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Pilot study on monitoring climate-induced changes in penguin colonies in the Antarctic using satellite images

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Pilot study on monitoring climate-induced changes in penguin colonies in the Antarctic using satellite images

by

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16. Abstract

We investigated the possibility of monitoring penguin colonies across the Antarctic using remote sensing by satellites. We selected six test sites with a number of penguin colonies, focussing on the species Pygoscelis adeliae (Adélie penguin) and Pygoscelis papua (gentoo penguin). The remote sensing platforms used were optical systems with medium (Landsat7) and high resolution (WorldView1/2 and QuickBird2), as well as a radar system (TerraSAR-X). The analyses of the images taken during the 2011/2012 breeding season were compared with the corresponding count data from the sites. In addition, we used historical count data to investigate the detectability of changes in colonies, to assess the efficiency of each method, and the possibilities of automation.

As a result of these investigations, we recommend a process comprising three levels of research, conducted in parallel. Level 1 consists of a comprehensive investigation of all ice-free coastal areas of Antarctica using automated analysis of Landsat7 images. In order to detect detailed changes in area, high-resolution sensors should be used in Level 2 to record images of approximately 30 selected representative colonies and the images should be analysed manually. For each of these colonies, ground validation should be carried out at least once during the study period. For Level 3, 10 colonies should be selected and analysed in detail at various times during the season with the help of high-resolution images. The analyses should be compared with precise counts and mapping data obtained on the ground.

We consider the proposed process to be appropriate for achieving valid and meaningful monitoring of penguin colonies with sufficient accuracy and at an acceptable cost.

17. Keywords

Antarctic, Landsat, QuickBird, WorldView, TerraSAR-X, Monitoring, Penguins, Guano,

Satellite remote sensing, Radar, Automation

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Summary

We investigated the possibility of monitoring penguin colonies across the Antarctic using remote sensing by satellites. We selected six test sites with a number of penguin colonies, focussing on the species *Pygoscelis adeliae* (Adélie penguin) and *Pygoscelis papua* (gentoo penguin). The remote sensing platforms used were optical systems with medium (Landsat7) and high resolution (WorldView1/2 and QuickBird2), as well as a radar system (TerraSAR-X). The analyses of the images taken during the 2011/2012 breeding season were compared with the corresponding count data from the sites. In addition, we used historical count data to investigate the detectability of changes in colonies, to assess the efficiency of each method, and the possibilities of automation.

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1 Introduction

The effects of global climate change can also be seen in the Antarctic, particularly on the western Antarctic Peninsula in winter. Meteorological data from the Faraday/Vernadsky station show that the temperature in June has risen by 6°C over the last 50 years (Smith et al. 2003). This rising trend in temperature has far-reaching effects on the marine ecosystem and triggers a cascade of changes. Satellite images taken over the past two decades show that the extent of sea ice cover is shrinking (Smith et al. 2003, Turner et al. 2009). Sea ice plays a key role in the life cycle of Antarctic krill (*Euphausia superba*) which is at the centre of the food web of the Antarctic ecosystem. The distribution and density of krill have an effect on the survival and reproduction rate of its predators and thus also on penguin populations.

Population change and relocations of penguin breeding areas, in particular those of gentoo (*Pygoscelis papua*), chinstrap (*Pygoscelis antarctica*) and Adélie penguins (*Pygoscelis adeliae*) in the Antarctic Peninsula region, are the result of such climate change and have been observed in diverse areas of the Antarctic (Fraser & Patterson 1997, Woehler et al. 2001, Sander et al. 2006, Ainley et al. 2005, 2010, Ballard et al. 2010, Trivelpiece et al. 2011). These studies show that populations of Adélie penguins and, to some extent, chinstrap penguins, are decreasing in the northern parts of the Antarctic Peninsula. In contrast, evidence has been found of positive population trends in southern Antarctic areas.

So far, investigation of population development in penguin colonies have usually involved population counts and mapping on the ground (Peter et al. 2008) or using selective aerial photographs taken from aeroplanes and helicopters (Wilson et al. 2001). These methods are comparatively laborious and very costly. The population details thus obtained for small areas are mostly used in maintaining valuable long-term data sets (e.g. Peter et al. 2008). The number of colonies is large (it can be assumed that many are as yet undiscovered) and access to them is generally very difficult. It would thus appear that, objectively speaking, very comprehensive monitoring is only possible using remote sensing data from satellites. It is in this context that the present project investigated the possibility of creating a penguin monitoring system that is as comprehensive and representative as possible.

In order to assess the feasibility of a monitoring programme, the satellite-based remote sensing systems available have to be assessed as to their ability to detect particular features (e.g. colony area, number of individuals, changes over time, separation of species). In addition, the possibilities of automation are explored and preliminary proposals made as to the course of action to be taken internationally to create a comprehensive monitoring project.

The project involves selecting six test sites which cover the required range of species (target: all five Antarctic penguin species) as well as the diversity of the landscape and where population counts were carried out during the 2011/2012 season. Two of the test sites (Cape Bird and Kopaitic) have two colonies, while another has five (Adélie Land). In five of the test sites there are count data from previous years which were used for multitemporal analyses (Section 3.4).

The next stage of the study is to analyse the images and to draw up proposals for a monitoring programme. Separately, counts of emperor penguins will be carried out during the 2011/2012 Antarctic winter, when this species breeds, and the relevant satellite images obtained and analysed.

2 Methods

2.1 Obtaining data on the location and size of colonies

In preparation for the project both the contractor and the Federal Environment Agency contacted a large number of scientists, scientific institutions and Committee for Environmental Protection (CEP) representatives of the Antarctic Treaty Consultative Parties to request their cooperation. By studying the relevant literature and through good contacts with relevant scientists, we were able to settle on the following six locations as test sites for which population data are available:

- Ardley Island
- Point Thomas
- Torgersen Island
- Cape Bird (2 colonies)
- Kopaitic (2 colonies)
- Adélie Land (5 colonies)

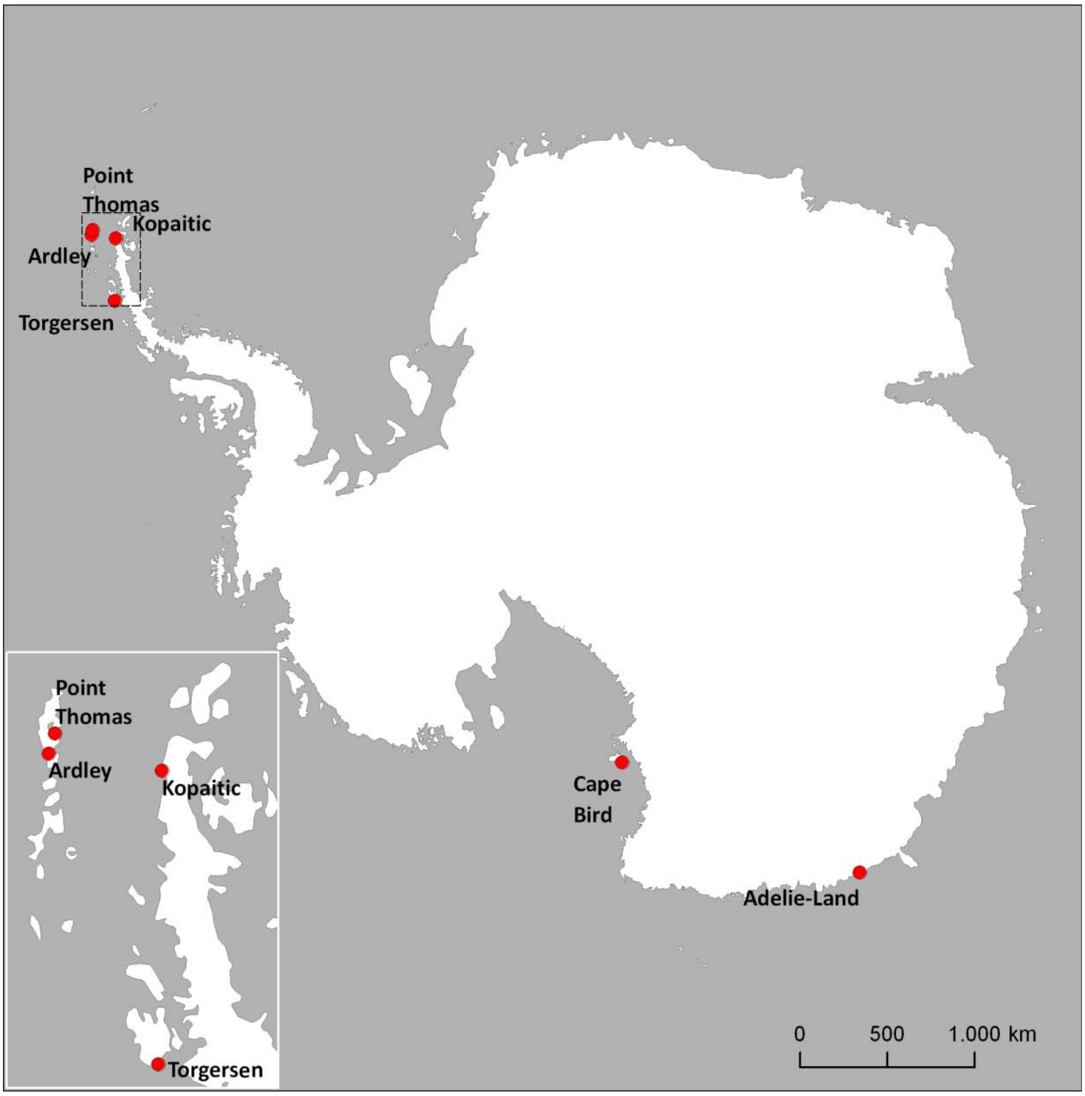


Figure 1: Location of the test sites

Figure 1 gives the location and a brief overview of the test sites. There is a detailed description in Section 2.3.

At each of these sites, diverse scientists carried out counts of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins) at the beginning of December 2011. However, those working at the Cape Bird test site were unable to finish preparing their count data and send them on time. For all sites, apart from Kopaitic, there are historical count data available. These locations are precisely documented in Section 2.3. Whereas the above-mentioned species breed in the Antarctic summer, the species *Aptenodytes forsteri* (emperor penguin) breeds in the Antarctic winter. As part of the collaboration between the *German Aerospace Centre* (Deutsches Zentrum für Luft- und Raumfahrt e. V. - DLR) and the *Alfred Wegener Institute of Polar and Marine Research* (AWI), it was therefore arranged for counts to be carried out of the emperor penguin colony located close to the research station Neumayer III during the Antarctic winter of 2012. It is expected that these results will be analysed and incorporated with the rest by October 2012.

2.2 Evaluation of the suitability, availability and possibility of interpreting satellite images

A wide variety of factors must be considered when selecting suitable satellites for detecting penguin colonies or breeding pairs of penguins. First we prepared an overview that was as comprehensive as possible of all remote sensing satellites currently in operation and available for civilian use. We considered the spatial and spectral characteristics of these satellites' sensors and the spatial and temporal availability of data in the Antarctic. Finally, we compiled an overview of the possible costs of purchasing archived and new satellite images.

2.2.1 Current remote sensing satellites with high-resolution sensors

Table 1 shows those remote sensing satellites currently in operation, which are available for civilian use and which are equipped with a high-resolution optical sensor. Together with the length of the mission so far, the planned length of the mission was also given, where available. Spatial resolution varies in many sensors, depending on the wavelength used. The sensors' bands are divided into PAN (Panchromatic), VNIR (Visible Near Infrared), SWIR (Short Wave Infrared), TIR (Thermal Infrared) and Hyperspectral bands (HS). The highest spatial resolution for PAN is 0.5m, while for TIR it is 60m. The specifications for spatial resolution in PAN are aligned to the images that can actually be obtained by civilians. Thus, for example, WorldView2 records in 0.4m resolution but has to reduce this to 0.5m for images made available to civilians. The satellite's repetition rate indicates the time period within which it is possible to have two images of the same place. This depends on the latitude of the location where the image is taken and on whether the satellite uses a swivelling or non-swivelling sensor. Satellites without a swivelling mechanism, such as Landsat7 and Terra-Aster, thus have relatively long repetition rates. The swath width defines the width of an image on the ground. This is of relevance to monitoring penguin colonies insofar as small swath widths reduce the likelihood of capturing two neighbouring colonies in a single scene, which would be more economical.

Table 1: General overview of current remote sensing satellites

Satellite	Length of the mission	Spatial resolution at nadir [m]					Spectral resolution [Bands]	Repetition rate [Days]	Swath width at nadir [km]
		PAN	VNIR	SWIR	TIR	HS			
CARTOSAT1	since 2007 + minim. 5 yrs.	2.5	-	-	-	-	PAN	5	27
CARTOSAT2	since 2007 + minim. 5 yrs.	1	-	-	-	-	PAN	4	10
DEIMOS1	since 2009 + minim. 5 yrs.	-	22	-	-	-	Green, Red, NIR	2 - 3	600
EO1	since 2000 - today	10	30	-	-	30	PAN, 7MS, 220HS	16	7 - 37
EROSB	since 2006 + minim. 10 yrs.	0.82	3.28	-	-	-	PAN, Blue, Green, Red, NIR	3	7
FORMOSAT2	since 1999 - today	2	8	-	-	-	PAN, Blue, Green, Red, NIR	1	24
GeoEye1	since 2008 + minim. 10 yrs.	0.5	2	-	-	-	PAN, Blue, Green, Red, NIR	3	15
IKONOS2	since 1999 + minim. 8 yrs.	1	4	-	-	-	PAN, Blue, Green, Red, NIR	1.5 - 3	12
KOMPSAT2	since 2006 - today	1	4	-	-	-	PAN, Blue, Green, Red, NIR	3	15
Landsat7	since 1999 - today	15	30	30	60	-	PAN, Blue, Green, Red, NIR, SWIR, TIR	16	180
Pléiades	since 2011	0.5	2	-	-	-	PAN, Blue, Green, Red, NIR	1	20
Proba1	since 2001 - today	5	18	-	-	-	19 VNIR	7	4 - 14
QuickBird2	since 2001 - today	0.6	2.4	-	-	-	PAN, Blue, Green, Red	3 - 6	16
RapidEye	since 2009 - today	-	5	-	-	-	PAN, Blue, Green, Red, RedEdge, NIR	1 - 5	77
Resourcesat1	since 2003 + minim. 5 yrs.	5.8	6 - 24 - 56	23.5 - 56	-	-	PAN, Green, Red, NIR, SWIR	5	23 - 141-740
Resourcesat2	since 2011 + minim. 5 yrs.	5.8	6- 24 - 56	23.5 - 56	-	-	PAN, Green, Red, NIR, SWIR	5	70 - 141-740
SPOT4	since 1998 - today	10	20	20	-	-	PAN, Green, Red, NIR, SWIR	2 - 3	60
SPOT5	since 2002 - today	2.5-5	10	20	-	-	PAN, Green, Red, NIR, SWIR	2 - 3	60
Terra-ASTER	since 2000 + minim. 6 yrs.	-	15	30	90	-	Green, Red, NIR, 6 SWIR (until 2007), 4 TIR	16	60
UK-DMC2	since 2009 - today	-	22	-	-	-	Green, Red, NIR	2 - 3	80
WorldView1	since 2007 - today	0.5	-	-	-	-	PAN	2 - 6	17
WorldView2	since 2009 + minim. 7 yrs.	0.5	2	-	-	-	PAN, 2 Blue, Green, Yellow, Red, 3 NIR	1 - 4	16
KOMPSAT3	launch 2012	0.7	2.8	-	-	-	PAN, Blue, Green, Red, NIR	n.d.	n.d.

2.2.2 Spatial and spectral characteristics of sensors

The sensors of the satellites listed cover different spectral bands. Figure 2 shows the distribution of the spectral bands. This makes it clear that the satellites chosen for this project (indicated in red at Figure 2) cover all spectral bands. WorldView2 can, for example, detect very short-wave light and large sites in NIR with high spatial resolution, while Landsat7 also includes SWIR and TIR.

The satellites for this project were chosen so that they covered a broad spectrum of spatial and spectral characteristics. Landsat7, with 30m in the multispectral band, has a rather coarse spatial resolution but covers a large range in the mid-wavelength and far infrared regions. RapidEye, selected for the mid-range spatial area, records multispectral data with 5m ground resolution and is the only sensor for this range that has five multispectral bands. Two high-resolution platforms were chosen. The first was QuickBird2, with 0.6m in PAN, for which there are images of the Antarctic from as early as 2002, and the second was WorldView2, which is the only high-resolution sensor with eight multispectral bands.

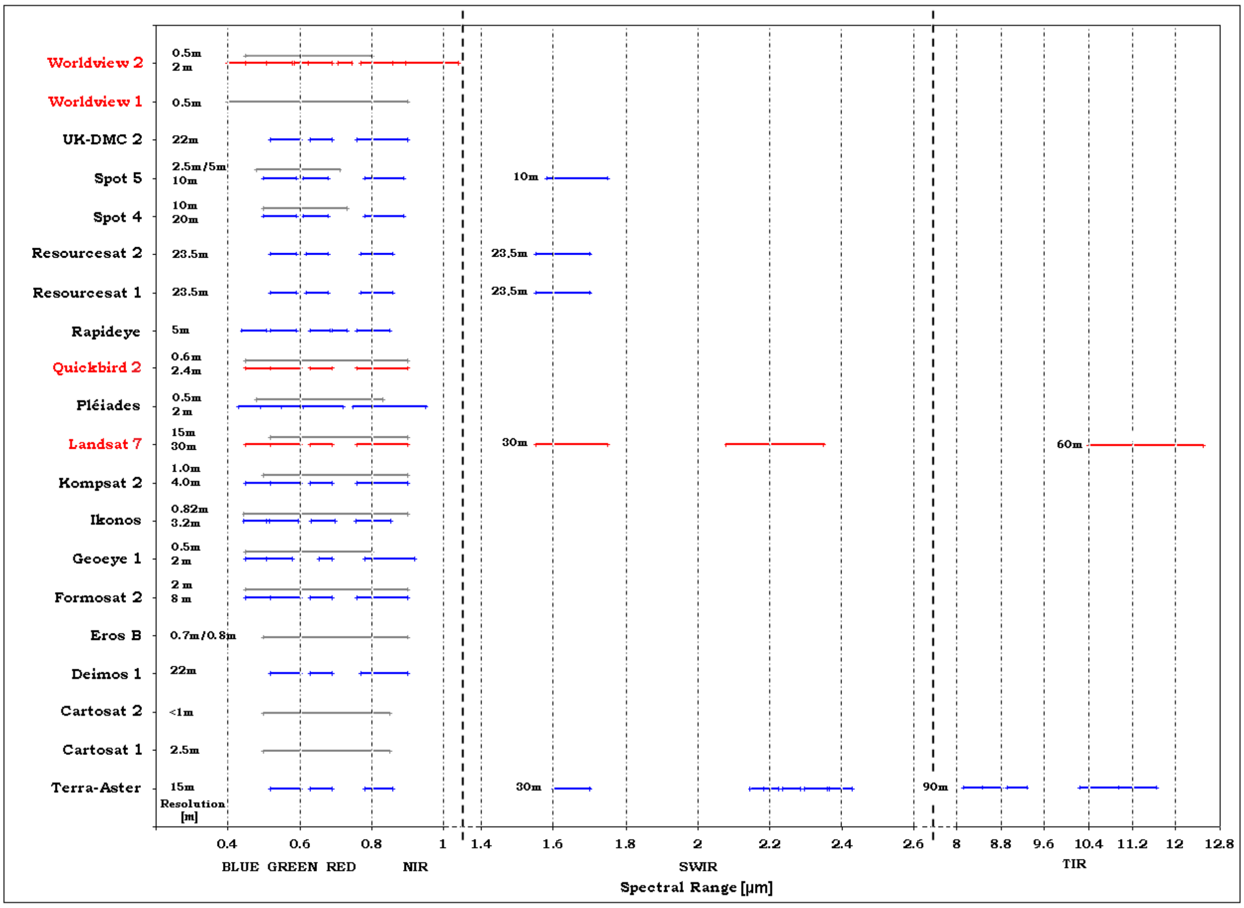


Figure 2: Overview of the multispectral and spatial resolutions of existing remote sensing satellites – satellites marked in red were used in the project

2.2.3 Spatial and temporal availability of the data

It is difficult to determine the spatial coverage of the Antarctic on archived images. With most online archives only a relatively small area can be searched and they only show a relatively small list of hits, which makes it virtually impossible to estimate availability over a large area. Nevertheless, we used random samples to attempt a rough estimate of availability over a wide area (Table 2). No data for the Antarctic were found for the Indian IRS satellites (Cartosat1/2 and Resourcesat1/2) or for EROS B. As a result, no data (n.d.) can be provided concerning these satellites. For Formsat2 we only found a diagram giving an overview of worldwide coverage up to 2007, so that no information can be given as to the age of the picture archive. It is noticeable that, as a rule, coverage is very selective and concentrates particularly on places near to Antarctic stations. The reason for this irregular coverage is that, because of the huge amounts of data and small swath widths, the very high-resolution satellites cannot take images continuously but only take pictures of specific targets on request.

