The nests were investigated according to the same criteria in both seasons. For this purpose, the nests were divided into a) nests that contained at least one egg, b) nests with at least one chick, and c) abandoned nests. Abandoned nests were defined as empty nests which were not occupied by a breeding bird at the time of the observation but which had previously been occupied during the season in question.

11.2.2 Results

Table 29 summarises all relevant parameters of the two seasons. Due to a relatively late arrival, investigators were unable to calculate the Peak of Egg-laying for the 2015/16 season. A number of different – and in several cases imprecise – indications were found in the literature for establishing the Peak of Egg-laying point. Hardly any exact instructions for the calculation have been made by the CCAMLR Ecosystem Monitoring Programm (CEMP) except that the central dates for breeding events should be used. In this study, we used the definition of Peak of Egg-laying of Müller-Schwarze (1984) and Lynch et al. (2009). This definition is that the Peak of Egg-laying is the time at which 50 % of the breeding pairs observed have laid at least one egg.

The parameter or characteristic value for analysing breeding chronology is the "Peak of Hatching" that is, just as is the Peak of Egg-laying, only defined to a limited extent in the literature. We therefore defined it in this study as the date when there was a chick hatched in 50 % of the maximum number of nests previously counted.

Table 29: The parameters obtained by nest checking for the 2014/15 and 2015/16 seasons for gentoo (*P. papua*) and Adélie (*P. adeliae*) penguins

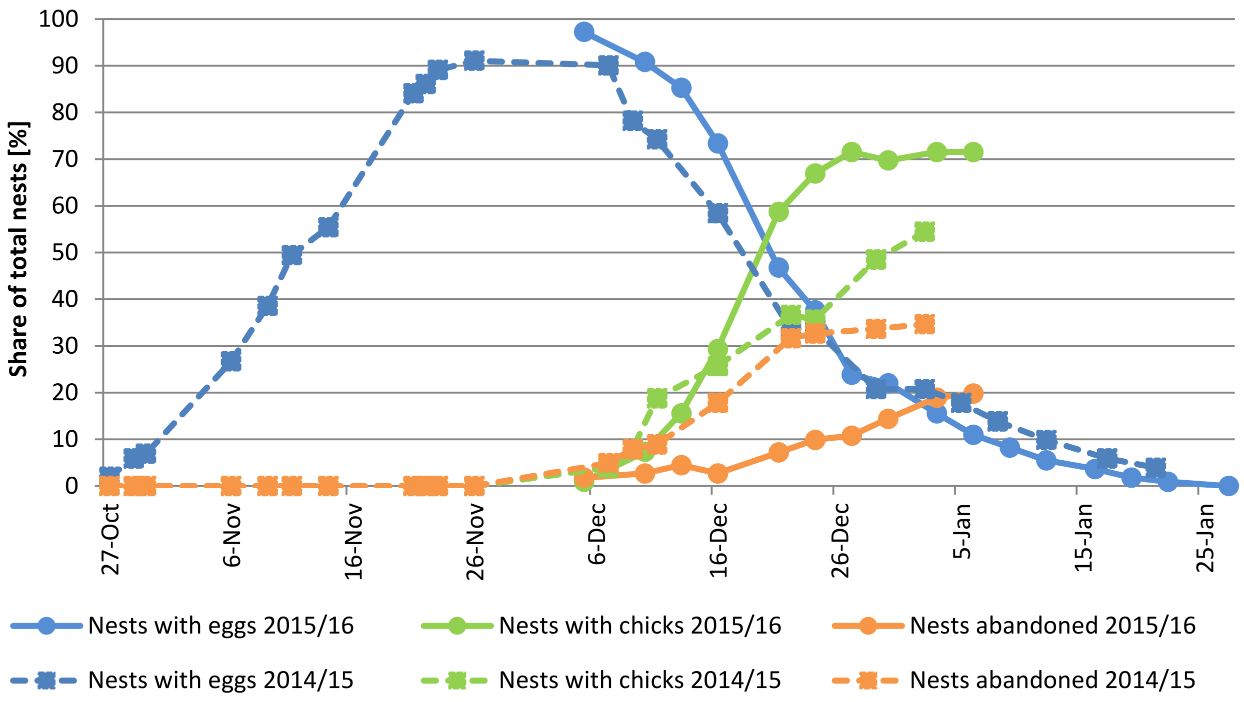
	Season 2014/15		Season 2015/16	
Parameter	Gentoo p.	Adélie p.	Gentoo p.	Adélie p.
Nests	103	22	109	40
Chicks	81	9	114	33
Max. number nests with eggs	92	19	106	19
Peak of Egg-laying	14 - 21 Nov	06 - 09 Nov	-	-
Max. number nests with chicks	92	5	78	16
Peak of Hatching	16 - 22 Dec	-	16 – 21 Dec	10 – 13 Dec

11.2.2.1 Gentoo penguins

Figure 67 summarizes the results for the 2014/15 and 2015/16 seasons. There is no data after 05-Jan-2015 on the number of nests with chicks or the total number of chicks. This is because the chicks start to form crèches at this time and it becomes thus clearly impossible to assign chicks to nests. In 2015/16 we arrived somewhat later at the research area and therefore were only able to start checking the nests on 05th of December, which makes it impossible to come to any conclusion about the course of the first part of the breeding season. This lack applies predominantly to egg laying and to assessing Peak of Egg-laying.

It should be noted from the data series (Figure 67) that the numbers of nests with eggs do not decrease to the same degree as the increase in the numbers of nests with chicks plus the numbers of abandoned nests. The reason for this is that some nests contain a chick as well as an unhatched egg. Such nests thus remain in the category "Nests with eggs". The category "Nest abandoned" contains all nests no longer occupied by any adult. However, this category excludes nests with neither eggs nor chicks but still occupied by adults.

Figure 67: The course of breeding for gentoo penguins on Ardley Island during the seasons 2014/15 and 2015/16. The y-axis represents the number of nests as a percentage of the total number of nests recorded



By comparing the course of breeding in gentoo penguins for the two seasons (Figure 67), it is easily seen that during the 2014/15 season the numbers of nests with eggs rose continually until 28-Nov-2014 (The plateau between 26-Nov. and 07-Dec-2014 arises from the lack of data for this interval.) In both seasons it is clear that the number of nests with eggs declines after the beginning of December. A countervailing trend is visible from this point onwards in the number of nests with chicks and that of abandoned nests. The number of nests with eggs decline in very similar ways in both seasons and by the 22th of January has nearly reached zero.