Table 2: Overview of general spatial coverage in the Antarctic and availability of images in the archive

Satellite	General spatial coverage in the Antarctic	Availability of historic data in the Antarctic since
CARTOSAT1	n.d.	n.d.
CARTOSAT2	n.d.	n.d.
DEIMOS1	very low (37 images in entire Antarctic)	2009
EO1-Ali	good	2003
EROS B	n.d.	n.d.
FORMOSAT2	very low	n.d.
GeoEye1	good	2009
IKONOS2	average	2001
KOMPSAT2	very low	2008
Landsat7	complete	1999
Proba1	very low (23 images in entire Antarctic)	2005
QuickBird2	good	2002
RapidEye	low	2009
Resourcesat1	n.d.	n.d.
Resourcesat2	n.d.	n.d.
SPOT4	selected areas good, elsewhere low	2002
SPOT5	selected areas good, elsewhere low	2002
Terra-Aster	complete	2000
UKD-MC2	very low	2009
WorldView1	good	2008
WorldView2	average	2009

The following diagrams (Figure 3) show the availability of archived satellite images of each satellite for the five test sites for which historical count data are available. These are Ardley Island, Point Thomas, Torgersen Island, Adélie Land and the two northerly colonies on Cape Bird. In each case we counted the number of images with cloud cover below 10%, those with 10% to 50% cover and those with more than 50% cloud cover. There were no data available on the percentage of cloud cover for UK-DMC2, Proba1 and EO1, so that no such classification could be made for these satellites. For DEIMOS1 there are no archived data for the stations named. No information could be provided for satellites without an online archive (Cartosat1/2, Resourcesat1/2, and EROS B). It is noteworthy that the colonies of Adélie Land and Cape Bird in the eastern Antarctic have less cloud cover, in relation to the total number of images seen, than the colonies further north on the Antarctic Peninsula (*cf* Figure 4 and Table 3).

Figure 3: Availability of historical satellite images of each individual satellite for the five locations selected, grouped according to the percentage of cloud cover

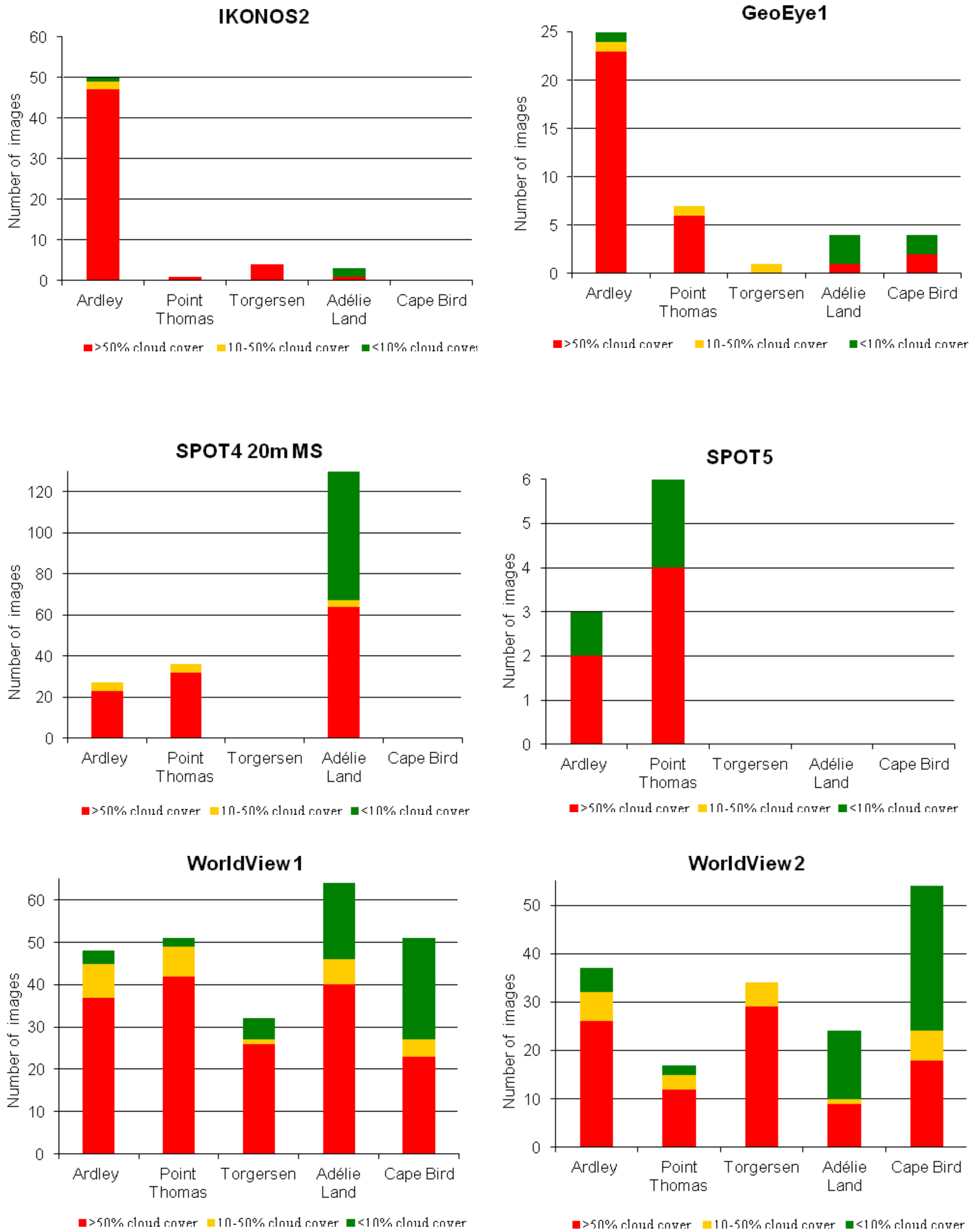
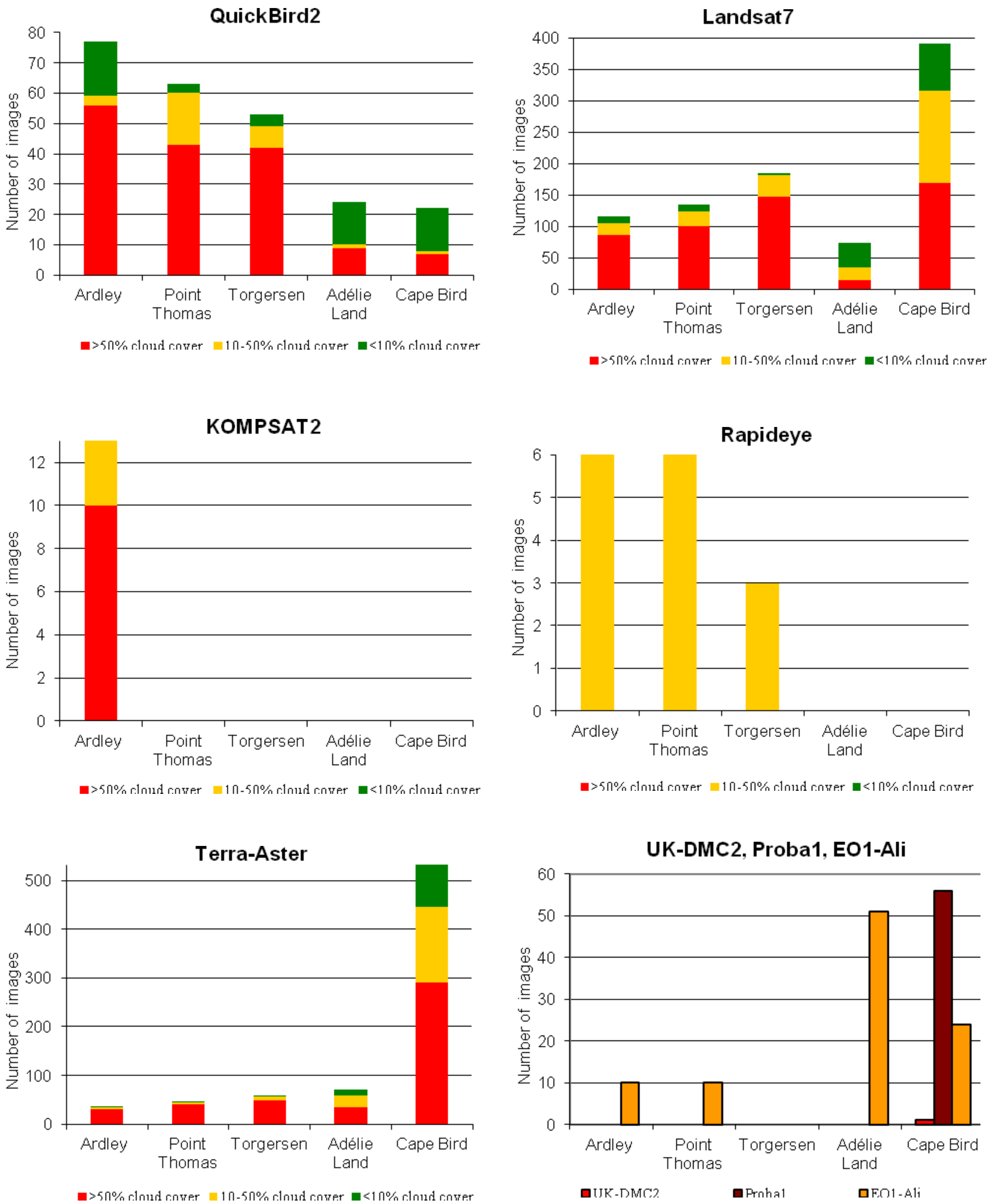


Figure 3 (continued): Availability of historical satellite images of each individual satellite for the five locations selected, grouped according to the percentage of cloud cover



For optical remote sensing systems, the period during which images can be recorded is limited by day length and cloud cover. In order to describe the probability of obtaining a usable image during the breeding season, we show average visibility for the months November to February (Figure 4). Visibility was calculated using an internet-based tool for calculating the hours of sunshine (Giesen 2006) in five steps. The number of hours obtained in this way was combined with the average monthly cloud cover percentages (spatial resolution: 2.5° latitude or longitude) recorded by Jubier (2006). While up to 21 hours of visibility per day were recorded in the central continental part of the eastern Antarctic, this dropped to as little as three hours of visibility in the northern coastal zone. Thus, the two more continentally situated test sites (Cape Bird and Adélie Land) had significantly greater visibility than those sites that were more maritime, northerly and situated closer to the precipitation-rich polar front (Table 3).

Table 3: Visibility of test sites for optical remote sensing systems, dependent on day length (Giesen 2006) and cloud cover (Jubier 2006) between 60 and 90° S

Test sites	Visibility [h/Day]
Ardley	3
Point Thomas	3
Kopaitic	4
Torgersen	3
Cape Bird	7
Adélie Land	8

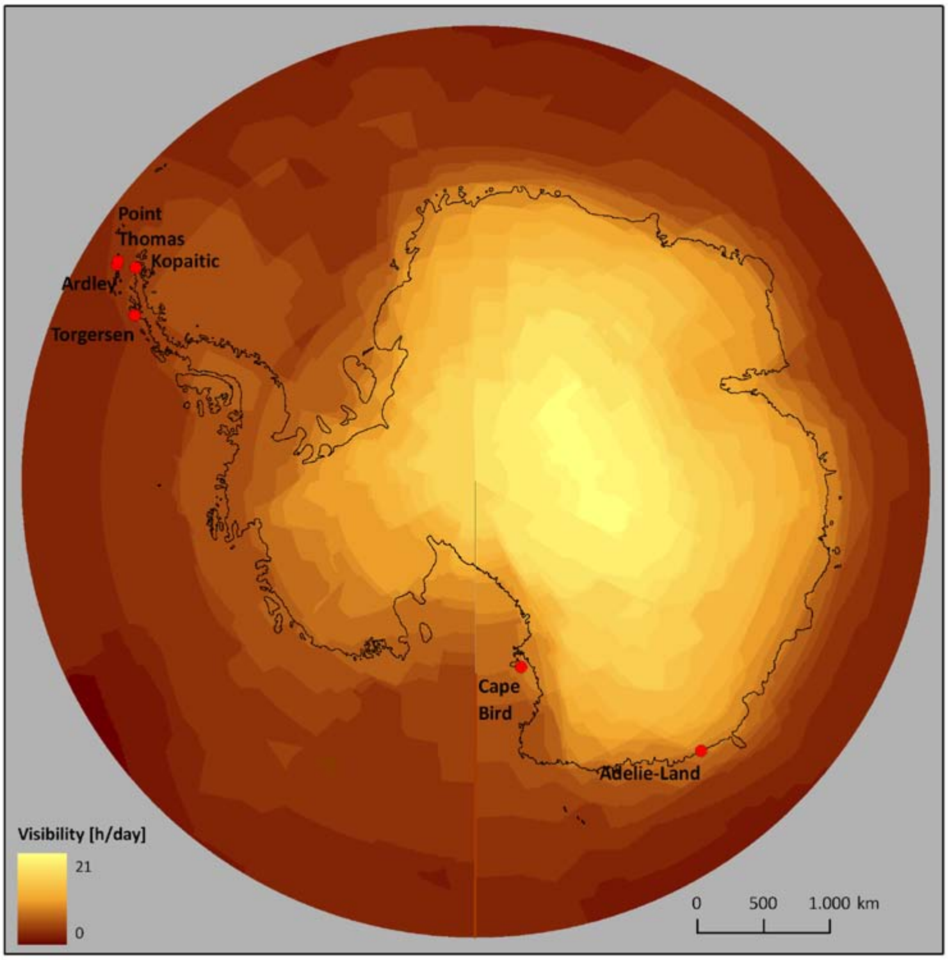


Figure 4: Visibility distribution of optical remote sensing systems, dependent on day length (Giesen 2006) and cloud cover (Jubier 2006) between 60 and 90° S and between November and February.

2.2.4 Costs and acquisition of the satellite images

The costs of currently available satellite images are shown (Table 4). Depending on the supplier, it is possible to buy data by the km² and/or by scene. Where it was possible to order by the km², the minimum area that could be ordered was also given. The data for new images always refer to the product with the highest possible spatial and spectral characteristics of the sensor. In the case of EOS1 and Proba1, it is possible to obtain images for free if an application to that effect by the U.S. Geological Survey (USGS) or the European Space Agency (ESA) is approved. To provide a better comparison, we calculated the actual costs of an image of 4km² of the Ardley Island test site.

Table 4: Overview of the costs of satellite images

Satellite	Provider	Costs of archived Images per scene	Costs of archived Images per km² (minimal)	Costs of new acquisitions (minimal)	Costs of Ardley Island test site (example)	
					Archive [€]	New acquisition [€]
CARTOSAT1	Antrix/Euromap	1,145 US$	-	1,800 €	851	1,800
CARTOSAT2	Antrix	470 US$ (older 1 Year)	-	780 US$	349	579
DEIMOS1	Spot Image	-	0.06€ (6,000km²)	0.15€ per km² (10,000km²)	360	1,500
EO1	USGS	free of charge	-	registration	free of charge	n.d.
EROS B	ImageSat intl.	n.d.	n.d.	n.d.	n.d.	n.d.
FORMOSAT2	Spot Image	1,500€ (older 1 Year)	-	4,000 €	1,500	4,000
GeoEye1	e-Geos	-	12.5 US$ (25km²)	25 US$ per km² (100km²)	232	1,857
IKONOS2	e-Geos	-	10 US$ (25km²)	20 US$ per km² (100km²)	186	1,486
KOMPSAT2	Spot Image	-	7.5 US$ (50km²)	15 US$ per km² (100km²)	279	1,114
Landsat7	USGS	free of charge	-	-	free of charge	-
Perba1	ESA	registration	-	-	n.d.	n.d.
QuickBird2	EUSI	4,625 US$	17 US$ (25km²)	23 US$ per km² (1,800 US$)	316	1,337
RapidEye	RapidEye	-	0.95€ (1,000km²)	0.95€ per km² (5,000 km²)	706	3,528
Resourcesat1	Antrix/Euromap	1,070 US$	-	4,500 €	795	4,500
Resourcesat2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
SPOT4	Spot Image	1,090 €	-	1,890 €	1,090	1,890
SPOT5	Spot Image	3,060 €	-	3,860 €	3,060	3,860
Terra-Aster	ASTER GDS	9,800 Yen (~95€)	-	n.d.	95	n.d.
UK-DMC2	DMCii	-	0.058€ (25,600km²)	0.144€ per km2 (25,600km²)	1,485	3,686
WorldView1	EUSI	4,625 US$	17 US$ (25km²)	23 US$ per km² (1,800 US$)	316	1,337
WorldView2 8-Band	EUSI	8,704 US$	32 US$ (25km²)	38 US$ per km² (1,800 US$)	594	1,337
WorldView2 4-Band	EUSI	4,625 US$	17 US$ (25km²)	23 US$ per km² (1,800 US$)	316	1,337

2.3 Test sites

2.3.1 Ardley Island

Position: 62.2°S/ 58.9°W

The geological subsoil of Ardley Island is of volcanic origin (weathered olivine basalt and basaltic andesite; rare pyroxenic andesite and dacite; see Smellie et al. 1984). However, the nesting ground of the breeding sites varies greatly. The penguins brood on ridges that stand slightly higher than the surrounding area, as these are free from snow early in the spring, but also on craggy rocks further inland. Near the beach and also reaching far inland, the ground surface mainly consists of coarse, greyish-black gravel; the rocks are dark in colour (Figure 6). The green algae species *Prasiola crispa* occurs in patches due to the high concentration of nutrients near the penguin colonies and its green colour makes it very conspicuous. However, in long-lasting dry conditions (and wind) the alga drifts and, in damp weather, it is covered by guano trickling downhill and trampled into the ground by penguins, so that it is no longer visible in places, at least in the vicinity of colonies. Gentoo, chinstrap and Adélie penguins breed there together.

Detailed mapping of all breeding colonies on Ardley Island was carried out by the working group Polar and Bird Ecology of Friedrich Schiller University, Jena, during the 2003/2004, 2004/2005 and 2005/2006 breeding seasons (Figure 5).

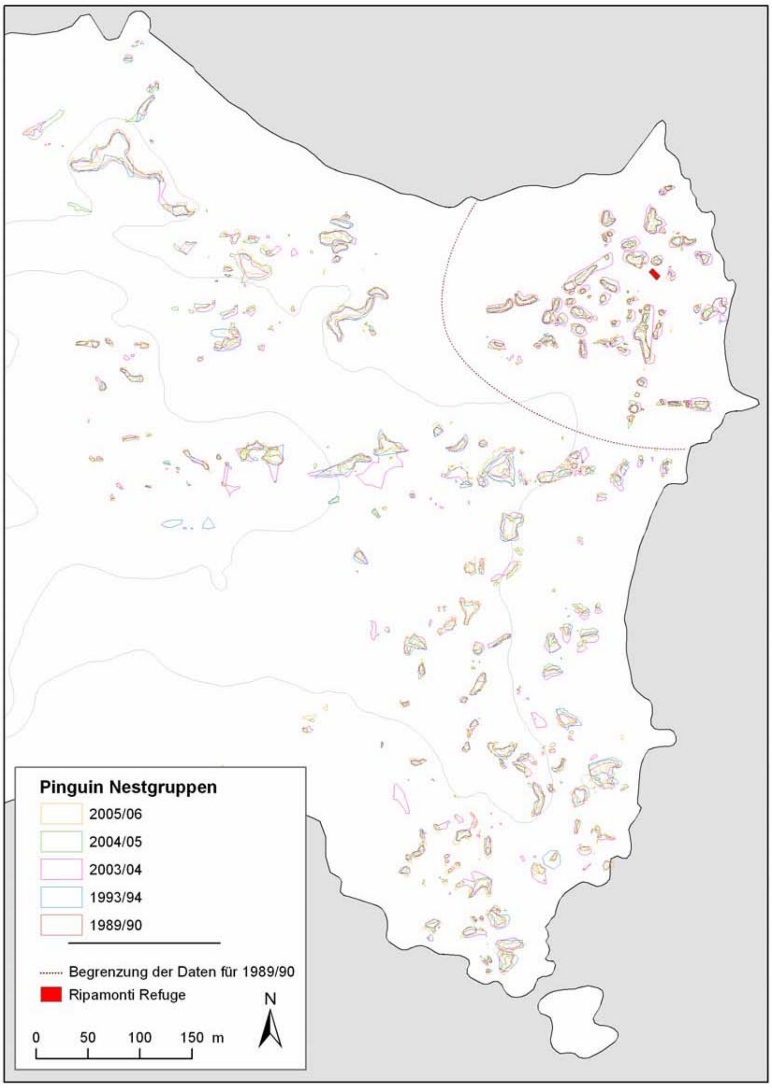


Figure 5: Change in the spatial extent of penguin nest groups on Ardley Island during five different seasons between 1989 and 2006 (Peter et al. 2008).

Figure 6: Beach area of Ardley Island with penguin colonies, and with skuas in the foreground (Image: Kopp)

2.3.2 Point Thomas

Position: 62.2°S/ 58.5°W

The subsoil of this point is described as volcanic rock by Jablonski (1986) − comparable with that of Ardley Island (see Section 2.3.1).

With the help of a high-resolution satellite image, Polish colleagues (Artur Body and Malgorzata Korczak-Abshire, Polish Academy of Sciences, Department of Antarctic Biology in Warsaw) were able to match the Adélie penguin nest groups to the detailed count data (Figure 7).

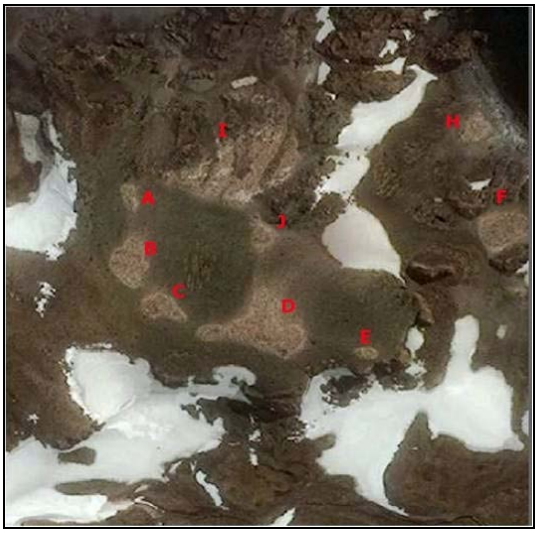


Figure 7: Distribution and number of Adélie penguin nests in the Point Thomas area at penguin Ridge during the 2011/2012 breeding season (Courtesy of Korczak-Abshire, by letter; Image © EUSI/DigitalGlobe 2012)

2.3.3 Torgersen Island

Position: 64.8°S/ 64.1°W

This island is the project's most southerly test site in the Antarctic Peninsula area. The subsoil is characterised by dark, granitic-volcanic rock and the weathered products thereof. The rocks are partially covered in large patches of reddish crustose lichens.

Torgersen Island is divided into a visitor zone in the north-east and a protected zone with limited access (Figure 8).

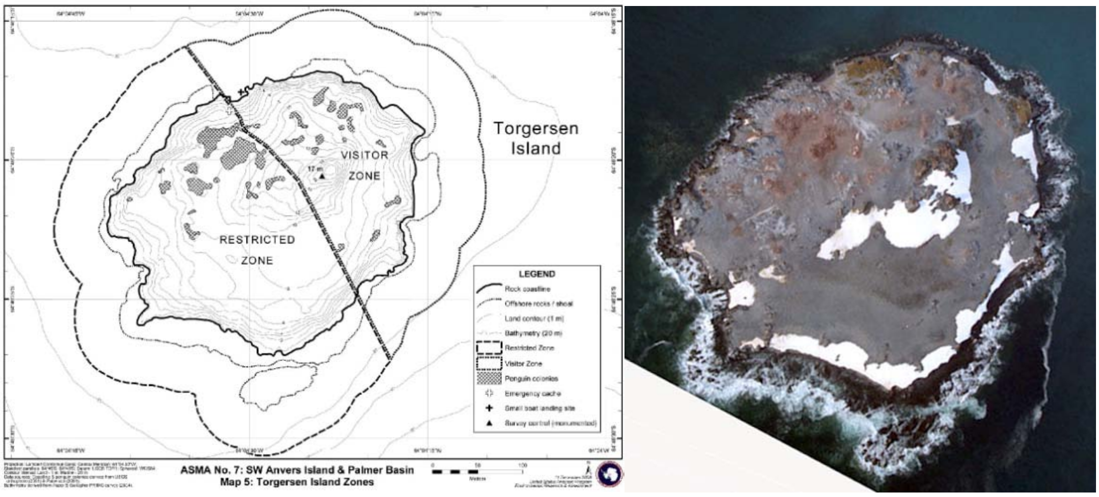


Figure 8: Torgersen Island with the location of the penguin colonies (dark areas; from: Management Plan Area No 7 (2010)) and an aerial photograph of the island (Image courtesy of Fraser, written communication)

Penguin breeding pairs have been counted annually since 1975, between 20 November and 7 December (the count data were made available by William Fraser (Polar Oceans Research Group, USA)). Figure 8 shows the location of the penguin colonies (situation as of 2008/2009 season) as well as an aerial photograph of the island. Only Adélie penguins breed there.

2.3.4 Cape Bird

Position: 77.2°S/ 166.4°E

The study site 'Cape Bird' is an ice-free coastal area below Mt. Bird Volcano in Ross-Sea/ McMurdo Sound (Figure 9). Three penguin colonies are situated in the area; we worked with the northernmost and the middle one which were later referred to as Cape Bird N and Cape Bird M, respectively. Cape Bird consists of dark igneous rock (Cole and Ewart 1968; Figure 10). It is continental and is characterised by temperatures below freezing, even in summer.

Data collection in the colonies is carried out indirectly by overflying and the analysis of aerial photographs. Historical count data are available for analysis, although processing of the data from the 2011/2012 season had not been completed during the period of the project (Phillip Lyver, Landcare Research - Manaaki Whenua, New Zealand).

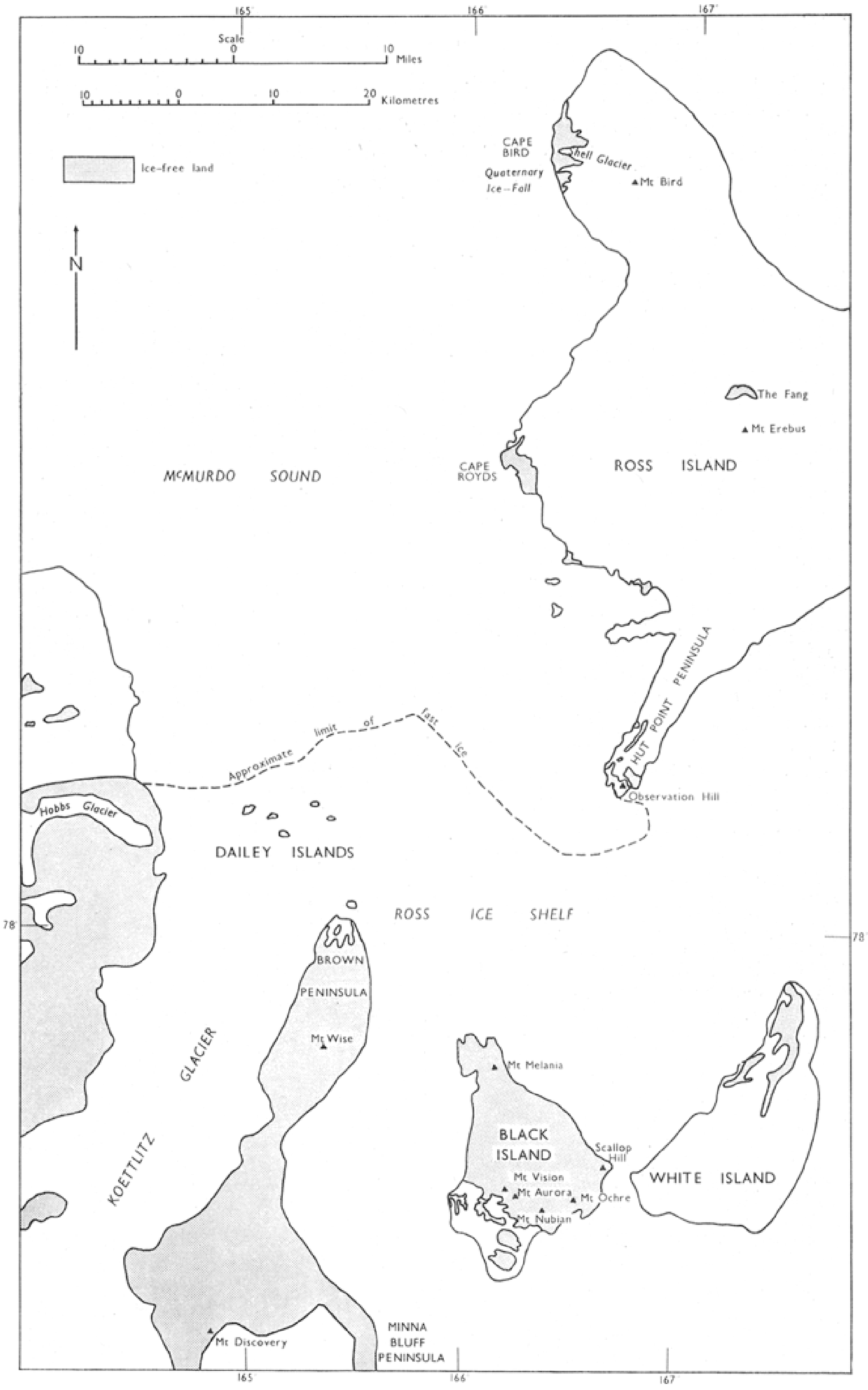

165°
166°
167°
Scale
10
0
10
Miles
10
0
10
20
Kilometres
Ice-free land
N
CAPE BIRD
Shell Glacier
Quaternary Ice-Fall
Mt Bird
The Fang
Mt Erebus
MCMURDO SOUND
CAPE ROYDS
ROSS ISLAND
HUT POINT PENINSULA
Approximate limit of fast ice
Observation Hill
Hobbs Glacier
DAILEY ISLANDS
ROSS ICE SHELF
78°
BROWN PENINSULA
Mt Wise
KOETTLITZ GLACIER
Mt Melania
BLACK ISLAND
Scallop Hill
WHITE ISLAND
Mt Vision
Mt Aurora
Mt Ochre
Mt Nubian
Mt Discovery
MINNA BLUFF PENINSULA

Figure 9: Cape Bird is one of the few ice-free coastal sections of Ross Island, which is connected to the Antarctic continent by the Ross Ice Shelf (Map by Cole and Ewart 1968)

Figure 10: Distribution of penguin nest groups in the northerly Cape Bird colony (Image courtesy of Lyver)

2.3.5 Kopaitic

Position: 63.3°S/ 57.9°W

The test site called Kopaitic in the following includes Kopaitic Island and the Schmidt Peninsula (Figure 11). The andesite and diorite rocks of the site are predominantly greyish-black in colour (Halpern 1965; Figure 12). The penguins brood on ridges standing slightly higher than the surrounding area and also to some extent on craggy rocks further inland.

There are count data from the 2011/2012 season for penguin breeding pairs on the Schmidt Peninsula and for part of the colony on Kopaitic Island (Figure 11, made available by Robert Metzig, German Aerospace Center - DLR, Oberpfaffenhofen, Germany). No historical count data are available. Gentoo, chinstrap and Adélie penguins breed together on Kopaitic Island. Only gentoo penguins breed on the Schmidt Peninsula.

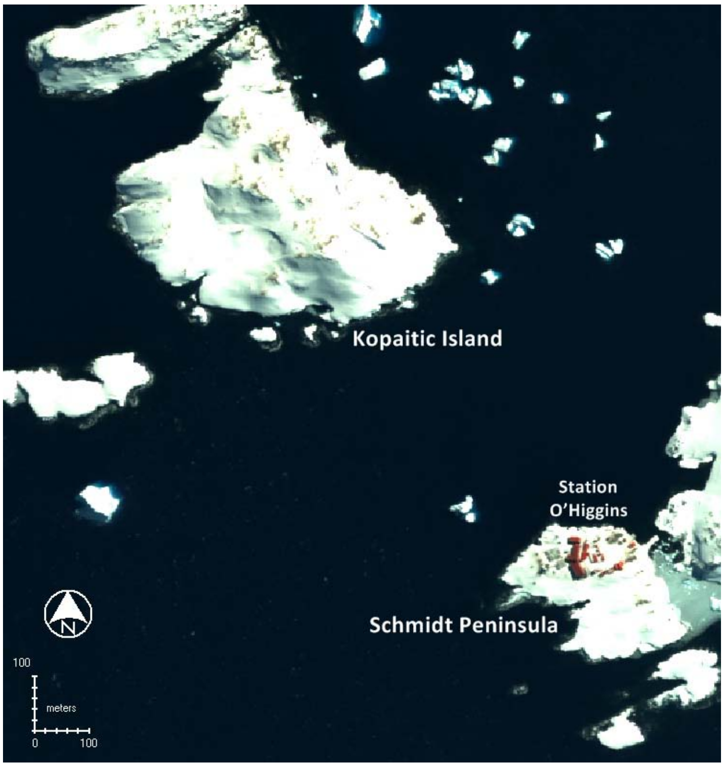


Figure 11: QuickBird2 image of the Kopaitic test site (Image © EUSI/DigitalGlobe 2012); Kopaitic Island and the Schmidt Peninsula are neighbouring breeding areas on Cape Legoupil on the western side of the Antarctic Peninsula

Figure 12: Penguin breeding sites on Kopaitic Island (Image: Metzig)

2.3.6 Adélie-Land

Position: 66.7°S/ 140.0°W

Adélie Land is the name given to a section of coast situated in the eastern Antarctic. The area is characterised by gneiss rock, which is predominantly grey (Figure 14), streaked with coarse pink granite (Peucat et al. 1999).

Penguin nest counts are predominantly carried out indirectly by overflying and analysing aerial photographs (directed by Henri Weimerskirch, Chizé Centre of Biological Studies (CNRS), Villiers en Bois, France). In addition to Adélie penguins, emperor penguins are also present in the area. Emperor penguins are counted during the polar night, (with the sun always below the horizon) around mid-June, when the males stand close together.

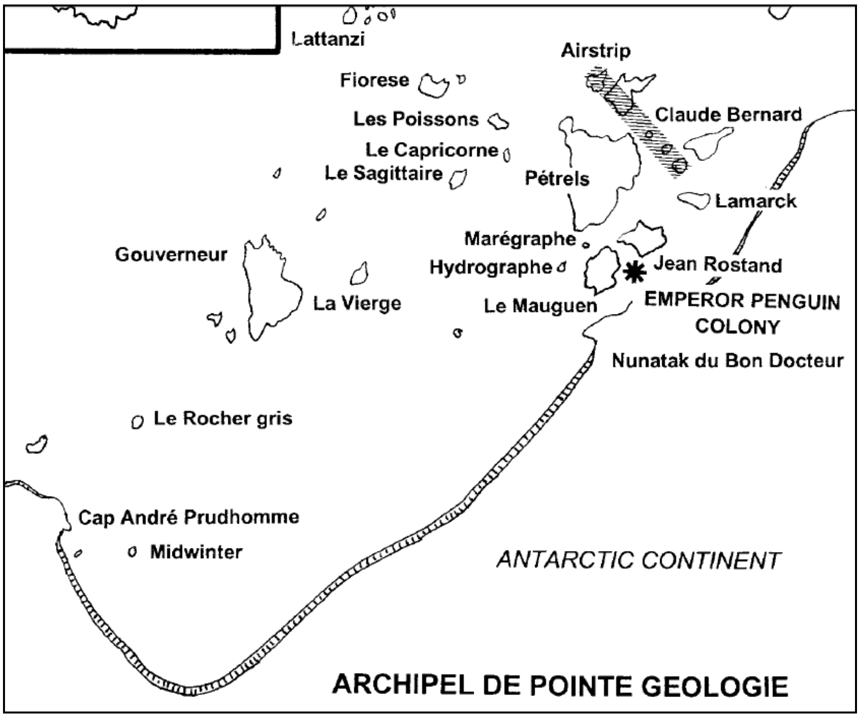


Figure 13: The colonies at the Adélie Land test site (extract from Micol and Jouventin (2001))

The following colonies are included in the analysis for the Adélie Land test site (Figure 13):

- Le Mauguen Island: 66.66238°S, 140.02223°W
- Jean Rostand Island: 66.66859°S, 140.00943°W
- Claude Bernard Island: 66.67037°S, 140.00421°W
- Petrels Island: 66.66481°S, 140.00330°W
- Lamarck Island: 66.66618°S, 140.02005°W

Figure 14: Aerial photograph of the Adélie penguin colony in Adélie Land (Image courtesy of Weimerskirch/Delord).

3 Results

3.1 Remote sensing data and processing data

3.1.1 Optical remote sensing data

Table 5 shows the available optical remote sensing images. Overall seventeen images from QuickBird2, WorldView2 and WorldView1 were purchased from European Space Imaging (EUSI), either as new images or from the archives. Commissioned by EUSI, DigitalGlobe tried a number of times to obtain images of Ardley and Torgersen as well, in the 2011/2012 breeding season, using QuickBird2 and WorldView2. However, this was not possible because of nearly permanent cloud cover. There are, however, suitable historical QuickBird2 or WorldView2 images of these sites. No analysis of RapidEye archive data was possible in this study because they were not available in time.

Table 5: Optical satellite images used

	Ardley	Point Thomas	Kopaitic	Torgersen	Cape Bird	Adélie Land
Landsat7	12.01.2012	12.01.2012	07.01.2007	14.11.2011	03.12.2011	28.11.2011
	09.02.2005	22.11.2010	20.01.2006	12.03.2011	28.01.2011	04.02.2011
	06.12.2001	28.01.2003		15.12.2010	01.01.2011	15.12.2009
		03.01.2003		15.11.2006	09.12.2010	29.01.2009
		31.12.2001		09.02.2003	05.11.2010	28.12.2008
		22.11.2001			08.12.2007	12.12.2008
		21.02.2000			09.12.2001	
QuickBird2	28.11.2009	03.12.2011	21.11.2011	03.12.2007	03.12.2011	07.01.2012
	08.12.2005	16.01.2006		15.12.2004	16.12.2007	03.12.2007
WorldView2	08.01.2010	27.12.2011			18.12.2010	04.12.2011
WorldView1	10.12.2011					04.12.2011

3.1.1.1 Geometric correction

In georeferencing, geographical coordinates are given to each pixel. The images used in this project are products that have already been georeferenced. The Landsat7 images are of product type 'Level 1Gt' with an absolute geodetic precision of at least 250m (NASA 2011). The QuickBird2 and WorldView1 images are of the 'Standard' product type. Here, the level of precision is 23m CE90 for QuickBird2 and 5m CE90 for WorldView1 and WorldView2, with an off-nadir angle (look angle) of less than 30° (DigitalGlobe 2012).

Retrospective georeferencing with Ground Control Points was not carried out as for these areas there are either no Ground Control Points, or too few, or they are too imprecise. Orthorectification (georeferencing with the help of digital terrain models) was not possible, as no digital terrain model of the required resolution was available.

If slight shifts in colony location are to be detected, the satellite images must be georeferenced before any analysis. For this, an already georeferenced image can be used.

3.1.1.2 Radiometric correction

The reflected radiation of the Earth's surface recorded directly by the satellite is subject to diverse atmospheric absorption and scattering effects, which alter the actual reflection from the Earth's surface. These atmospheric effects vary greatly and thus prevent a comparison of satellite images taken at different times (Hadjimitsis and Clayton 2008).

In order to minimise the atmospheric disturbance, the model of Moran et al. (1992), modified and improved by Chavez (1996), was used for atmospheric correction. It was chosen because, in a comparison of different models, it gave the most consistent results for classification (Song et al. 2001). In practice, atmospheric correction was performed with a model created using ERDAS IMAGINE software. This gives atmospherically corrected reflection values for every pixel in the output image. Figure 15 shows a Landsat7 image of Cape Bird, without contrast stretching, before and after atmospheric correction.

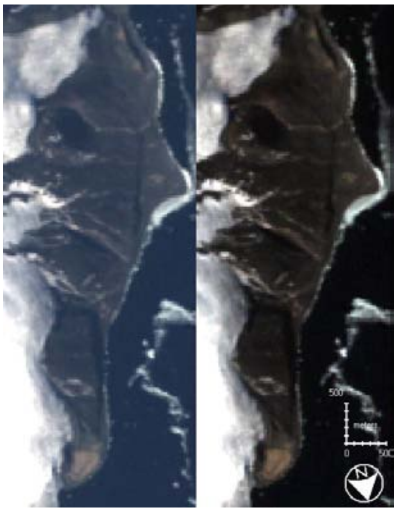


Figure 15: Comparison of original (left) and atmospherically corrected (right) Landsat7 image (bands 321) of Cape Bird (Image courtesy of NASA GSFC & USGS 2012)

3.1.1.3 Pansharpening

In pansharpening, or image fusion, the spectral characteristics of the multispectral bands are fused with the spatial characteristics of the PAN band in a single image. As a result, the fused image shows high spectral and spatial resolution (Vijayaraj et al. 2004).

The HCS process (ERDAS 2010) was used for pansharpening the Landsat7 and WorldView2 images. According to Padwick et al. (2010) this process produces the best overall result in a comparison of various pansharpening methods for WorldView2 images. The result of pansharpening can be seen in a Landsat7 image of Adélie Land (Figure 16). The results for WorldView2 were significantly less sharp than those obtained with the SRM process (ERDAS 2010) for QuickBird2.

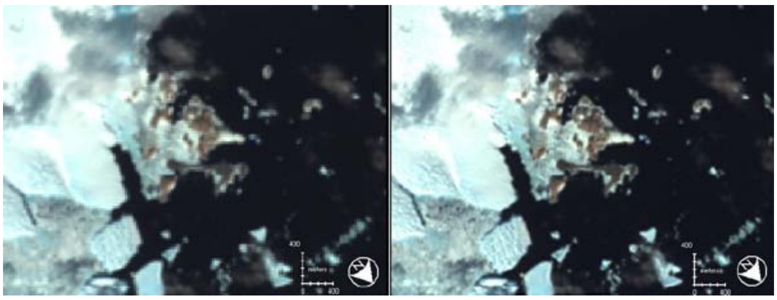


Figure 16: Comparison of an original Landsat7 image (left; band 321) of Adélie Land with a fused image using HCS pansharpening (Image courtesy of NASA GSFC & USGS 2012)

SRM pansharpening (ERDAS 2010) was used for the QuickBird2 images. To use this process, a PAN band is required, as is appropriate for QuickBird2, which covers the multispectral bands that need to be made sharper (Figure 2; ERDAS 2010). Ashraf et al. (2011) demonstrated the efficiency of the process in a comparison of diverse pansharpening methods in which the SRM method gave the best results.

3.1.1.4 Image selection

If clouds are too thick (e.g. in the case of cumulus clouds), it is only possible to pick up their reflected radiation but not that of the Earth's surface below. Where there are cirrus clouds, and also at the edges of cumulus clouds, the cloud layer is thin enough for a sensor to detect reflected radiation from the Earth's surface. However, the spectral signature of the land cover classes is then seriously distorted. In contrast to the atmospheric correction in Section 3.1.1.2, clouds, depending on their thickness, alter spectral signatures only over very small areas. There are methods with which relatively small and thin cloud layers can be computationally removed. However, this alters the spectral signature, which at the very least makes classification more difficult.

For the purpose of detecting penguin colonies, no images were used in which there were clouds in the sky above the colonies.

3.1.2 Radar remote sensing data

As regards radar data, only TerraSAR-X SAR data were used in this study. TerraSAR-X is an X-Band-SAR system with a 3.1cm wavelength. All TerraSAR-X images that were analysed are listed in Table 6. The images were taken in diverse imaging modes, with reference both to resolution (StripMap with 3m and SpotLight with up to 1m) and polarisation (Single-Pol (HH) and Dual-Pol (HH/VV)).