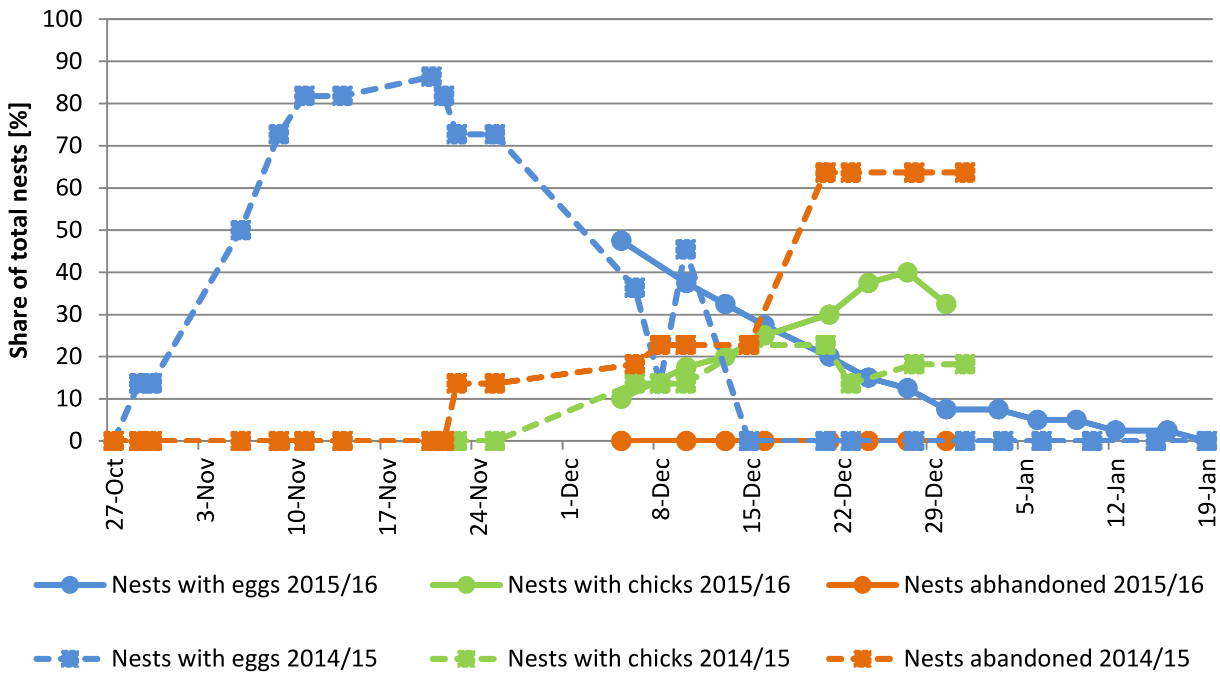
In both years, chicks start to hatch around 5th of Dezember. In the season 2014/15 the numbers rose rapidly up to 27-Dec-2014. In the following season, however, the rise is not so strong but longer lasting, aiming to the conclusion that the beginning of the breeding season in 2014/15 extended over a longer period than in the season afterwards.

The number of abandoned nests started to increase on 11-Dec-2014 in 2014/15. In the season thereafter the start was postponed five days. The possible reasons include increased mortality of the newly hatched chicks in the first few days of their existence. In addition, increasing numbers of nests were abandoned by adults that had not laid eggs or that had already lost them.

11.2.2.2 Adélie penguins

In the 2014/15 season the Adélie penguin nests that we observed were of limited extent with the total number being 22. With a sample as small as this, even small mistakes in data gathering produce great variation in the statistics. One of the reasons for inexactitudes in data acquisition is that breeding birds do not always rise from their nests when counts are made. It is thus not possible to determine precisely whether or not eggs of chicks are present without causing unreasonable high disturbance. This is clear above all in the trend for nests with eggs between 07-Dec-14 and 16-Dec-2014 (Figure 68). It is necessary, therefore, to treat the derived date for the Peak of Egg-laying with caution. The limited extent of the sample also meant that the Peak of Hatching was determined from only five remaining nests. There was a heavy snowfall between 18-Nov-2014 and 23-Nov-2014 in the 2014/15 season. During this period, field observations revealed that a greater number of nests than usual were abandoned by Adélie penguins because the nests were snow covered. In this period, the number of nests with eggs slumped and there was a similar up-tick in the number of "abandoned nests".

Figure 68: Progress of breeding in the Adélie penguins on Ardley Island in the seasons 2014/15 and 2015/2016. The y-axis represents the number of nests as a percentage of the total number of nests recorded