Table 6: TerraSAR-X SAR images used

	Ardley	Point Thomas	Kopaitic	Torgersen	Cape Bird	Adélie Land
TerraSAR-X StripMap Single-Pol (HH)	04.11.2010 (a_011R)	28.12.2011 (d_s004R)	12.01.2012 (a_014R)	07.11.2008 (a_004R)	06.12.2009 (a_004R)	
	15.11.2010 (a_011R)	08.01.2012 (d_s004R)	23.01.2012 (a_014R)	18.11.2008 (a_005R)	23.01.2010 (a_004R)	
	18.12.2010 (a_011R)	19.01.2012 (d_s004R)	03.02.2012 (a_014R)			
	20.01.2011 (a_011R)	30.01.2012 (d_s004R)	14.02.2012 (a_014R)			
		10.02.2012 (d_s004R)				
		21.02.2012 (d_s004R)				
TerraSAR-X StripMap Dual-Pol (HH/VV)		05.11.2010 (d_sn004R)				
		27.11.2010 (d_sn004R)				
		19.12.2010 (d_sn004R)				
		10.01.2011 (d_sn004R)				
		01.02.2011 (d_sn004R)				
TerraSAR-X SpotLight Single-Pol (HH)	22.10.2010		20.11.2007	20.02.2012	19.02.2012	20.02.2012
	19.02.2012		20.11.2007			
			21.11.2007			

3.1.2.1 Geometric and radiometric correction, and geocoding

All TerraSAR-X scenes analysed were processed as EEC products according to Basic Product Specification (TX-GS-DD-3302) and Level 1b Product Format Specification (TX-GS-DD-3307). Geometric and radiometric correction, as well as geocoding, were performed by the TMSP in accordance with these specifications. No georeferencing with Ground Control Points was carried out.

3.1.2.2 Image analysis

The TerraSAR-X SAR data was analysed using NEST-Software, together with various SAR analysis tools of the DLR. The analysis included the variation of the dynamic range, analysis of the image statistics, the combination of polarisation channels (in the case of Dual-Pol), and change detection in the case of multiple images with the same imaging geometry.

3.1.2.3 Image selection

SAR data can be obtained independently of light conditions and cloud cover. In this respect they are not subject to the limitations of optical systems. However, planned acquisitions are sometimes not obtained if in conflict with higher-priority acquisitions. During the study period there were conflicts with the TanDEM-X Mission in particular. Nevertheless, we were able to evaluate more than 33 scenes with regard to their suitability for monitoring penguin colonies. Images from various Antarctic summers since 2007 were selected. TerraSAR-X StripMap and/or SpotLight data were made available for all test sites. For the Point Thomas test site, Dual-Pol images (HH/VV) were included in the analysis in addition to Single-Pol images (HH).

3.2 Possibility of detecting individual penguin colonies using optical remote sensing data

The detectability of individual penguin colonies was tested using four different methods: manual image interpretation, supervised classification, ratio analysis and subpixel analysis. All available images were investigated, in order to be able to form conclusions about the individual sensors.

Figure 17 provides an overview of the individual methods, with a visual comparison of different results by way of example.

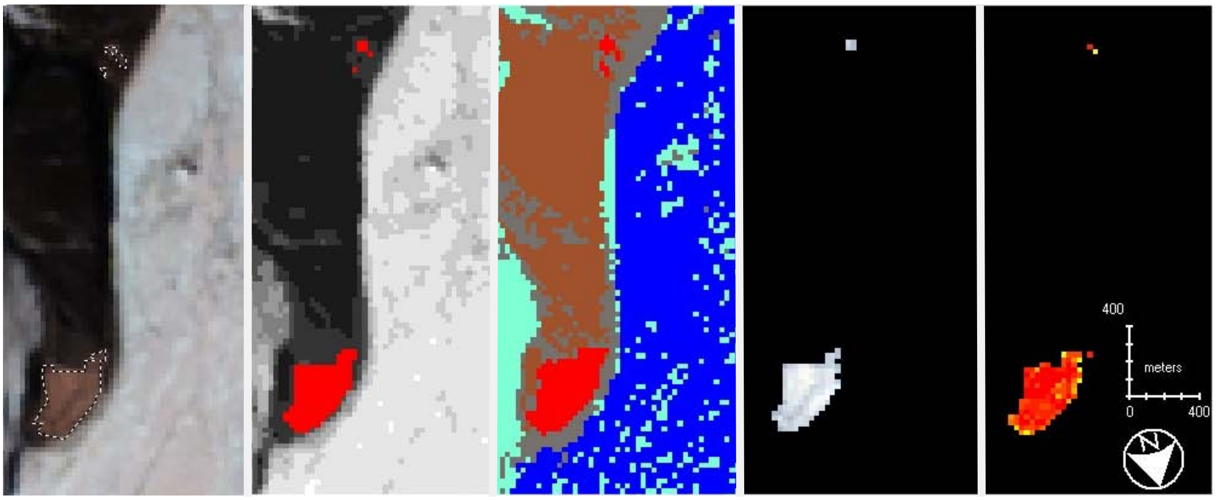


Figure 17: Landsat7 Cape Bird - comparison of different methods; from left to right: manual image interpretation, unsupervised classification, supervised classification, ratio approach, and subpixel analysis

3.2.1 Manual image interpretation

In order for penguin colonies to stand out as well as possible against their surroundings, contrast stretching was carried out and appropriate band combinations selected. With all sensors, the penguin colonies (Point Thomas, Ardley and Torgersen Island), where large parts of the surrounding area are covered with vegetation, are most easily recognised in the true colour representation red-green-blue. In this representation, the penguin colonies are indicated by a slightly reddish colour. In the penguin colonies of Cape Bird, Adélie Land and Kopaitic, guano stood out even more prominently in the Landsat7 images with spectral bands 753. In the false colour composite 432 image, nest groups could be distinguished most easily from their surroundings in the QuickBird2 and WorldView2 images. The last two combinations were more troublesome in the case of penguin colonies with vegetation in the surroundings as they also made the vegetation stand out, thus making it more difficult to distinguish it from guano.

In a subsequent procedure, the penguin colonies were digitised using GIS software and their size calculated. This resulted in the following picture of the individual colonies (overview Table 7):

Table 7: Summary of results of the manual image interpretation of penguin colonies – clearly visible colonies (green), colonies that are difficult to see (orange), colonies that are not visible (red)

	Ardley	Point Thomas	Kopaitic		Torgersen	Cape Bird	Adélie Land
			Kopaitic Island	Schmidt Peninsula			
Landsat7	12.01.2012	12.01.2012	07.01.2007	07.01.2007	14.11.2011	03.12.2011	28.11.2011
	09.02.2005	22.11.2010	20.01.2006	20.01.2006	12.03.2011	28.01.2011	04.02.2011
	06.12.2001	28.01.2003			15.12.2010	01.01.2011	15.12.2009
		03.01.2003			15.11.2006	09.12.2010	29.01.2009
		31.12.2001			09.02.2003	05.11.2010	28.12.2008
		22.11.2001				08.12.2007	12.12.2008
		21.02.2000				09.12.2001	
QuickBird2	28.11.2009	03.12.2011	21.11.2011		03.12.2007	03.12.2011	07.01.2012
	08.12.2005	16.01.2006			15.12.2004	16.12.2007	03.12.2007
WorldView2	08.01.2010	27.12.2011				18.12.2010	04.12.2011
WorldView1	10.12.2011						04.12.2011

Landsat7

Three images were examined for Ardley Island. One was taken during the breeding season, one at the end and one definitely after the breeding season. The colony could not be detected on any of these images, as the nest groups are too small and spread out over too large an area.

It was also impossible to see the Schmidt Peninsula colony on any of the images due to its limited size. This was in contrast to the colony on Kopaitic Island, which we were able to digitise successfully. It was not possible to distinguish between the three penguin species that occur on Kopaitic Island.

The penguin colonies on Point Thomas and Torgersen Island were only visible on a few historical images, taken at a time when there were significantly more occupied nests in the colonies than appear in current images. However, it was too difficult to see the borderline between the colony and the surrounding area to be able to attempt digitalisation with any confidence (Figure 18).

Detection of the colony on Cape Bird was very successful, as the surrounding dark volcanic rock presents a stark contrast to the light-coloured guano and there is no vegetation to cause confusion. The relatively small penguin colony Cape Bird M can therefore be easily distinguished.

The various penguin colonies of Adélie Land were also identifiable, although not as clearly as those of Cape Bird.

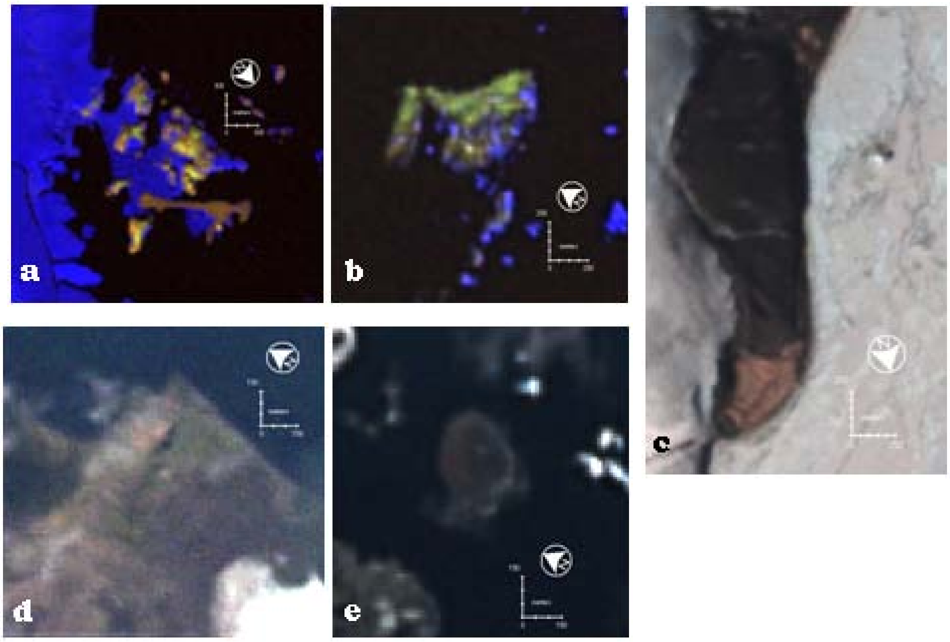


Figure 18: Landsat7 - general views of (a) Adélie Land 04.02.2011 (bands 753), (b) Kopaitic Island 07.01.2007 (bands 753), (c) Cape Bird 09.12.2001 (bands 312), (d) Point Thomas 21.02.2000 (bands 312) and (e) Torgersen 09.02.2003 (bands 312) (Image courtesy of NASA GSFC & USGS 2012)

The colony areas for the individual years, which were manually digitised with the help of Landsat7 images, are shown in Figure 19. It can clearly be seen that Cape Bird N is significantly larger than the other colonies.

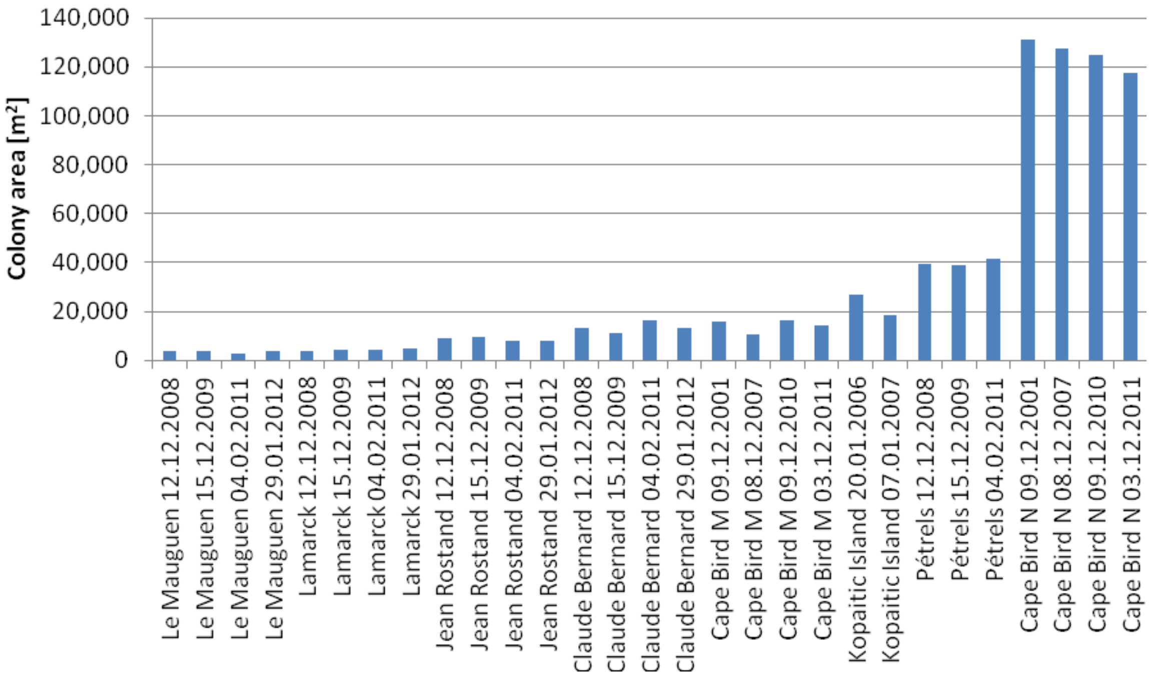


Figure 19: Colony areas manually determined using Landsat7 images – ordered according to average size

WorldView1

Even with the high-resolution panchromatic WorldView1 image of Ardley, it was barely possible to distinguish the nest groups clearly. They are too small and too spread out, and there is too little contrast in the grey-scale image. In Adélie Land, in contrast, the light-coloured guano could be clearly distinguished from the dark rock (Figure 20). In neither of the two images was it possible to recognise individual penguins nesting on rocks. It is theoretically possible to detect the emperor penguin colonies of Adélie Land with high-resolution panchromatic satellite images, if images from the period June to October are available (Barber-Meyer 2007).

Figure 20: WorldView1 image sections (PAN) of Ardley Island (left) and Claude Bernard (right) – on Ardley the nest groups are barely distinguishable from the surroundings (left), whereas they are clearly visible on Claude Bernard (right); see red arrow and dark grey area in front of black area (Image © EUSI/DigitalGlobe 2012)

QuickBird2 & WorldView2

It was perfectly possible to digitise the individual nest groups on Ardley Island with the QuickBird2 and WorldView2 images. Only the groups of nests on rocks directly on the beach did not stand out as clearly as those on the flat beach (Figure 23). On the QuickBird2 image of 28.11.2009 the nest groups were difficult to distinguish from the rock and were thus barely identifiable. One reason could be the early date the image was obtained, at the start of the breeding season. At that time there was unlikely to have been a sufficient accumulation of guano for it to be detected. Furthermore, at such an early date, only the higher, snow-free areas would be occupied. Because of the mapping that had been carried out on the ground, it was also possible to check whether the nest groups of Adélie penguins and gentoo penguins could be distinguished from one another in the images. The result was that neither a visual nor a spectral distinction was possible. The colony areas of the individual years that were digitised with the help of QuickBird2 and WorldView2 images are show in Figure 21 and Figure 22.

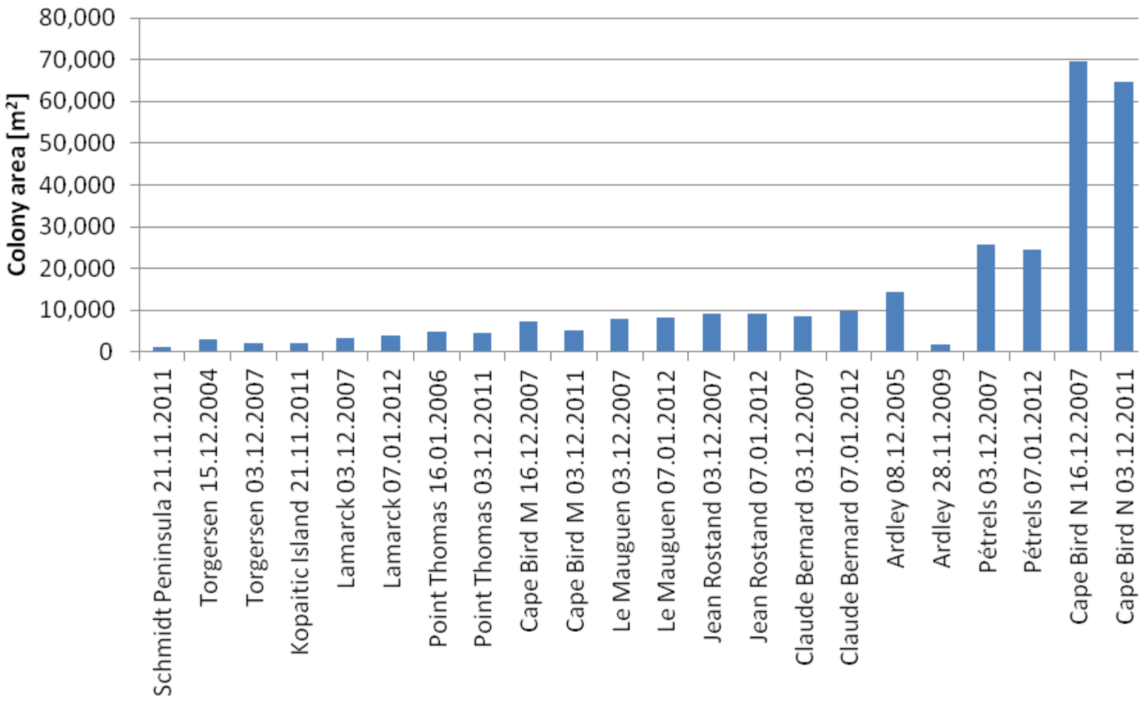


Figure 21: Colony areas manually determined using QuickBird2 images – ordered according to average size

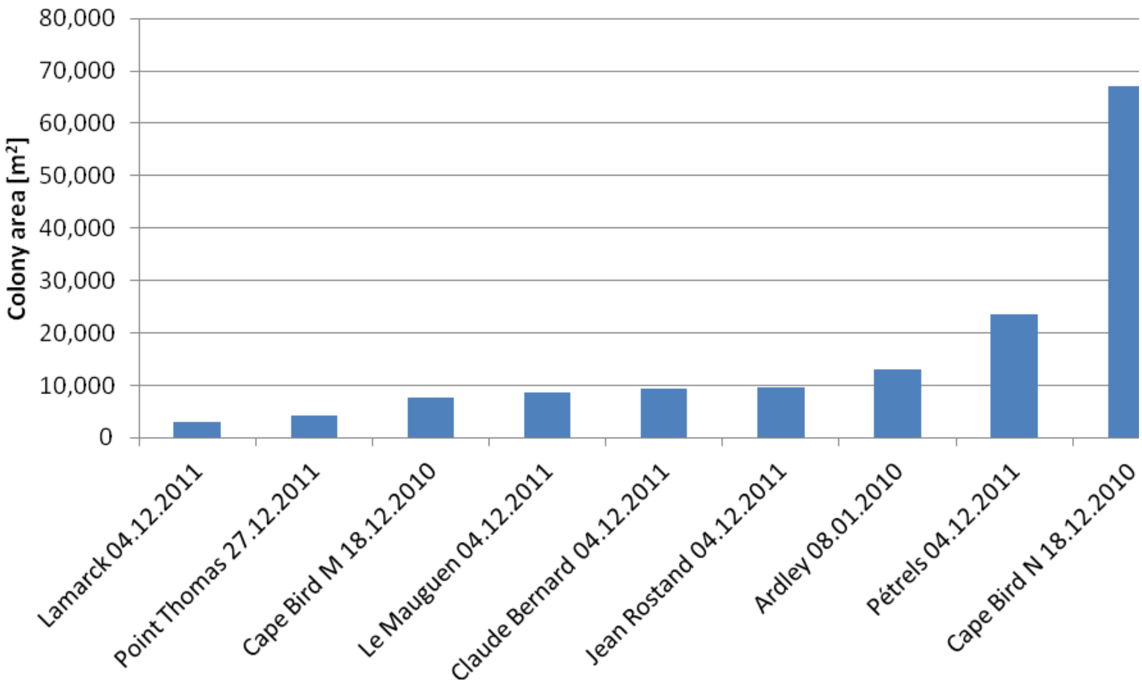


Figure 22: Colony areas manually determined using WorldView2 images – ordered according to average size

Figure 23: QuickBird2 images (bands 432) of Ardley Island on 08.12.2005 (left) and on 28.11.2009 (right) – nest groups can be clearly distinguished on the flat, scree-strewn surface (green arrow) and are hard to distinguish on rocks (red arrow) – yellow arrow marks nest groups covered by snow (Image © EUSI/DigitalGlobe 2012)

For Point Thomas the nest groups could be successfully manually digitised on all the images, although on the image of 03.12.2011 an unbroken layer of mist limited visibility. As the images show not only Point Thomas but also a colony situated around 1.5km further south, by the Pieter J. Lenie Field Station (USA), they were also visually examined. By comparison with a map drawn up by Jablonski (1986) from the year 1978/1979, which shows the distribution of species in the colony, it was possible to surmise that the dark areas in the eastern beach colony were Adélie penguin nests in an area otherwise dominated by gentoo penguins. Another factor to support this is that gentoo penguin nest groups are usually distributed around a wide area and are not as compact as those of Adélie penguins. These distinctions were visible in the images from 2006 and 2011 (Figure 24), which were not affected by mist. This demarcation also matches observations by Lynch et al. (2012), showing that areas with Adélie penguin nests are darker than areas with brooding chinstrap penguins. It was not possible to reach a definitive conclusion as to whether these really were Adélie penguins due to a lack of up-to-date count and mapping data.