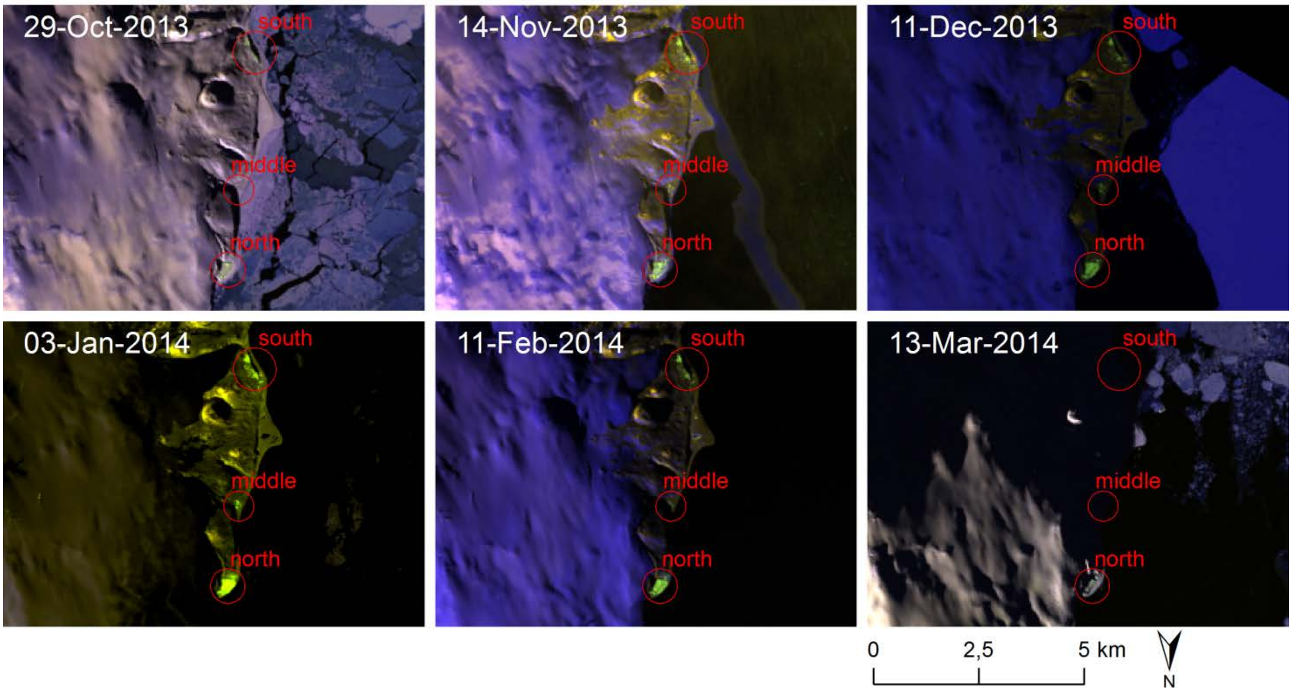
11.2.2.3 The "optimal time"

The comparison of the chronology of breeding in gentoo and Adélie penguins in the two seasons applies only to a limited period of time and is therefore unrepresentative. It suggests, however, that the time course of breeding between years is very similar. This is particularly true for Adélie penguins but also for gentoo penguins in overall terms. How much the time course might vary between seasons over longer periods can only be determined after many years of continued observation. The period between middle of October and the end of January should be set for these observations. Our data suggests that the period between the 25th November and 10th December matches the optimal time for counting the number of gentoo penguin breeding pairs in the South Shetlands area. For Adélie penguins the optimal period indicated is between 10th and 20th of November.

11.3 Landsat 8

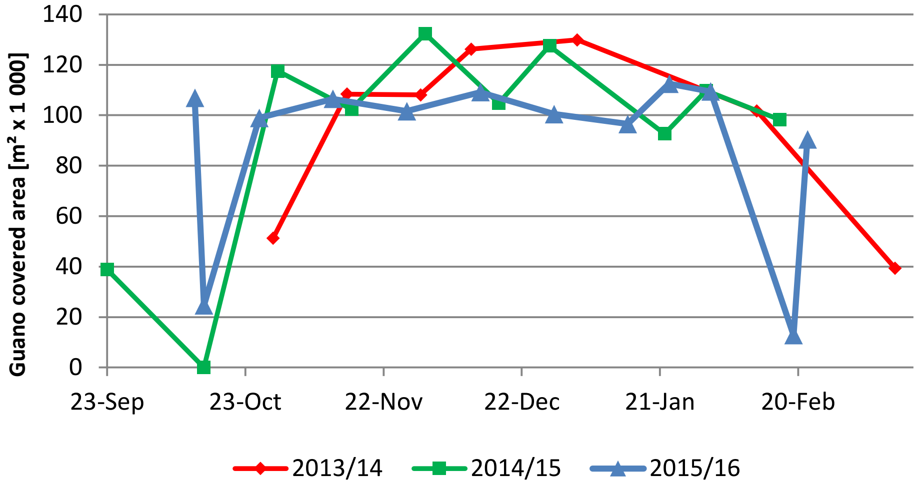
Because of their relatively coarse ground resolution of 30 m of the multispectral bands of the Landsat 8 OLI sensor, the only colony in the research areas that can be reliably detected is the large and dense one on Cape Bird. In order to test variation between seasons using Landsat 8, we attempted to obtain at least one Landsat 8 image for each month (chapter 5.2.2). The guano areas in the images were then determined manually and, for comparison, classified automatically (Figure 69).

Figure 69: Landsat 8 images in the OLI 567 bands showing the colonies on Cape Bird at different times during the course of the season. The guano-covered areas are differentiated by their yellowy-green colour from their surroundings. The different colonies are indicated by the red circles



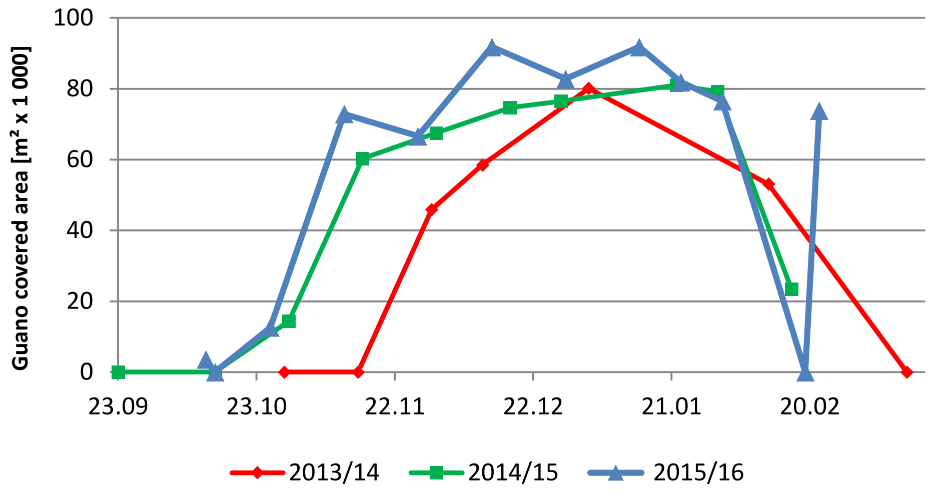
The guano-covered areas derived from manual delineation assessment are shown in Figure 70. The strong decreases in area at the beginning and the end of the season were caused by a temporary cover of snow (Figure 69), overlaying most of the colony and thus hindering detection of guano areas. When all three seasons are considered together, it is clear that the guano areas detectable on Cape Bird do not change during the season (apart from the changes due to snowfall mentioned above). The smaller variations between seasons in the guano areas are within the measurement error because, given the low resolution of Landsat 8 images and the small size of the colonies, even a difference of a few pixels produces large changes in the apparent areas.

Figure 70: Comparison of the seasonal changes in manually detected guano areas on Cape Bird for seasons 2013/14, 2014/15, 2015/16



In parallel with the manual assessment, we also carried out a SAM classification of the Landsat 8 images in order to exclude subjective criteria. The SAM classification was applied to all of the Landsat 8 images with a guano signature (Figure Figure 19, chapter 6.3.1) from the centre of the northern colony on Cape Bird. The results indicate that the SAM classification of seasonal changes in the colony area is indeed less variable (Figure 71) but is nevertheless similar to the pattern produced by manual assessment. It is also clear that, exactly as might be expected based purely on spectral characteristics, SAM classification does not assign snow covered guano areas to guano. However, such areas can be recognised in manual assessment.

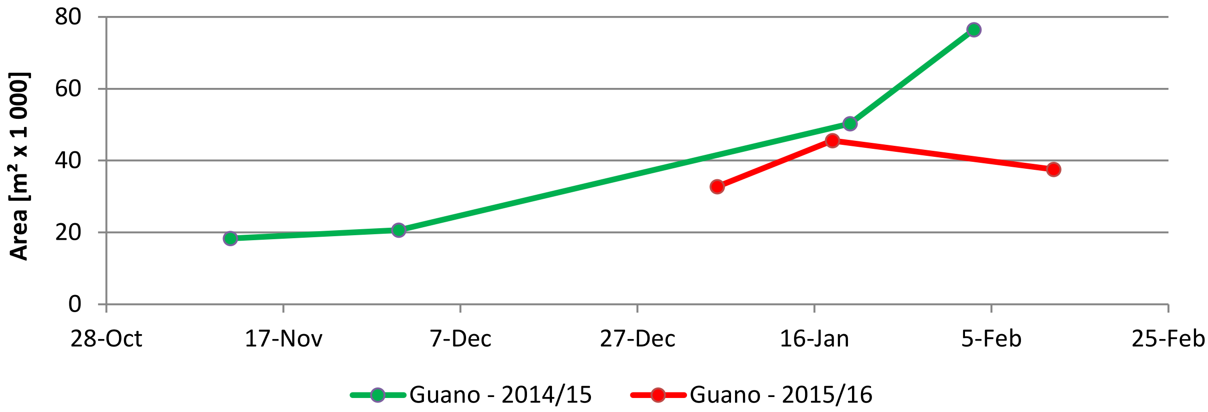
Figure 71: Comparison of the seasonal changes in guano areas by SAM classification on Cape Bird for seasons 2013/14, 2014/15, 2015/16



11.4 High resolution satellites

For the 2014/15 season, it was possible to acquire four cloud-free high resolution images of Ardley Island from the DigitalGlobe satellite constellation. These images covered the period from the beginning of November to the beginning of February (chapter 5.2.1). In the following season, because of cloud cover, the earliest suitable images possible to acquire were from the beginning of January. The guano areas in these images were assessed using manual image interpretation in order to investigate the seasonal variation in guano area (Figure 72).

Figure 72: Seasonal changes in guano areas from manual assessment of high resolution satellite images of the Ardley Island penguin colony



There is generally a clear increase in the guano area during the course of the season (Figure 72). Examining the results in more detail, it can be seen that the guano areas are the same size in October/November at the beginning of the season. The increase starts only thereafter. Because there is no increase in the number of nests after the beginning of December (Figure 67 and Figure 68) the cause of the increase in area covered by guano might be the result of guano distribution. This is suggested by interpretation of the satellite images. There are two mechanisms that might be responsible for the spread of guano over the surface. One is fluvial processes (erosion) and the other is distribution by the penguins themselves. Both these processes are particularly evident at the end of the season when the snow has melted and the chicks have already formed crèches. They therefore correlate well with the increase in area observed that takes place at the same time. As is easily seen in Figure 73, the images of the research area for October and November 2014 show considerable snow cover whereas hardly any large areas of snow can be seen between nest groups in images from January and February. It can also be observed that new guano-covered areas form near the beach at the end of the season. These are just the areas where crèches can be frequently found (Figure 74). As can be seen in the images from mid of February, reductions in the guano areas can also occur very late in the season. Such reductions are possibly caused by the increase in abandoned nests and the consequent reduction in guano addition from adults, in combination with erosion going on at the same time.

Figure 73: The Ardley Island colony (mostly gentoo penguins) imaged by Worldview 2/3 at four dates during the 2014/15 season with the guano-covered areas manually highlighted in red