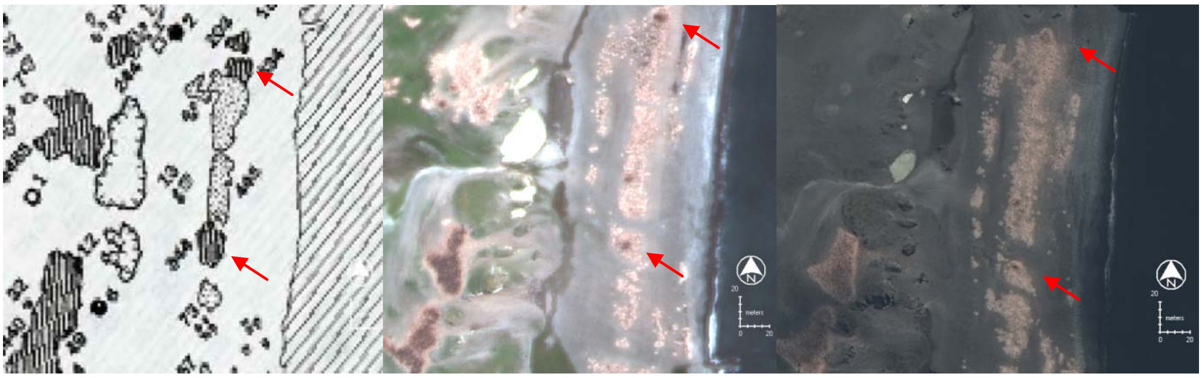


Figure 24: Pieter J. Lenie Field Station; left: georeferenced map according to Jablonski (1986); centre: WorldView2 image of 27.12.2011 (bands 532); right: QuickBird2 image of 16.01.2006 (bands 321) – on map left: horizontal stripes = Adélie penguins, dotted areas = gentoo penguins – red arrows mark the same dark patch in eastern section of colony, which probably denotes Adélie penguins in gentoo penguin colony (Image © EUSI/DigitalGlobe 2012)

Occupied nests on both Kopaitic Island and the Schmidt Peninsula could easily be recognised as reddish areas, as can be clearly seen in Figure 25.

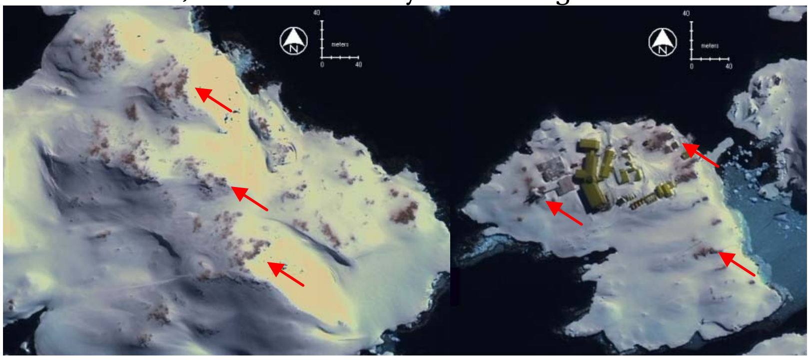


Figure 25: Kopaitic Island (left) and Schmidt Peninsula (right) on a QuickBird2 image of 21.11.2011 (bands 432) – nest groups are marked by a red arrow (Image © EUSI/DigitalGlobe 2012)

In the image from Torgersen Island of 15.12.2004, the nest groups could barely be distinguished from the ground around them, in contrast to the aerial photograph from Figure 26. This is not caused here by the size of the nest groups, as the nests can be seen fairly clearly in the image of 03.12.2007, although the number of occupied nests has declined significantly. In the 2007 image the nest groups are easier to recognise but still much harder to distinguish than in the later images of Ardley Island or Point Thomas. Here too, the reason could be that the images were recorded relatively early in the season, at the beginning of December, so that there was only a limited accumulation of guano.

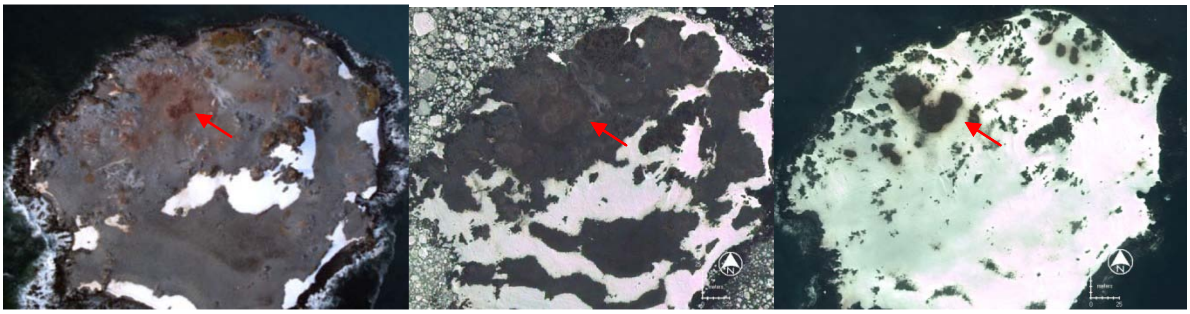


Figure 26: Torgersen Island: comparison between aerial photograph from 1998 (left) (Image courtesy of Fraser, written correspondence); QuickBird2 images from 15.12.2004 (bands 312) (middle) and 03.12.2007 (right) – in the QuickBird2 images the nest groups are difficult to recognise – the red arrow marks the same nest group in each case (Image © EUSI/DigitalGlobe 2012)

On Cape Bird both the large northern colony and the small colony in the centre are very easy to distinguish. As in the Landsat7 images there is a stark contrast between the light-coloured guano and the dark volcanic rock. Particularly clearly visible on Cape Bird is the distinction between colony areas, which are thickly covered with occupied nests, and areas that consist only of guano. The areas with nests are sprinkled with dark spots, while the guano-covered areas appear lighter and more evenly coloured (Figure 27).

Figure 27: Cape Bird N: QuickBird2 image of 18.12.2010 (bands 432; left) (Image © EUSI/DigitalGlobe 2012) and photograph (Image courtesy of Lyver; right) show the same nest groups – areas with dark spots can be recognised, which are thickly covered with occupied nests (broken white lines encircle two examples)

The colonies of Adélie Land were also easy to recognise on all images. The higher-resolution WorldView2 images were not found to offer any advantage for manual image interpretation than any of the images.

3.2.2 Supervised and unsupervised classification

Unsupervised classification is a statistical approach in which pixels are divided into classes with similar spectral characteristics, without the user knowing the contents of these classes. After classification, the user assigns classes to individual objects. This approach represents, among other things, a basis for, or a complement to, supervised classification. It can be used to check whether the data allow a separation of the desired object classes or whether the classes selected consist of several subclasses (Albertz 2007).

Supervised classification is mostly used to extract quantitative information from remote sensing data. This method makes use of what are called training areas. These are reference areas, as it is already known which class of object they belong to. At least one reference area must be determined for each object class (Albertz 2007). Supervised classifications of penguin colonies located on rocks have already been conducted by Schwaller et al. (1989) using Landsat7 images, and by Bhikharidas et al. (1995) with SPOT-HRV images.

First, unsupervised classifications (Convergence Threshold 0.975 ; 60 Iterations) with 10 and 20 classes were used to test whether penguin colonies could easily be distinguished from their surroundings and whether the class ‘penguin colony’ is consistent in itself. An overview of the results for each colony is given (Table 8).

Table 8: Summary of the results of unsupervised classification, showing colonies that are easily classifiable (green), classification results that are still usable (yellow) and colonies that cannot be classified or that are hard to classify (red)

	Ardley	Point Thomas	Kopaitic		Torgersen	Cape Bird	Adélie Land
			Kopaitic Island	Schmidt Peninsula			
Landsat7	unusable	unusable	still usable	unusable	unusable	good	still usable
WorldView1	unusable	-	-	-	-	-	unusable
QuickBird2	bad	bad	bad	bad	bad	good	bad
WorldView2	bad	bad	-	-	-	good	bad

Landsat7

Using the Landsat-7 images, it was determined that only the classifications of the penguin colonies of Cape Bird, Adélie Land and Kopaitic Island provided usable results. On Cape Bird the penguin colonies were very clearly distinguishable and were consistent in themselves. Results from Adélie Land and Kopaitic were suboptimal as there were fairly important false classifications. Even so, it is possible to distinguish between colonies and their surroundings there. For the remaining colonies, unsupervised classification was unable to provide a class for penguin colonies.

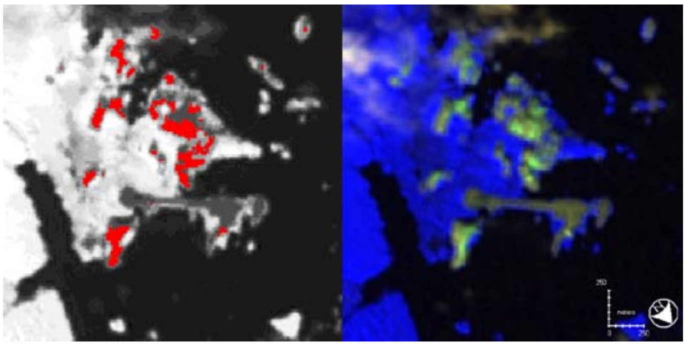


Figure 28: Adélie Land Landsat7 image of 15.12.2009: result of unsupervised classification (left), with colonies coloured in red, and the unaltered image (bands 753; right) (Image courtesy of NASA GSFC & USGS 2012)

WorldView1

With WorldView1 images it was not possible to find one or more classes which only represented penguin colonies, either on Ardley Island or Adélie Land. Particularly in the transition from ice to rock, grey values occur which are similar to those of occupied nests or guano. On Adélie Land there is not enough contrast with the surrounding rocks.

QuickBird2 & WorldView2

Only on Cape Bird was it possible, using the QuickBird2 and WorldView2 images, to define three classes, which correspond to the section of the penguin colony that was most thoroughly covered in guano. With all the other images, the guano classes were always assigned to other surface classes. The reason for this is the extreme variability of the land cover classes, which is a result of the high resolution of the images. This suggests that for a successful supervised classification, it is necessary to define a relatively large number of classes, in order to deal with the great variability in land cover classes.

Subsequently, we compared three types of supervised classification, the Maximum Likelihood, Minimum Distance and Mahalanobis Distance classifications (*cf* Albertz 2007, ERDAS Field Guide 2010). The outcome of this comparison was that the Maximum Likelihood Classification provided the best results.

In order to apply supervised classification to individual images, training areas were first determined for all the types of surface. Depending on the location of the image, these classes were penguin guano, rock, ice/snow, ocean, and vegetation. In addition, for each class it was determined whether a normal distribution predominated and a separability test (Jeffries-Matusita Distance) was done (see ERDAS Field Guide 2010). The training areas were not included in the analysis so that they did not distort the results. For this reason Jean Rostand, for example, was not analysed as this colony served as a training area for the other Adélie Land colonies. A summary of the results of the supervised classification is given in Table 9.

Table 9: Summary of the results of supervised classification, showing easily classifiable colonies (green), colonies that are difficult to classify (orange) and non-classifiable colonies (red)

	Ardley	Point Thomas	Kopaitic		Torgersen	Cape Bird	Adélie Land
			Kopaitic Island	Schmidt Peninsula			
Landsat 7	12.01.2012	12.01.2012	07.01.2007	07.01.2007	14.11.2011	03.12.2011	28.11.2011
	09.02.2005	22.11.2010	20.01.2006	20.01.2006	12.03.2011	28.01.2011	04.02.2011
	06.12.2001	28.01.2003			15.12.2010	01.01.2011	15.12.2009
		03.01.2003			15.11.2006	09.12.2010	29.01.2009
		31.12.2001			09.02.2003	05.11.2010	28.12.2008
		22.11.2001				08.12.2007	12.12.2008
		21.02.2000				09.12.2001	
QuickBird2	28.11.2009	03.12.2011	21.11.2011		03.12.2007	03.12.2011	07.01.2012
	08.12.2005	16.01.2006			15.12.2004	16.12.2007	03.12.2007
WorldView2	08.01.2010	27.12.2011				18.12.2010	04.12.2011
WorldView1	10.12.2011						04.12.2011

Landsat7

With supervised classification it was also not possible to classify the penguin colonies of Ardley, Point Thomas, Torgersen and the Schmidt Peninsula, as there were no training areas for guano that were large enough.

The classification of Cape Bird provided very good results. In particular, because of the presence of the large penguin colony in the north, it was possible to select a good training area. Using this training area, it was also possible to classify the much smaller Cape Bird M penguin colony.

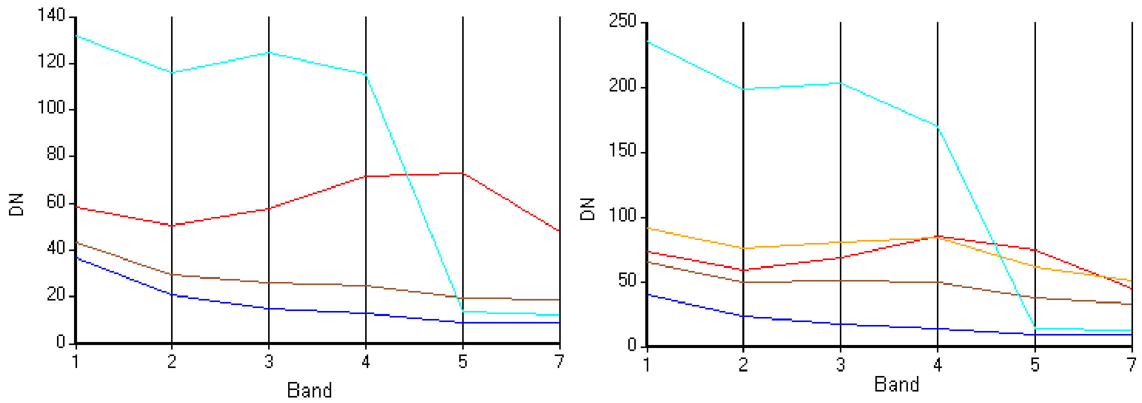


Figure 29: Averaged spectral signatures of the training areas of Cape Bird (left) and Adélie Land (right) for Landsat7 - Red = Guano; Brown = Rock; Turquoise = Ice; Blue = Ocean; Orange = Rock old

The results for Adélie Land and Kopaitic Island were of similar quality but they contained more false classifications than the Cape Bird classification. This was mainly because the spectral signature of the rock (class 'Rock old', Figure 29) on which the colonies were living, very strongly resembled that of guano, which led to more frequent false classifications. The higher the values in Figure 29, the greater the reflection in each individual spectral band. Classes that can easily be distinguished from one another show clear spectral differences.

Figure 30 gives the quantitative results of supervised classification for all colonies analysed in direct comparison to manual separation. It shows the great variability in the deviation of results of supervised classification from those of manual classification, except in the case of Cape Bird N. The cause lies partly in the spectral similarity of the rock on Adélie Land and Kopaitic Island and partly in the fact that false classifications of a few pixels weigh much more heavily in the case of small colonies than with large colonies. Figure 31 shows clearly that these deviations become smaller as the area size of colonies increases.

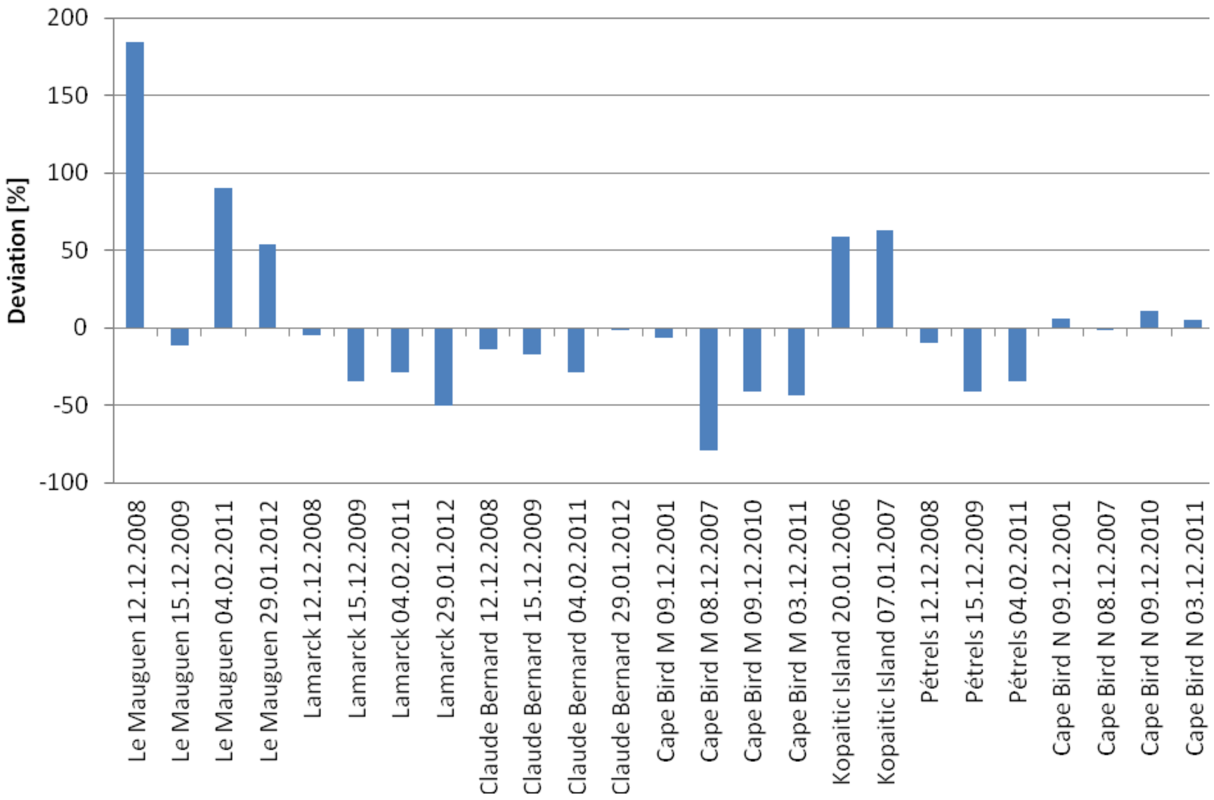


Figure 30: Deviation between colony area classified by supervised classification and manually determined area for individual Landsat7 images

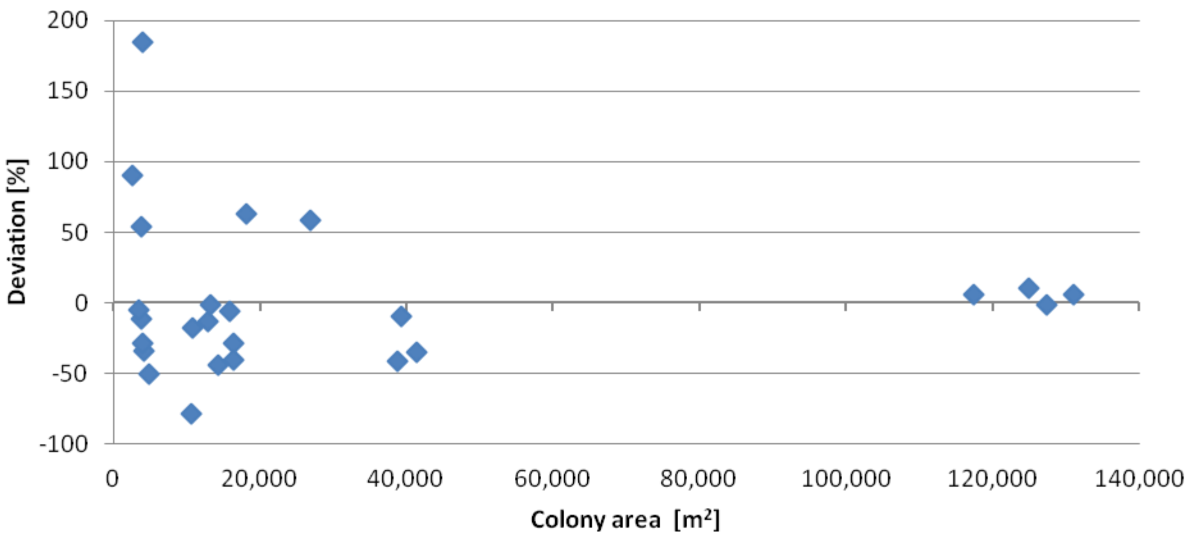


Figure 31: Deviation between colony area classified by supervised classification and manually determined area, sorted according to colony area for Landsat7 images

WorldView1

In the image of Ardley Island, individual nest groups could not be classified, as could already be presumed from the unsupervised classification. The grey values of the PAN band did not allow us to make an unequivocal distinction between nest groups and the similarly light-coloured rock. Results in Adélie Land were substantially better, even though there were frequent false classifications here too. For the most part, the guano-covered rock was detected, but also similarly light-coloured surfaces in the transition area where rock gave way to ice.

QuickBird2 & WorldView2

There was no problem in classifying colonies in the images of Cape Bird and Adélie Land and in the images without mist from Point Thomas. The classification was made significantly worse by the mist in the Point Thomas image of 03.12.2011 and as a result some nest groups could not be completely classified.

Areas with guano were also easily classified in the Ardley images of 08.12.2005 and 08.01.2010. However, it was not possible to achieve an absolutely clear distinction between these areas and the surrounding land cover classes. In particular, the mixed pixel areas of ice, vegetation and certain types of soil could not be separated unequivocally from guano and these were falsely classified. Even the additional spectral bands of the WorldView2 images were unable to improve the result.

Especially hard to classify were the snow-covered early images of Ardley (28.11.2009) and Kopaitic (21.11.2011), together with both images of Torgersen (03.12.2007 and 15.12.2004). For Ardley and Torgersen it was mainly the difficulty of distinguishing between guano and rock that caused problems and at Kopaitic it was the borderline with the areas of snow with their varying degrees of shadow. Figure 32 makes it clear that the spectral distinction between guano and the surrounding land cover classes is very limited on Ardley and Torgersen, in contrast to Cape Bird.