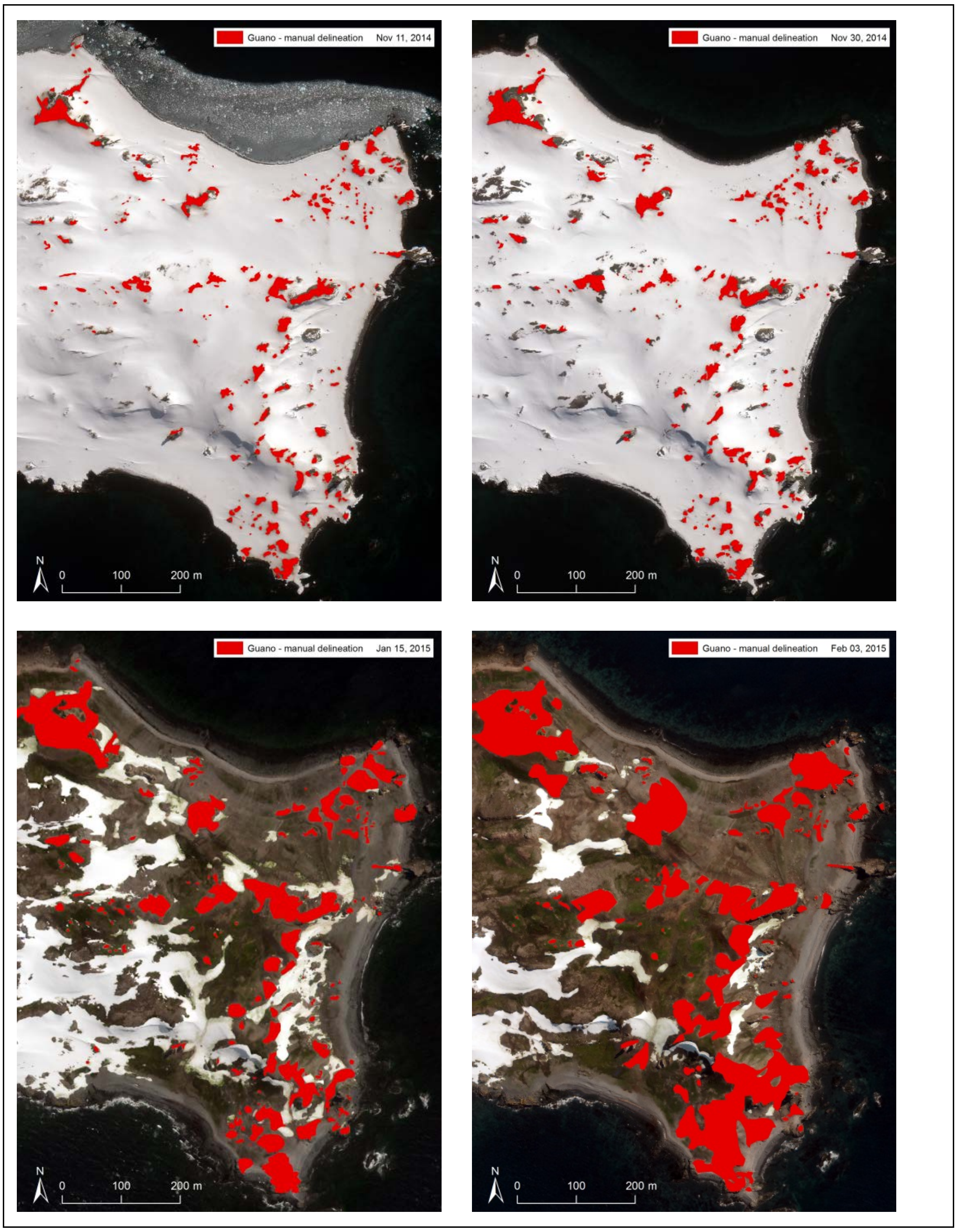


Figure 74: By comparison with the Worldview 3 image of 20-Jan-2015 (left), newly formed guano areas near the beach can be seen (within the red circles) in the Worldview 3 image of 3-Feb-2015 (right)

11.5 Matching breeding phenology with guano area from satellite images

It is sometimes possible, when satellite images are acquired, that the only images that can be obtained of particular areas are from times late in the season. By this time the penguin chicks have already gathered together in crèches and the former clear boundaries between nests are obliterated. At this point the area of the colony covered with guano is much larger than at the beginning of the season even though the number of nests steadily declines in the course of the breeding season. If the number of nests was then to be calculated solely on the basis of the area covered with guano, the result for the end of the season would be an unrealistically high number. In order to evaluate data even from these late and inconvenient time points, we investigated how much the guano areas change during the season and whether there is any connection between these changes and the breeding phenology of the colonies concerned.

We therefore calculated the mean density of nests in the guano covered areas of the Ardley Island colony for the four seasons 2005/06 and 2013/14 - 2015/16 (Figure 75). The number of nests was derived from the field counts of active nests made during the full surveys of the same four seasons. The area covered with guano was determined from the high resolution satellite images. The average nest densities were correlated (R^2= 0.84) with the date on which the satellite images were taken. The equation of the linear regression (2) herefore is

$$y = -0.0031x + 0.3824 \qquad (2)$$

where y is the density of nest groups (nests/m^2) and x the date of the satellite images (expressed as days since 11^{th} November).

The nest density of guano covered areas of the Ardley Island colony thus declines continually during the course of the seasons examined. In this analysis, however, it must be taken into account that only one image was available for two of the seasons and that it was not possible to analyse any image from mid of December.

Figure 75: Change during the season of the average nest density on Ardley Island derived from the guano area calculated from 9 high resolution satellite images and field counts of nests during complete surveys taken in the seasons 2005/6, 2013/14 - 2015/16

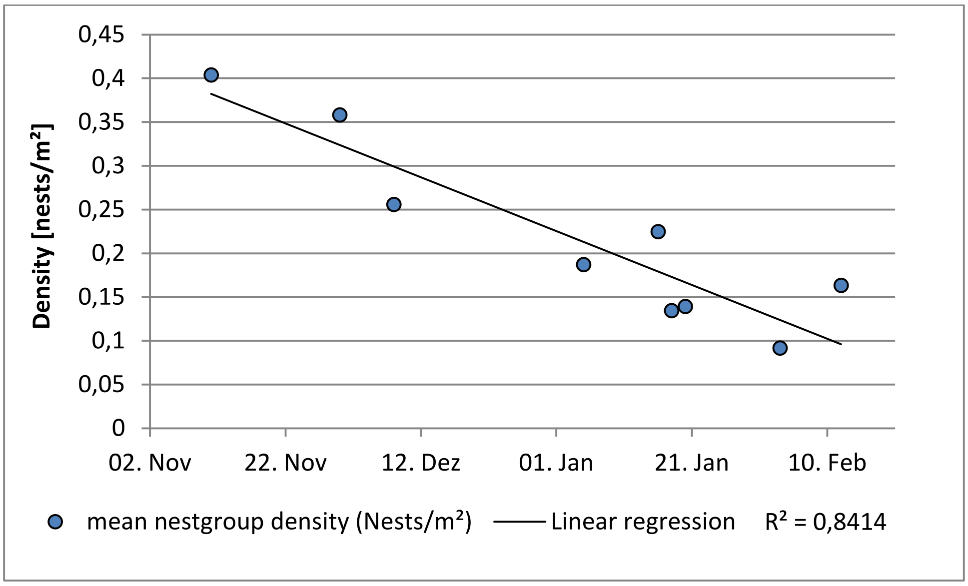


Figure 76 and Figure 77 show the relationships between the guano area detected in the satellite images and the state of breeding phenology in the colony at the times the images were taken. In season 2014/15 (Figure 76) it can be seen that the guano area stays the same during the incubation phase. In contrast, the data from season 2015/16 (Figure 77) show that the guano area starts to increase markedly no later than the start of the crèche phase, when the chicks leave their nests. Unfortunately, the exact point at which this increase starts can't be determined because of the absence of data for the hatching phase in December.

Figure 76: Breeding phenology of gentoo penguins on Ardley Island in the 2014/15 season, the breeding phases and the area of guano derived from satellite images

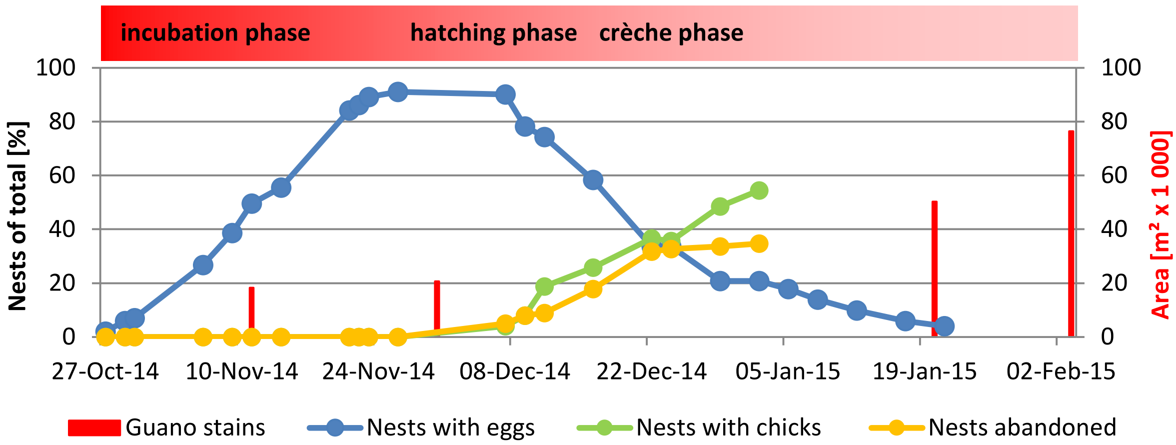
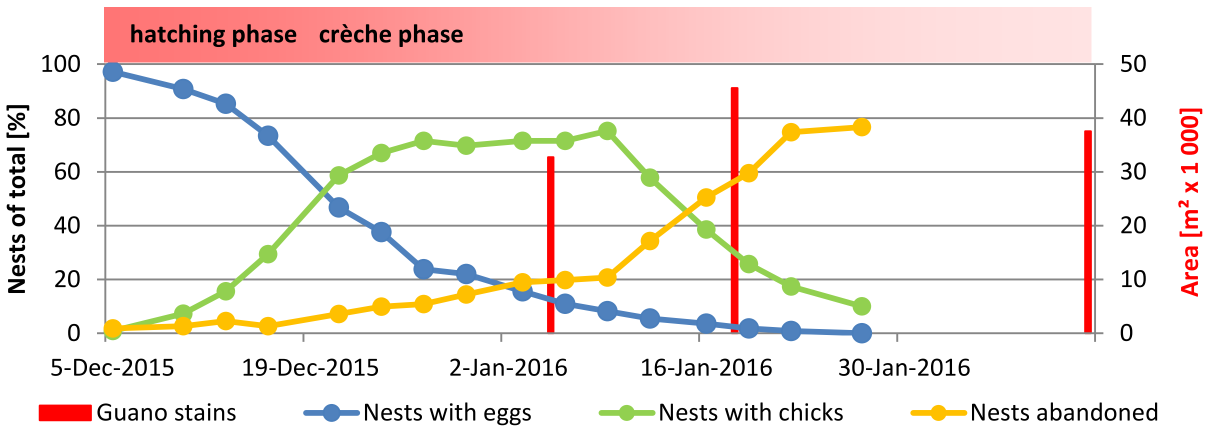


Figure 77: Breeding phenology of gentoo penguins on Ardley Island in the 2015/16 season, the breeding phases and the area of guano derived from satellite images ***



12 Investigating interseasonal variations in colony expansion and occupation and their detectability

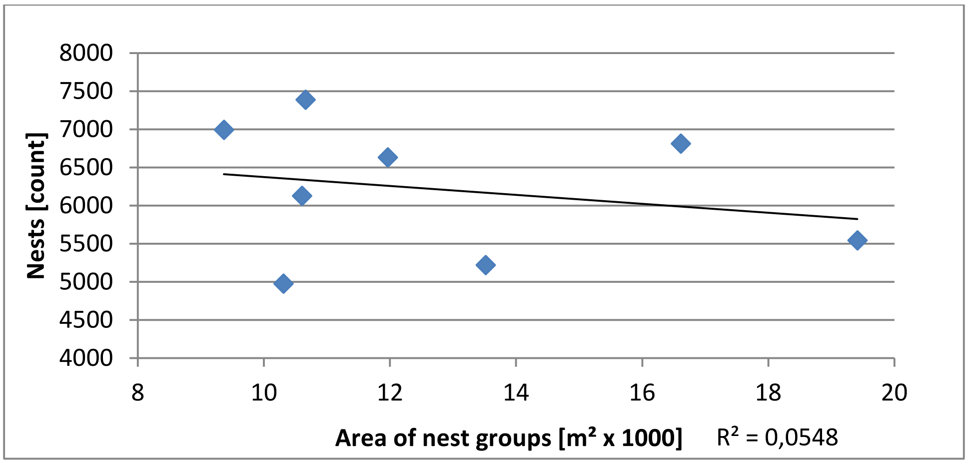
The detectability of interseasonal variations in colony expansion and occupation was investigated with high- and medium-resolution satellite images of colonies on Ardley Island and Cape Bird. For Narebski Point, only one snow- and cloud-free high-resolution satellite image was available for the study, and thus the analysis could not include this region. The method used and the results are described below.