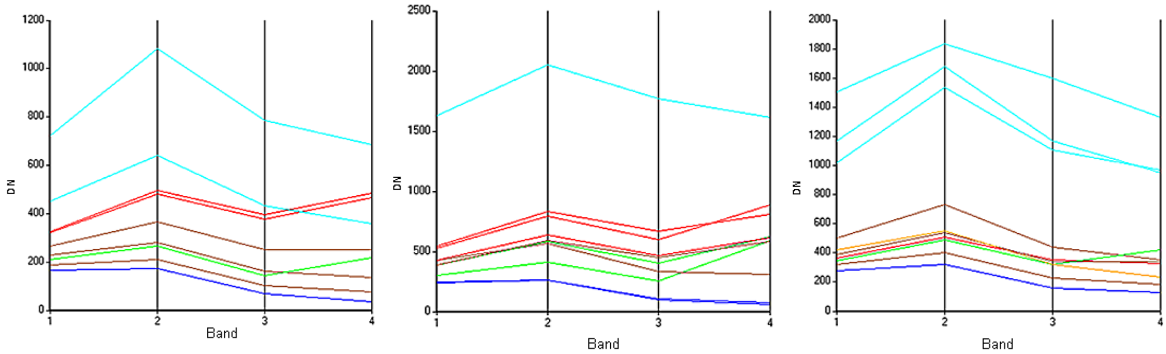


Figure 32: Averaged spectral signature of QuickBird2 training areas for Cape Bird (left), Ardley (centre) and Torgersen 2007 (right) – Red = Guano; Brown = Rock; Turquoise = Ice; Blue = Ocean; Green = Vegetation; Orange = Surf

With Cape Bird in particular it became clear that recognising the boundaries of the penguin colonies depended greatly on the choice of training areas. However, areas with high concentrations of occupied nests could not be distinguished from areas covered only in guano. The colony areas classified using supervised classification, for QuickBird2 and WorldView2, are shown in Figures 33 to 36. In contrast to the Landsat7 images, there is no connection between colony area and the deviation from the manually determined colony areas, which can be put down to the higher spatial resolution of the images.

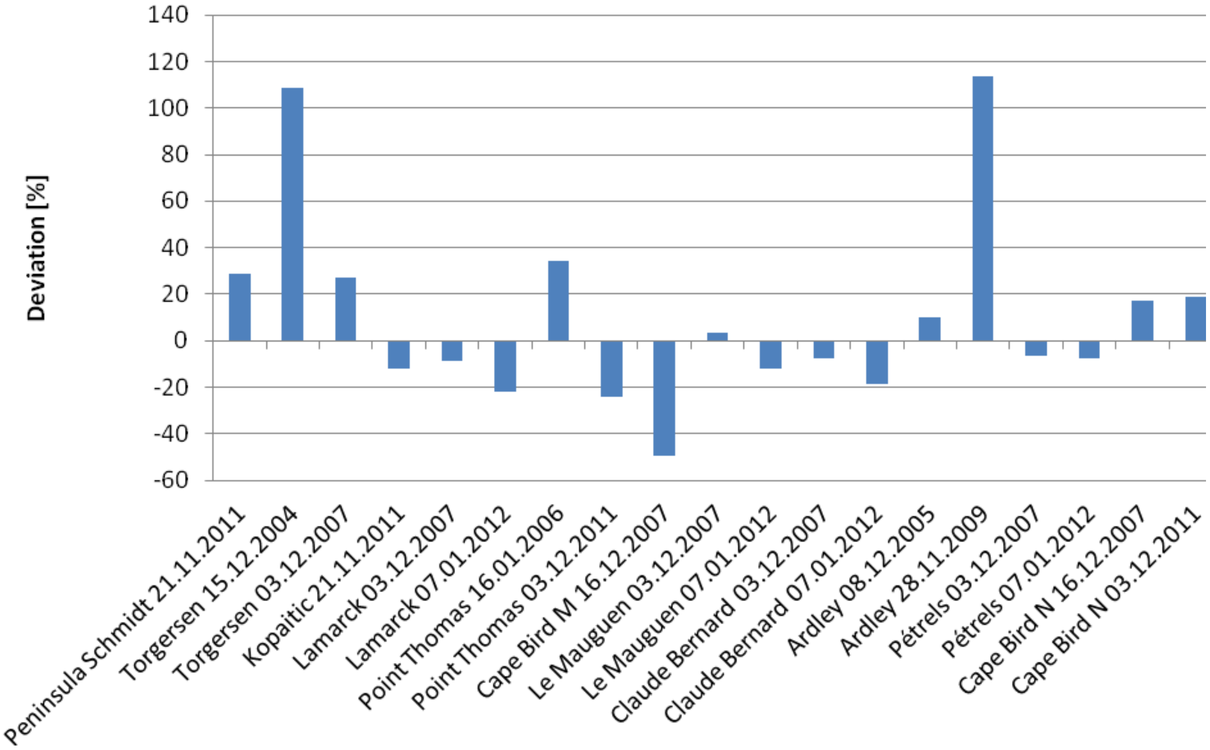


Figure 33: Deviation of colony area determined by supervised classification from the manually determined area for individual QuickBird2 images

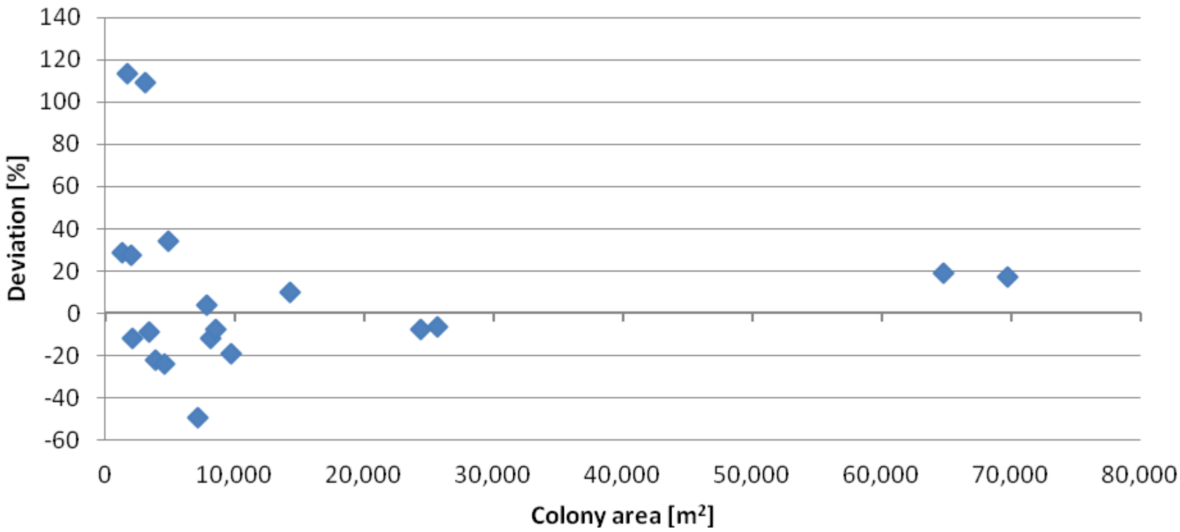


Figure 34: Deviation of colony area determined by supervised classification from the manually determined area, sorted by colony area for QuickBird2 images

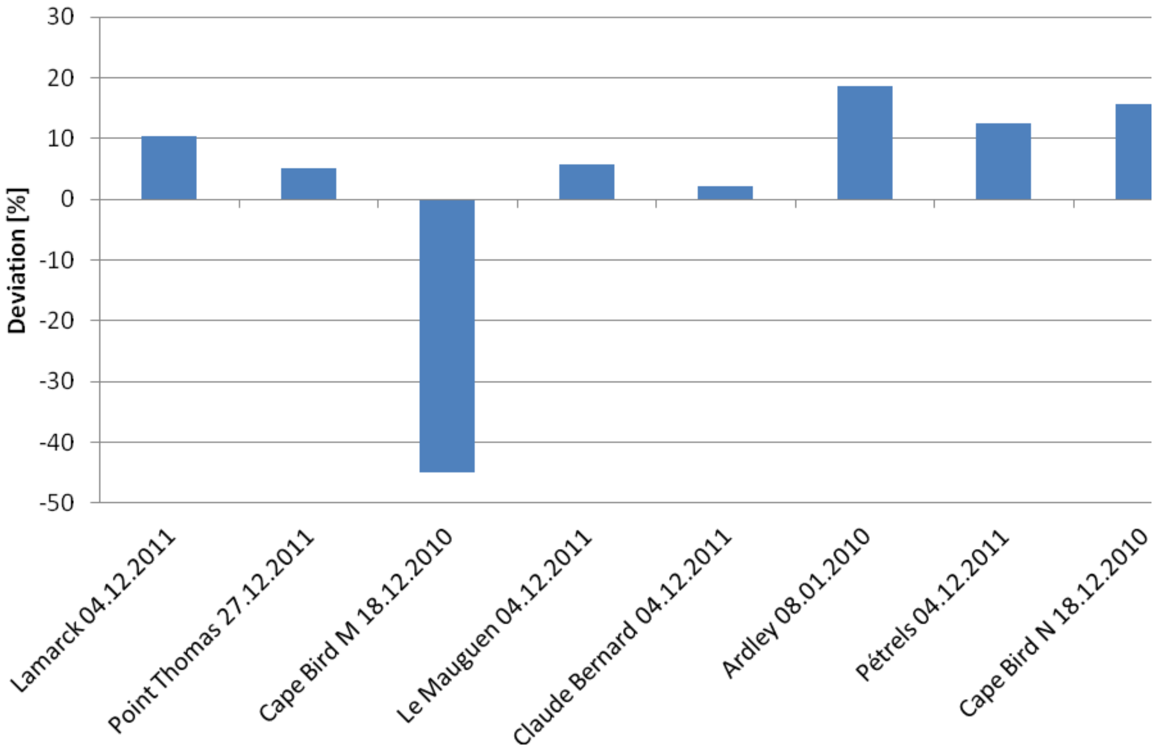


Figure 35: Deviation of colony area determined by supervised classification from the manually determined area for individual WorldView2 images

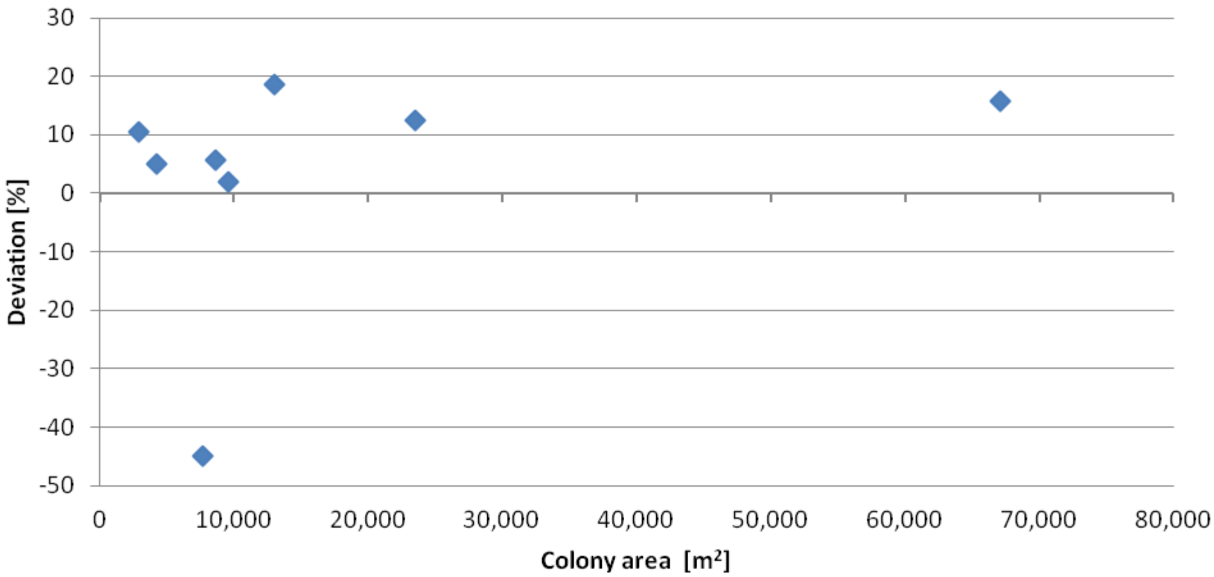


Figure 36: Deviation of colony area determined by supervised classification from the manually determined area, sorted by colony area for WorldView2 images

3.2.3 Ratio approach

Data from several spectral bands can be arithmetically combined to create new image data sets in order to obtain optimal information about a specific object. Ratios are calculated by dividing the grey values of one spectral band by those of another. Ratios can be used to highlight the distribution of a specific substance such as guano, while suppressing other signals from other substances (Albertz 2007). By setting a threshold value for the ratio image, desired and undesired classes are separated. This step is repeated with different ratio combinations and different threshold values until only the desired class remains (Lillesand et al. 2004).

Schwaller (1984) has already demonstrated that penguin colonies can theoretically be separated from surrounding material by using ratios. In order to test this in practice, an ERDAS-Imagine-Modell was used to work out all possible ratios (15 for Landsat7, 6 for QuickBird2 and 28 for WorldView2) of the input images. In these, training areas were determined for all the land cover classes that needed to be distinguished and the grey value distribution of each ratio calculated for each land cover class. Using the minimum and maximum values of the land cover classes, we were able to select the ratios that enabled a separation between classes. The result is a mask which, in an ideal situation, corresponds to the dimensions of the penguin colony. The training areas were excluded from the analysis so that they did not distort the results. Table 10 gives an overview of the quality of the results for each image.

Table 10: Summary of results for the ratio approach – with easily-classified colonies (green), colonies that are hard to classify (orange) and non-classifiable colonies (red)

	Ardley	Point Thomas	Kopaitic		Torgersen	Cape Bird	Adélie Land
			Kopaitic Island	Schmidt Peninsula			
Landsat7	12.01.2012	12.01.2012	07.01.2007	07.01.2007	14.11.2011	03.12.2011	28.11.2011
	09.02.2005	22.11.2010	20.01.2006	20.01.2006	12.03.2011	28.01.2011	04.02.2011
	06.12.2001	28.01.2003			15.12.2010	01.01.2011	15.12.2009
		03.01.2003			15.11.2006	09.12.2010	29.01.2009
		31.12.2001			09.02.2003	05.11.2010	28.12.2008
		22.11.2001				08.12.2007	12.12.2008
		21.02.2000				09.12.2001	
QuickBird2	28.11.2009	03.12.2011	21.11.2011		03.12.2007	03.12.2011	07.01.2012
	08.12.2005	16.01.2006			15.12.2004	16.12.2007	03.12.2007
WorldView2	08.01.2010	27.12.2011				18.12.2010	04.12.2011
WorldView1	10.12.2011						04.12.2011

Landsat7

The penguin colonies in the Antarctic Peninsula area could also not be masked using the ratio approach, for the reasons given above (see Section 3.2.1).

It was possible to distinguish the penguin colonies on Cape Bird, Adélie Land and Kopaitic Island. Figure 37 gives an overview of the ratios of the individual land cover classes of Cape Bird and Adélie Land. Land cover classes can be differentiated in those ratios in which they have the greatest possible variation in quotient size. For example, in all ratios with the multispectral bands five and seven, it is possible to distinguish ice from the other land cover classes. As neither location has vegetation that is measurable in the images, the ratios for vegetation were worked out using the Point Thomas images. It can be seen that the average ratios for ice and ocean differ considerably from guano, whereas guano and vegetation show a very similar distribution with the result that it is not possible to distinguish between them. In contrast to Cape Bird, it is difficult to separate guano and rock in Adélie Land and Kopaitic Island.

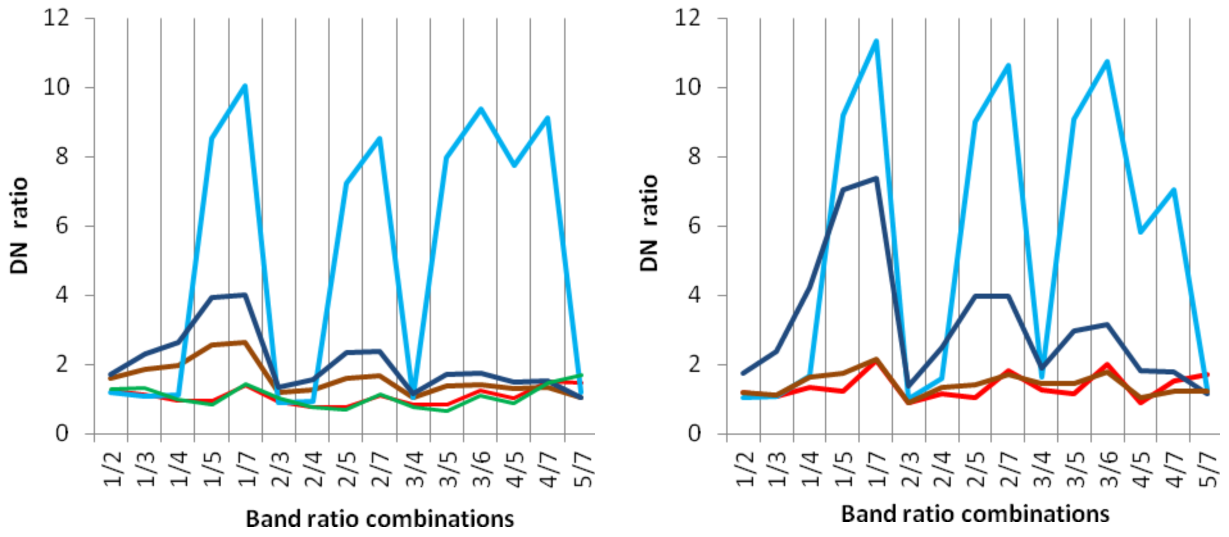


Figure 37: Averaged Landsat7 ratios of the land cover classes of Cape Bird (left) and Adélie Land (right) – Red = Guano; Brown = Rock; Turquoise = Ice; Blue = Ocean; Green = Vegetation

The results of the ratio approach generally show a strong deviation from manual determination (Figure 38). The tendency is for the size of the colony area to be underestimated in comparison with manual determination. The largest deviations occur with small colonies (Figure 39).

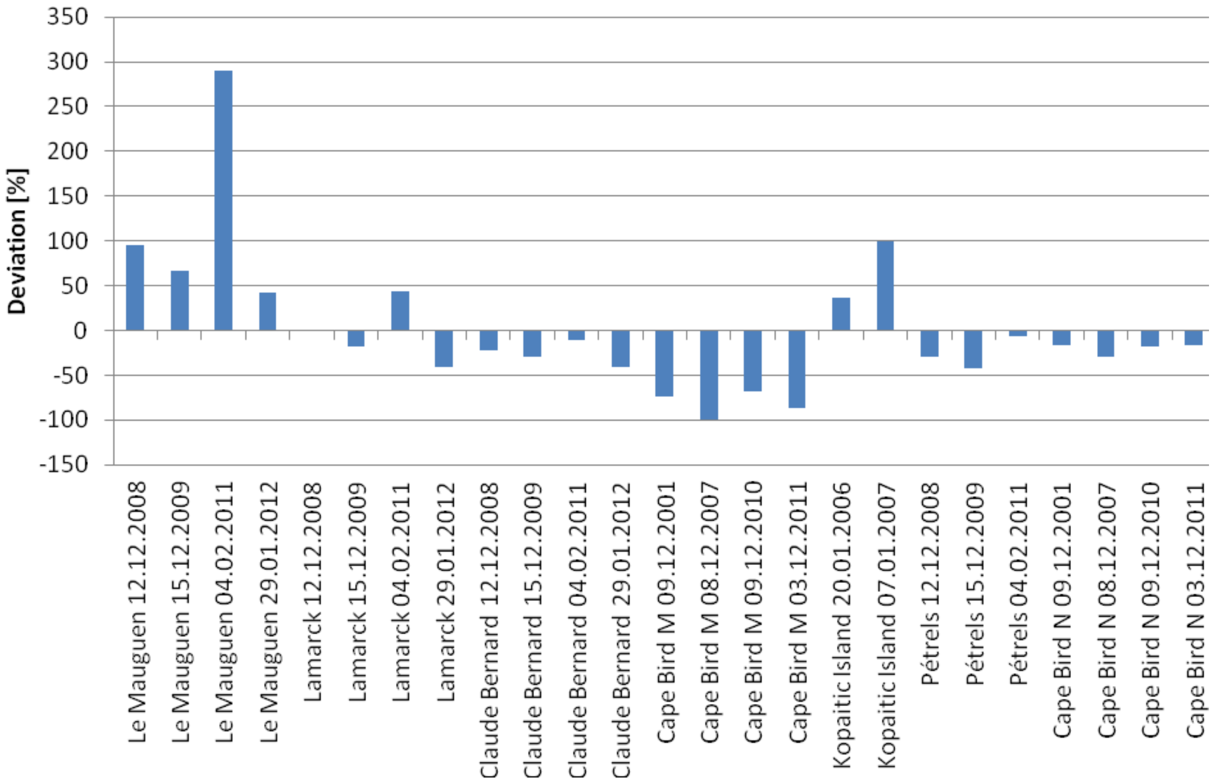


Figure 38: Deviation of colony area determined using ratios from the manually determined area for individual Landsat7 images

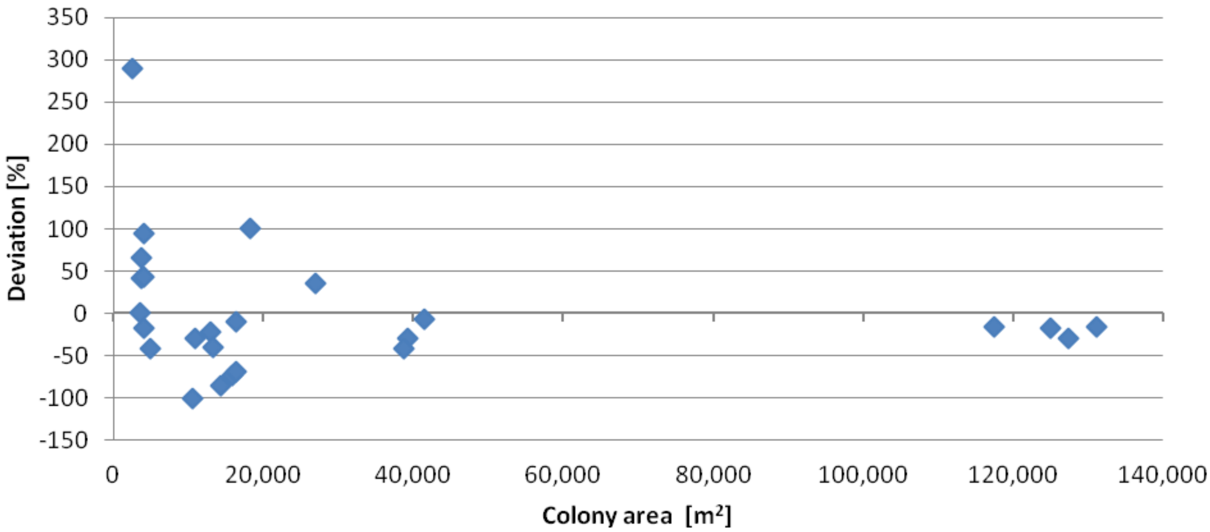


Figure 39: Deviation of colony area determined using ratios from the manually determined area, sorted by colony area for Landsat7 images

WorldView1

Multispectral data are a prerequisite for the ratio method. For this reason it cannot be applied to the panchromatic WorldView1 images.

QuickBird2 & WorldView2

In contrast to the Landsat7 images, it is possible to achieve rough masking of the penguin colonies on Ardley, Point Thomas and Torgersen, due to their better resolution. Nevertheless, a complete separation of guano from the surrounding materials is not possible. As with the supervised classifications (see Section 3.2.2), problems occur at the edges of areas of ice and with particular types of soil, as well as with images where there is only a limited accumulation of guano. As an example, Figure 40 contrasts the averaged ratios of Adélie Land, with good results, and those of Ardley, where it was not possible to make an analysis without major errors in classification. The diagram shows the overlapping of ratios and the limited differences between them in the case of Ardley. Table 10 shows with which images it was possible to obtain a classification using the ratio approach. Figures 41 to 44 show the results of the classified areas. No correlation can be recognised between the size of the colony area and the deviation from the manually determined colony areas.

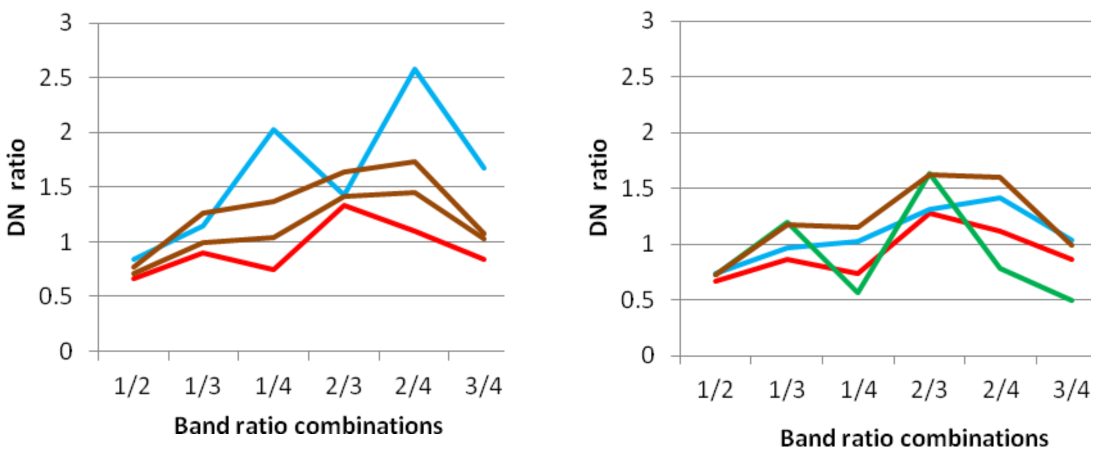


Figure 40: Averaged QuickBird2 ratios for Adélie Land (left) and Ardley (right) - Red = Guano; Brown = Rock; Turquoise = Ice; Blue = Ocean; Green = Vegetation

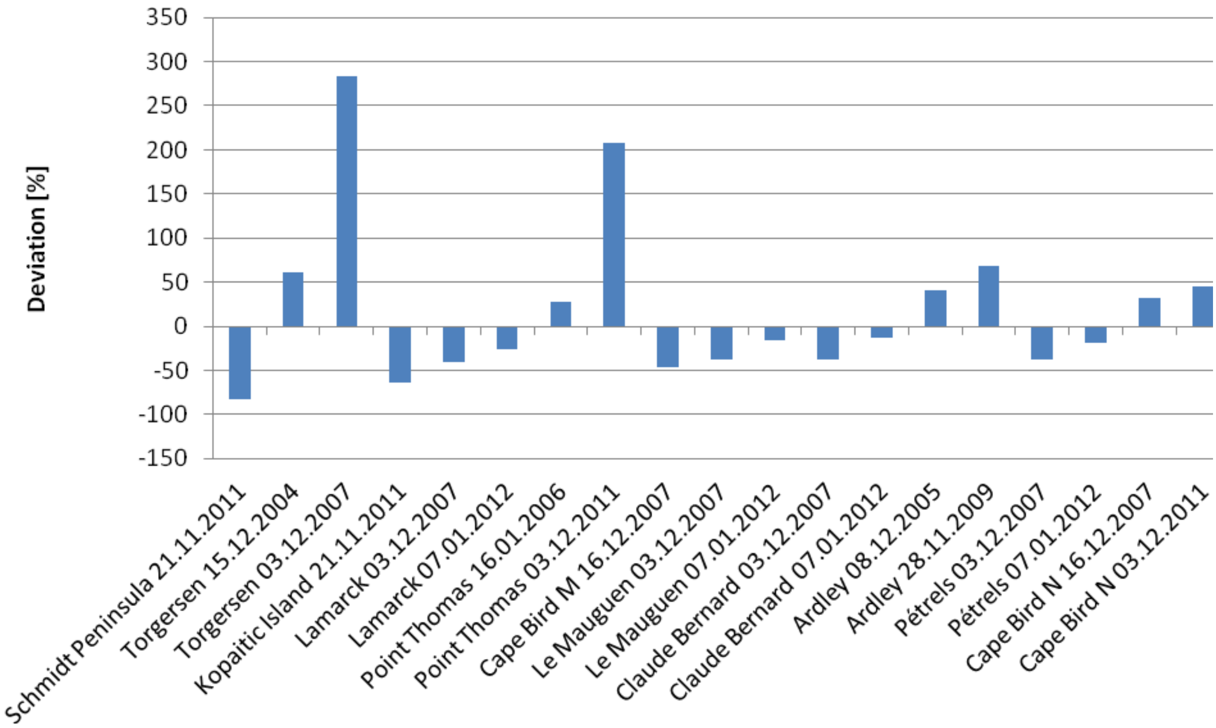


Figure 41: Deviation of the colony areas classified with ratios from the manually determined areas for individual QuickBird2 images

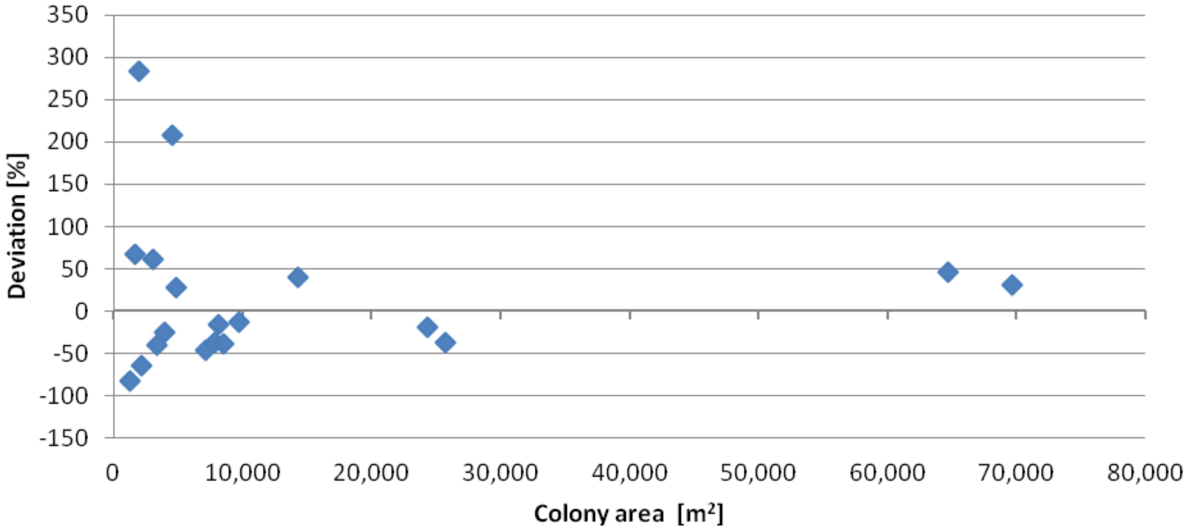


Figure 42: Deviation of the colony areas classified with ratios from the manually determined areas, sorted according to colony area for QuickBird2 images

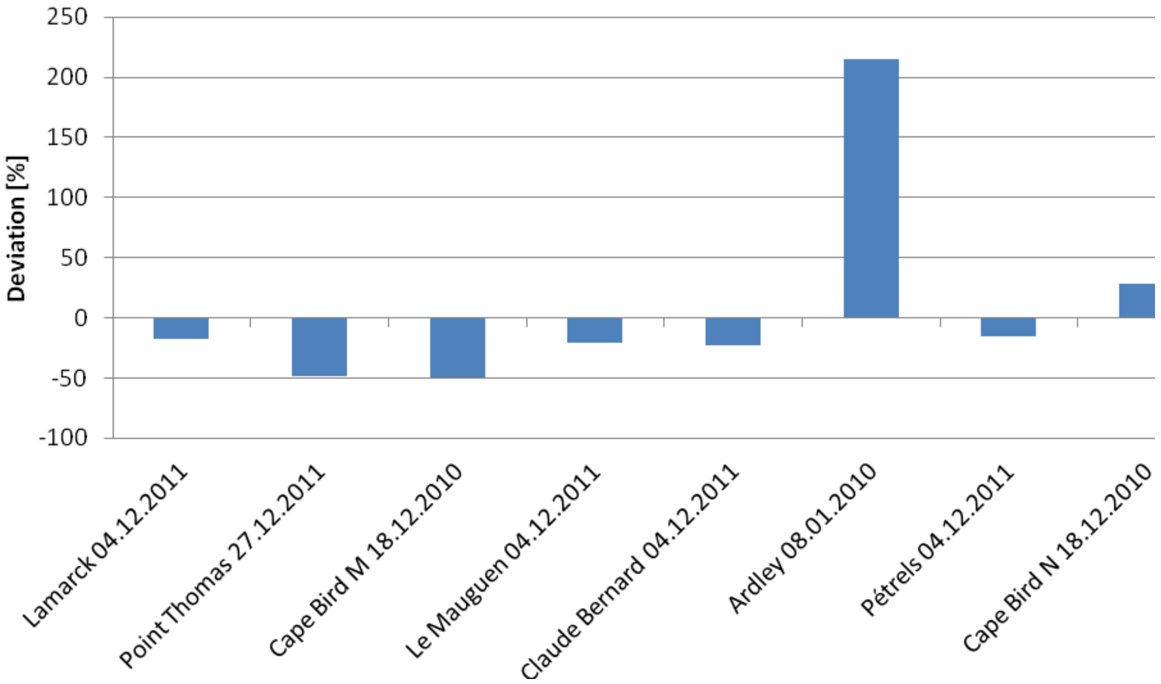


Figure 43: Deviation of the colony areas classified with ratios from the manually determined areas for individual WorldView2 images

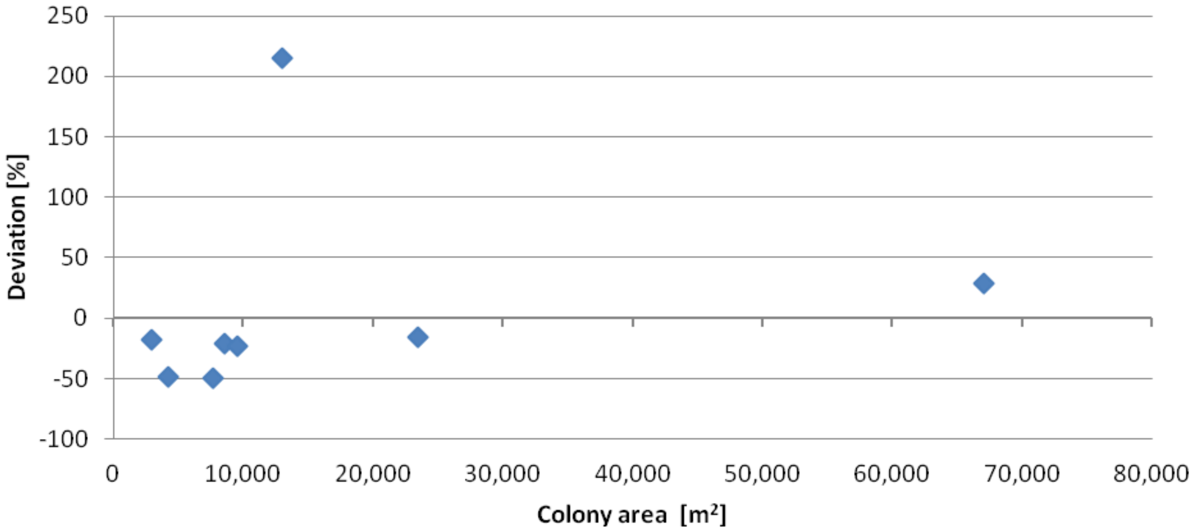


Figure 44: Deviation of the colony areas classified with ratios from the manually determined areas, sorted according to colony area for WorldView2 images

3.2.4 Subpixel analysis

The subpixel analysis is used to filter out a known spectral signature in pixels that are made up of more than one land cover class (mixed pixels) (ERDAS Field Guide 2010). If a pixel contains the spectral signature of guano and rock, for example, the subpixel analysis determines how large a proportion of the total signature consists of guano. To this end a training area was first determined, in which the proportion of guano was very high. Next, a training area was determined, which was spectrally similar to guano and which was mixed with it. This is usually the rocky surface on which penguins brood. As a result, an image was created which indicated, for every pixel of the input image, how high the percentage share of the guano signature was as a proportion of the total signature. Table 11 gives an overview of the results.

Table 11: Summary of the results of the subpixel analysis of penguin colonies, with colonies that were easily classifiable (green) and colonies that were either difficult or impossible to classify (red)

	Ardley	Point Thomas	Kopaitic	Torgersen	Cape Bird	Adélie Land
Landsat7	not possible	not possible	unusable	not possible	good	unusable
QuickBird2	unusable	unusable	unusable	unusable	unusable	unusable
WorldView2	unusable	unusable	-	-	unusable	unusable

Landsat7

Once again, due to a lack of training areas for guano, no analysis could be undertaken of the Ardley, Point Thomas, Torgersen and Schmidt Peninsula colonies. The analysis of Cape Bird gave good results as both the northern and central penguin colonies could be classified. In contrast, the results for Adélie Land and Kopaitic could not be used as we did not succeed in finding a signature that enabled us to classify the penguin colonies in their entirety.

WorldView1

Multispectral data are a prerequisite for subpixel analysis. For this reason, this type of analysis cannot be performed on panchromatic WorldView1 images.

QuickBird2 & WorldView2

The results for all colonies show that the guano-covered areas are only detected very patchily and there are frequent false classifications. The high-resolution images are too rich in detail for this classification method. Figure 45 gives an extract of the subpixel analysis as an example.

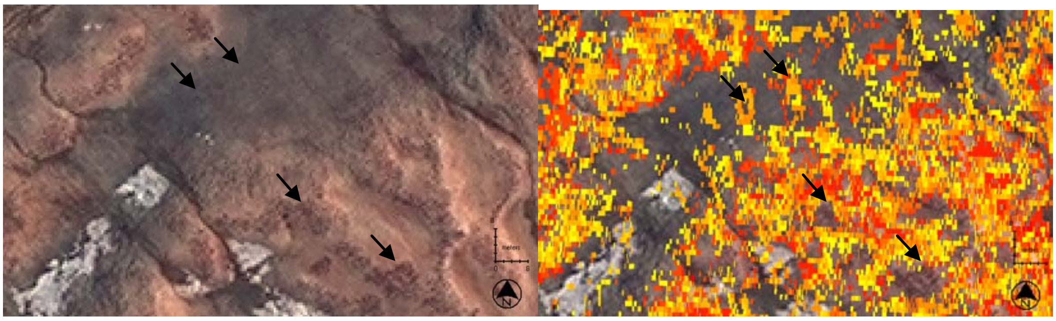


Figure 45: Cape Bird N: QuickBird2 image of 18.12.2010 (bands 432): original image (left) with guano in shades of light brown and result of the subpixel analysis (right); yellow and red = classified guano areas – large falsely classified areas were marked with arrows as examples (Image © EUSI/DigitalGlobe 2012)

3.3 Detectability of individual penguin colonies using radar data

While the DLR can provide positive examples for the detectability of colonies of the species *A. forsteri* (emperor penguin) using TerraSAR-X, penguin colonies of *P. papua*, *P. antarctica* and *P. adliae* (gentoo, chinstrap and Adélie penguins) could not be detected by means of TerraSAR-X SAR data. Even with the inclusion of the shape files of the colonies derived from the optical satellite data, no correlation could be identified with radar backscattering properties. This is true of both Single-Pol and Dual-Pol-SAR images. This can very probably be attributed to the fact that, with a 3.1 cm wavelength for TerraSAR-X, the radar backscattering properties are not – or not significantly – altered by a thin layer of guano on scree or rock. The composition of the ground in the breeding areas of these species is what makes them significantly different from the areas where emperor penguin colonies breed. Emperor penguins breed on sea ice, and guano deposits significantly alter the radar reflectivity of sea ice.

Below are examples of SAR images of the various test sites where gentoo, chinstrap and Adélie penguins occur (Figures 46 to 52). No colonies could be identified on any of these images. Figure 47 and Figure 48 illustrate that there are no significant differences in the radar reflectivity among the polarisation combinations HH and VV for the Point Thomas colony area.

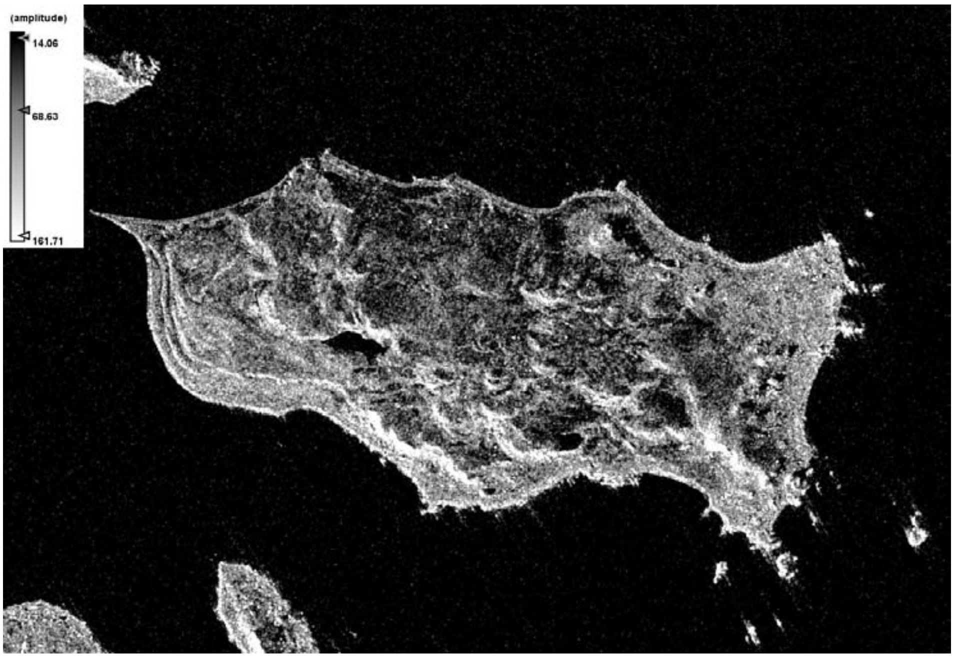


Figure 46: Ardley Island - TerraSAR-X SpotLight, Polarisation HH, 19.02.2012 (Image © DLR 2012)

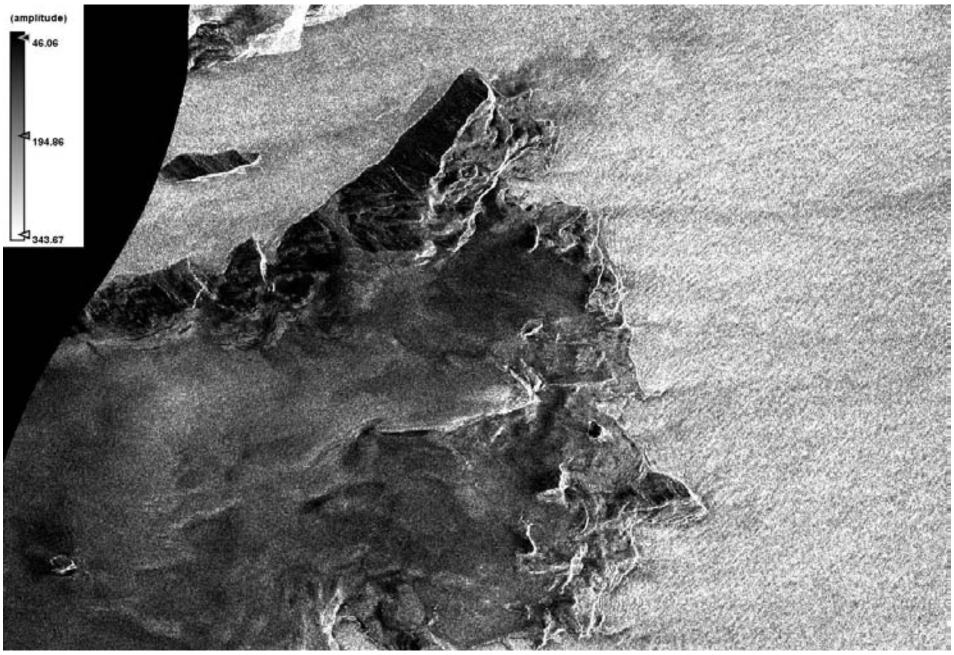


Figure 47: Point Thomas - TerraSAR-X StripMap (Dual), Polarisation HH, 27.11.2010 (Image © DLR 2012)