12.1 High resolution satellites

12.1.1 Ardley Island

Due to the large seasonal variability on Ardley Island (see chapter 0), no intersaisonal comparison can be made with the guano-covered areas detected on high-resolution satellite images. Therefore, we looked for a correlation between the number of nests and the area of the nest groups obtained from ground surveys. The surveys from eight seasons on Ardley Island (2003/04 - 2005/06 and 2012/13 - 2015/16) were evaluated. The result of the analysis given in Figure 78 shows no such correlation for Ardley Island (R = 0.05). A possible reason for this result, and one previously described by Mustafa et al. (2005), could be that a change in the number of breeding pairs alters the density among the nest groups rather than the area of the nest groups. This would mean that on Ardley Island, no changes in the number of breeding pairs can be detected based on the nest group area, at least when the colony numbers alter between 5000 and 7500 breeding pairs. If there is a radical increase or decrease in the number of breeding pairs, however, a significant change in the nest group area could be expected (see also Mustafa et al. 2005).

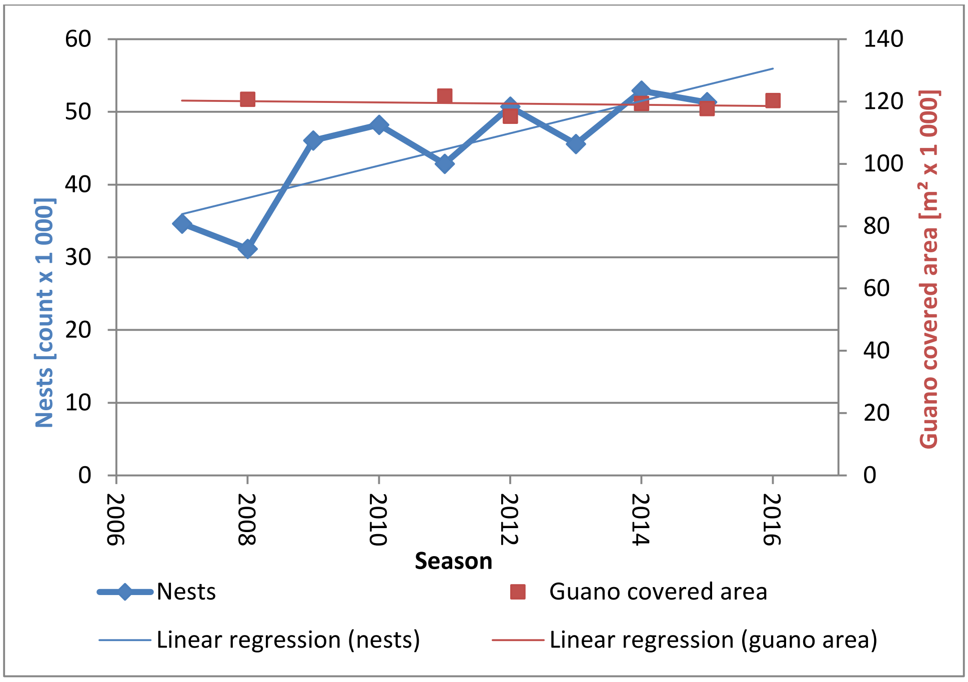
Figure 78: Correlation between the number of nests and the area of nest groups obtained from eight ground surveys conducted on Ardley Island in seasons 2003/04 to 2005/06 and 2012/13 to 2015/16



12.1.2 Cape Bird

In the research area located in East Antarctica, Cape Bird, we also investigated whether interseasonal fluctuations in breeding pairs could be detected with high-resolution satellite images. The database for the study was provided by six high-resolution satellite images from six different seasons in the period 2007/08 to 2015/16, in which the guano-covered areas of the Cape Bird North colony could be delimited manually. They were compared with the census data from the New Zealand Landcare Research (Landcare Research 2016) culled from aerial images from flyovers (Taylor et al. 1990) (see Figure 79). This comparison showed that the guano-covered area of the colony did not change significantly during the period of investigation, whereas in the same period the number of breeding pairs rose by 40 %. Thus, changes in the number of breeding pairs of Cape Bird North cannot be detected by the guano-covered surface area.

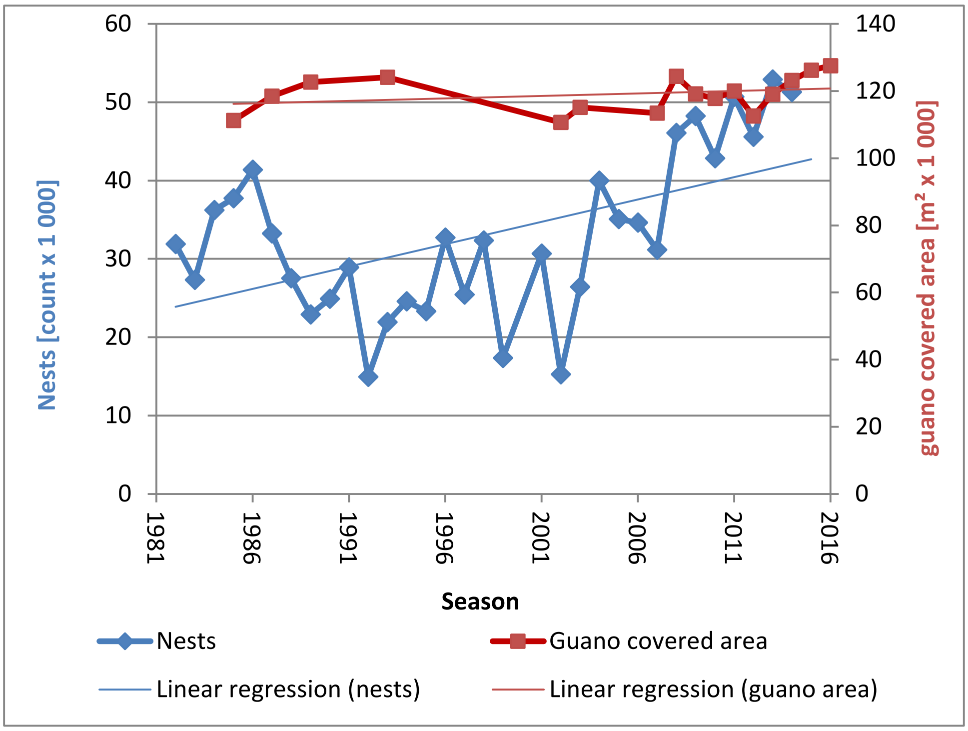
Figure 79: Comparison of manually delimited guano-covered areas of Cape Bird North in high-resolution satellite images and the census data from aerial images from over flights (Taylor et al. 1990)



12.2 Landsat

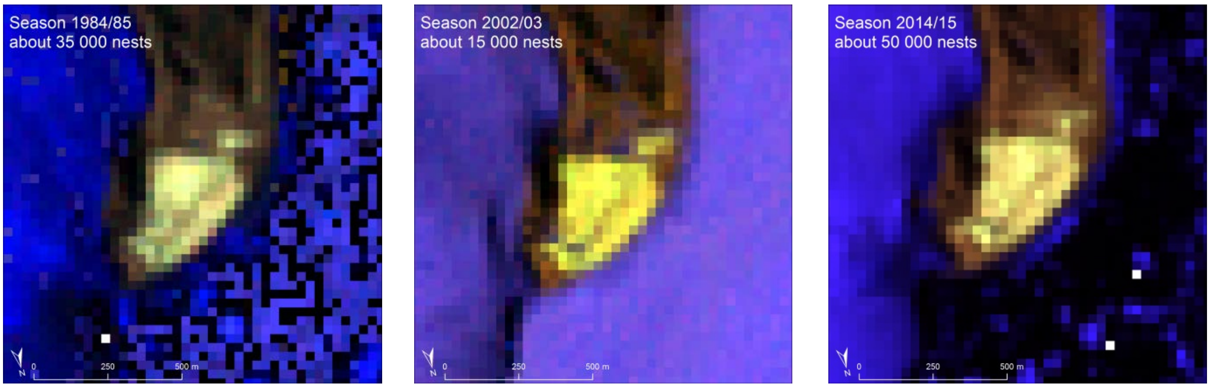
We also investigated whether interseasonal fluctuations in breeding pairs could be detected on the medium-resolution Landsat images. The number of breeding pairs (Landcare Research 2016) was again compared with the manually determined guano-covered areas of Cape Bird North on Landsat images. For this analysis, 17 cloud-free Landsat images at 30 m ground resolution were evaluated, which had been recorded between 1985 and 2015 with a variety of sensors (TM, ETM+ and OLI).

Figure 80: Comparison of manually delimited guano-covered areas of Cape Bird North from medium-resolution Landsat images and from the census data



The results show no correlation between the guano-covered areas detected and the number of breeding pairs (Figure 80). The same outcome was found for high-resolution images in chapter 12.1.2. This is illustrated in Figure 81, which shows that the colony's area barely changed at three different timepoints, although the number of breeding pairs more than tripled between 1984/85 and 2014/15. Thus Landsat images did not allow detection of any changes in the number of breeding pairs at Cape Bird North according to the guano-covered area, even when the population more than tripled. The cause is assumed to be a change in density within the borders of the colony or nest groups.

Figure 81: Example of the guano-covered areas of Cape Bird North at different timepoints in colour-coded Landsat images (TM/ETM+/OLI-bands 765)



13 Outlook

In the sections above we described the potential and the limitations of using remote sensing data to monitor Antarctic penguin colonies. We investigated how appropriate are current high resolution and intermediate resolution satellites in terms of their spatial, temporal, structural and scalar aspects. This investigation indicated that high resolution images were highly capable of detecting even small colonies. However, intermediate resolution Landsat 8 images had limited ability to detect small or structurally complex colonies. Nevertheless, these images have the advantage that they can be classified automatically. This has not yet been possible for high resolution images from a variety of different areas because of the limited spectral coverage of these images. This limitation might be alleviated by the SWIR bands of the Worldview 3 satellite. Also promising are the spectral configuration of the new intermediate resolution sensors such as Sentinel 2 which are like those of Landsat. In this respect, hyperspectral sensors, the intensive development of which has already begun, should also be considered.

It has not yet been possible to discriminate between different species of penguins in satellite pictures. Initial analyses of guano colours suggest that these colours could be classification characteristics. However, the development of a consistent method requires further investigation using in-situ data, particularly in order to account for the great inter- and intra-seasonal differences. The results of species differentiation from satellite images should also be verified using images from other seasons and other colonies.

The study also determined that differences between seasons in the numbers of breeding pairs were not very precisely reflected by changes in the area of ground covered by guano. In this respect, too, therefore, additional analyses must be carried out to determine the spatio-temporal associations of these changes. Equally, reliable methods must be developed to convert guano area signals into numbers of breeding pairs of penguins.

Strong changes of the guano extent during the season were found in the test locations. Owed to the frequent cloud coverage of the test locations it is hardly possible to acquire satellite images at a standardized date. Hence, it is necessary to understand the patterns of these changes to allow a temporally differentiated interpretation of the spatial signal. Possible approaches are intensive analyses of the breeding phenologies of the different species and an improved understanding of its regional and wheather-dependend variability. These information could be combined with more precise data on the variability of the spatial signal (e.g. by repeated ground mapping or UAV surveys).

Counts on the ground, as exact as possible (Ground Truth Data) are required for judging the predictive ability or the precision of information derived from satellite images. There are a number of approaches for the further development of such count methods. As such, a reliable method to derive breeding pair numbers from UAV orthomosaics of penguin colonies has to be found, answering the question of non-breeding individuals staying in the breeding area. Possible solutions are the use of high resolution thermal imagery as well as new count methods on the basis of total individuals instead of penguin nests.

The use of UAV technology in the Antarctic strongly increases. During this study first systematic analyses were performed to evaluate the influence of UAV overflights on breeding penguins. These analyses should be extended to include different flight situations, other UAV models, more penguin species and other breeding birds. To increase the reliability of such behavioral analyses the analysis could be extended qualitatively by physiological methods (e.g. heart rate measurements).

A major challenge for a supraregional monitoring strategy is the linking of data sets with different temporal and spatial scales, different qualities and from very different sources. Data base approaches have to be found to ensure this linkage.

Previous studies on the detection of colonies of rock-breeding penguins mainly focus on Adélie penguins. Large-scale studies on the other species of Pygoscelis penguins are rare. Particularly for Chinstrap penguins, major uncertainties exist on the dimension of the total population. For many colonies quantitative data is missing.

This study confirmed the feasibility of an Antarctic–wide monitoring of penguin colonies. However, there still is a need for research to ensure the necessary quality to achieve reliable results and an efficiency that allows a regularly monitoring across the whole area.

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