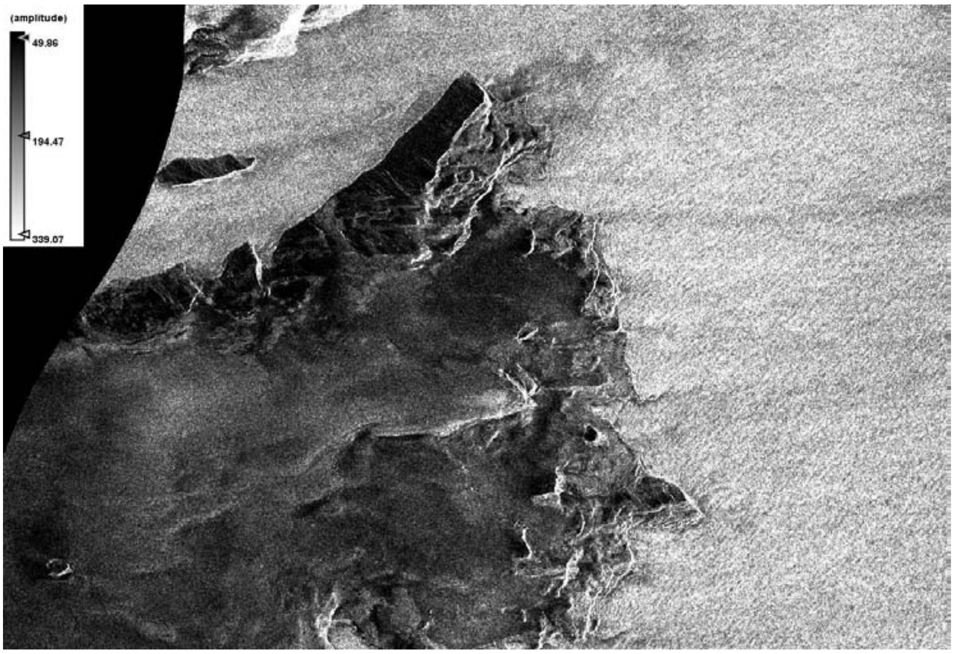


Figure 48: Point Thomas - TerraSAR-X StripMap (Dual), Polarisation VV, 27.11.2010 (Image © DLR 2012)

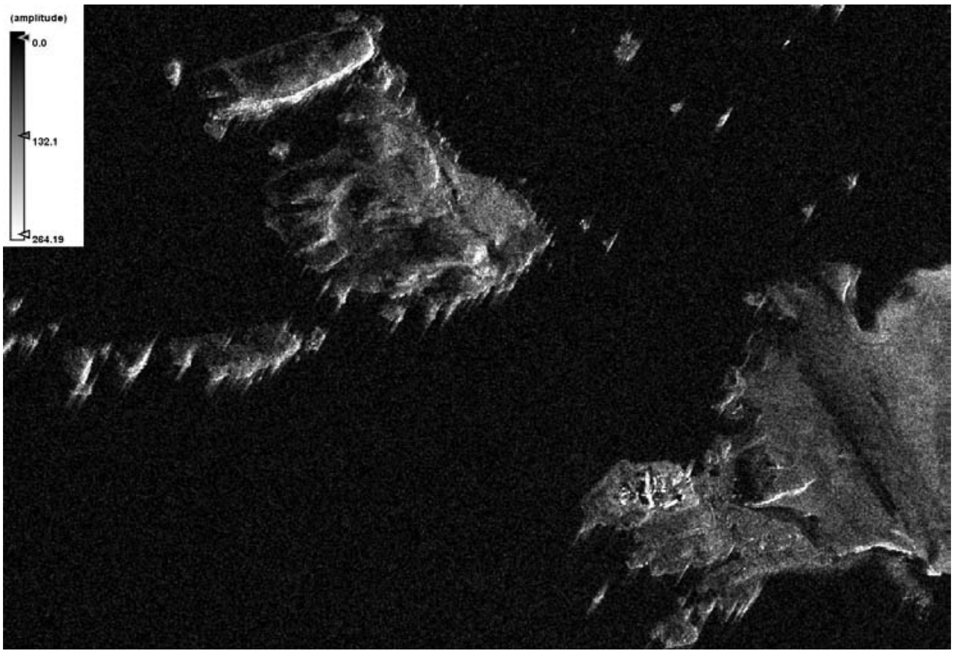


Figure 49: Kopaitic Island & Schmidt Peninsula - TerraSAR-X SpotLight, Polarisation HH, 20.11.2007 (Image © DLR 2012)

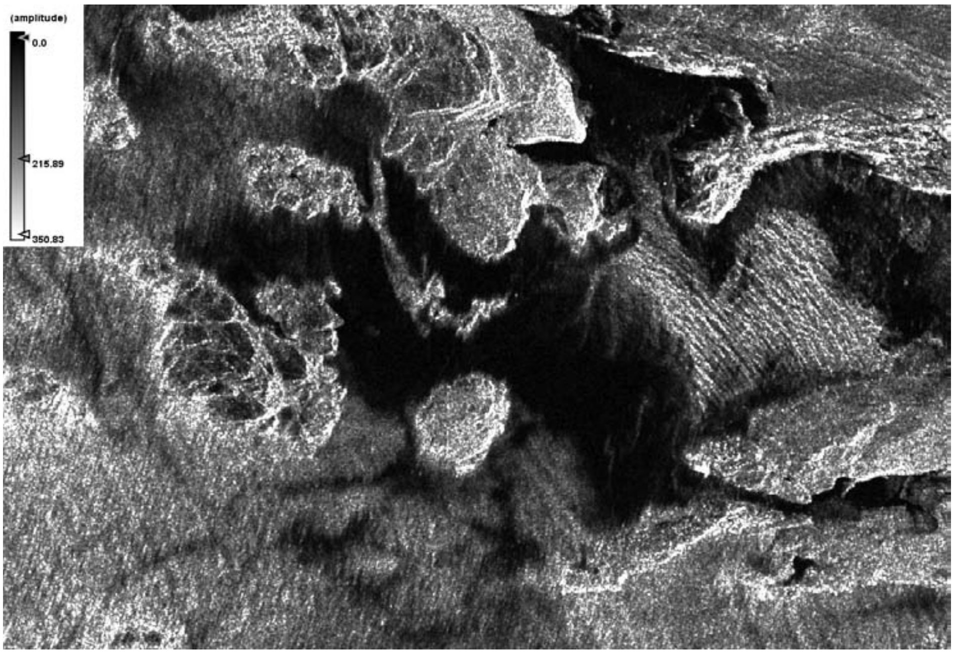


Figure 50: Torgersen Island - TerraSAR-X SpotLight, Polarisation HH, 20.02.2012 (Image © DLR 2012)

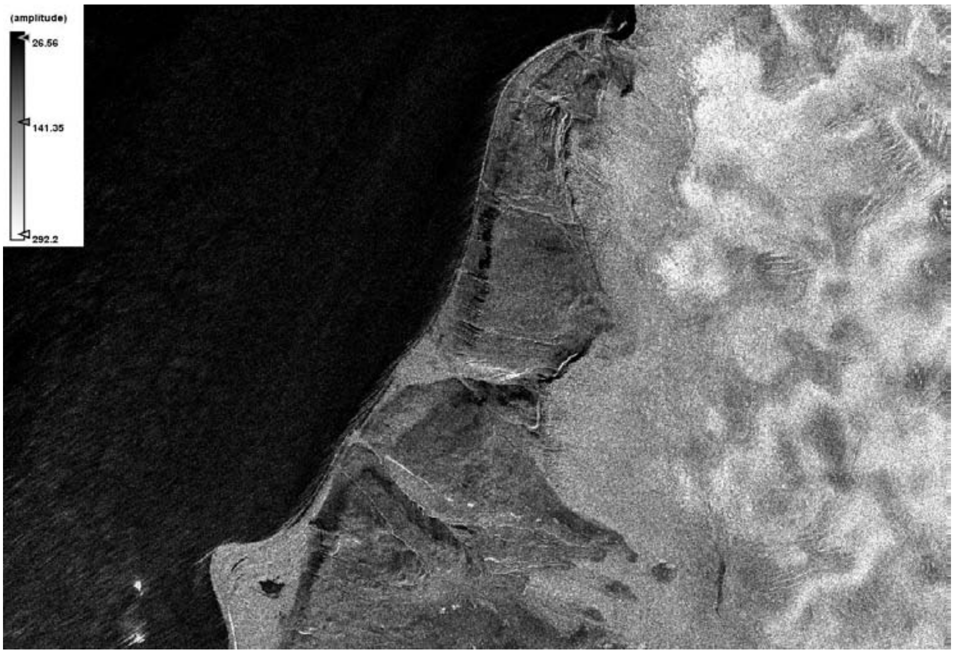


Figure 51: Cape Bird - TerraSAR-X SpotLight, Polarisation HH, 20.02.2012 (Image © DLR 2012)

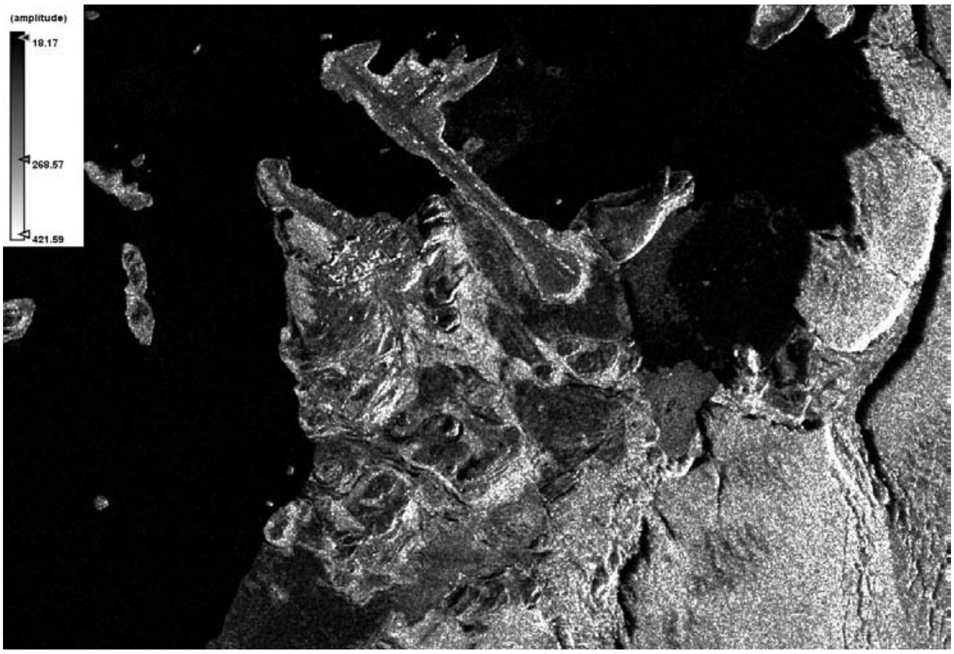


Figure 52: Adélie-Land - TerraSAR-XSpotLight, Polarisation HH, 19.02.2012 (Image © DLR 2012)

3.4 Multitemporal analysis of optical remote sensing data

In order to find out whether it is possible to detect changes in the number of occupied nests using the image recording systems and methods described in Section 3.2, we carried out analyses of multitemporal images for which count data were available. The essential precondition for detecting the number of occupied nests over the area of the colony is a correlation between total colony area and the number of occupied nests. Table 12 lists all the images for which count data are available and in which detectable penguin colonies (see Section 3.2) can be found. In addition, multitemporal images were analysed to determine whether a change in the colony during a breeding season is measurable. The factor to be checked was whether guano visibly spread and accumulated in the course of the breeding season so that it was easier to detect at the end of the season.

Table 12: Image data from usable satellite images, for which count data are available: from one season (orange) or several seasons (green)

	Ardley	Point Thomas	Kopaitic	Torgersen	Cape Bird	Adélie Land
Landsat7					08.12.2007	28.11.2011
					09.12.2001	04.02.2011
						15.12.2009
QuickBird2	28.11.2009	03.12.2011	21.11.2011	03.12.2007	16.12.2007	07.01.2012
	08.12.2005			15.12.2004		03.12.2007
WorldView2	08.01.2010	27.12.2011				04.12.2011

To test whether the results of the multitemporal analysis, which was performed with supervised classification and ratio analysis, are plausible, these results were compared with the results of manual image interpretation. Based on the experience described in Section 3.2, it can be assumed that the results from manual image interpretation are the best available. The results obtained using other methods, if they are to be plausible, should therefore deviate as little as possible from those with the manual method.

Subpixel analysis was not used for the multitemporal analysis because of the bad results described in Section 3.2.4.

3.4.1 Manual image interpretation

Landsat7

On Cape Bird and in Adélie Land, weather conditions were so good that monthly images were available for Cape Bird (2010/2011 season) and for Adélie Land (2008/2009 season). It was thus possible to look for changes in area over the course of a season. Figures 53 and 54 show the results of the analysis of the three images of Adélie Land and Cape Bird M, as well as the four available images of Cape Bird N. Only three images could be used to analyse the Cape Bird M colony, because in the image of 01.01.2011 the colony was slightly obscured by cloud. With the Adélie Land colonies, it can clearly be seen that the visible colony area varies greatly during a season, though it tends to grow slightly towards the end of the season. On Cape Bird, in contrast, visibility tends to increase in December and then decline after the breeding season. The increase in visibility in December can be explained by the fact that there was snow in the images from September, so that the colonies could not be seen as clearly.

Figures 53 and 54 show clearly that the large colonies tend to undergo the smallest relative changes in size and the smallest colonies (Le Mauguen and Cape Bird M) vary the most. This is probably because small colonies are at the limit of Landsat7 resolution. Tiny variations of a few pixels thus lead to big percentage changes.

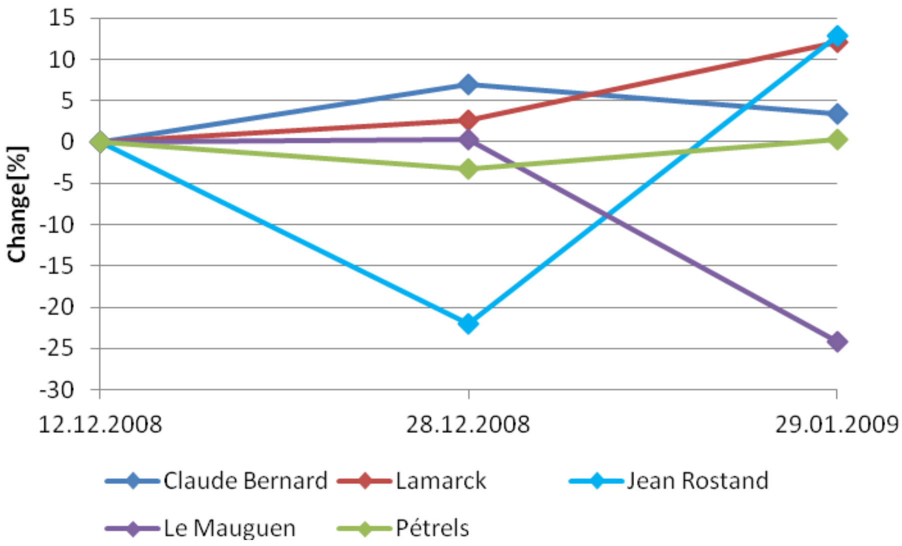


Figure 53: Percentage change in colony area during one season, in relation to the start of the season in Adélie Land for Landsat7 images, determined by manual image interpretation

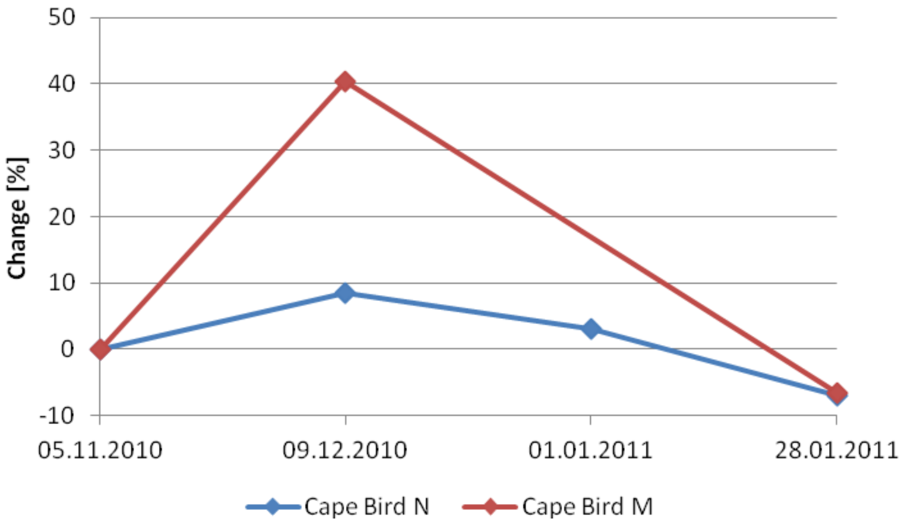


Figure 54: Percentage change in colony area during one season, in relation to the start of the season in Cape Bird for Landsat7 images, determined by manual image interpretation

Figure 55 shows the outcome of an investigation into whether in individual colonies there is a correlation between the number of occupied nests and the change in area. The results are very diffuse, probably once again due to the coarse spatial resolution of Landsat7, so that no definite conclusion can be reached regarding such a correlation. On Cape Bird N, however, which can be very successfully distinguished due to its large size, it is clear that there is no correlation. Although the number of occupied nests increased by 85% compared to the first year, the colony area remained the same.

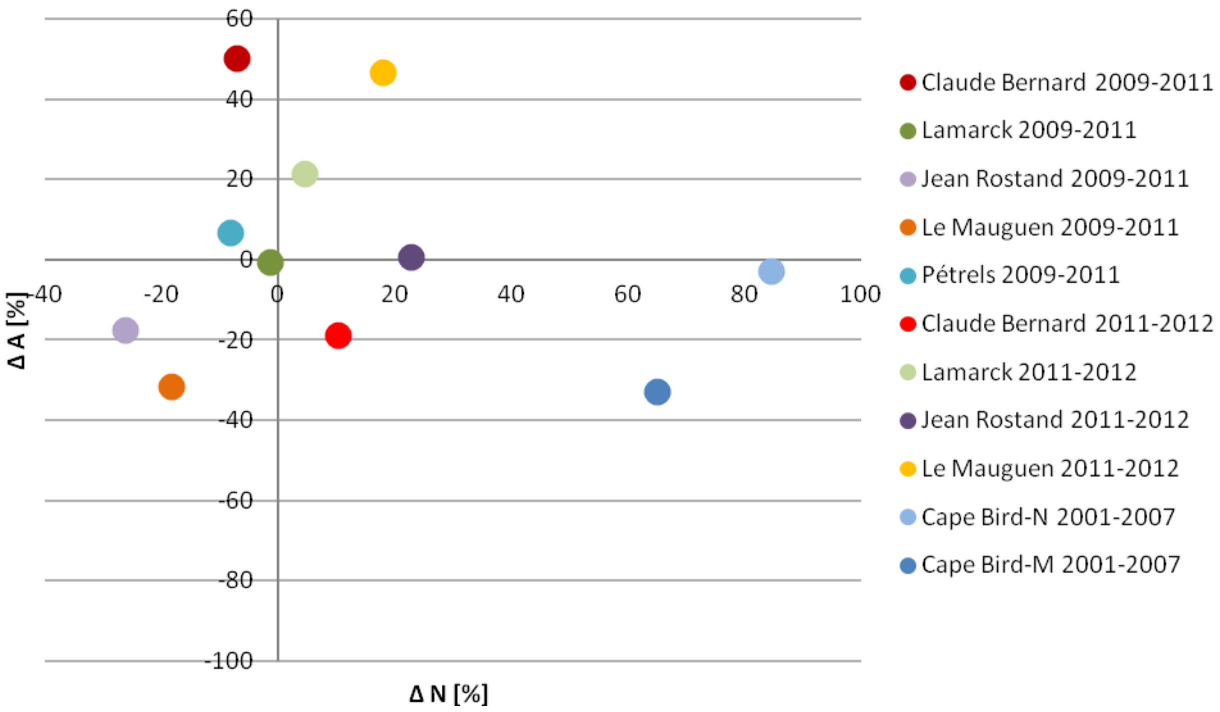


Figure 55: Relation between change in area (Δ A) and change in number of occupied nests (Δ N) for Adélie Land and Cape Bird – manual image interpretation, Landsat7

QuickBird2 & WorldView2

Due to a lack of different images from a single season, no change analyses of colony area could be carried out for QuickBird2 and WorldView2. However, the analysis in Section 3.2 demonstrates that images taken very early in the season along the Antarctic Peninsula tend to be more difficult to analyse than later images.

For Adélie-Land, it is only in the case of major changes in the number of occupied nests that there is a correlation with the extent of the change in colony area; when changes are small, there is no correlation (Figure 56). For Ardley Island, in contrast, it is clear that there can be problems comparing snow-covered images (i.e. snow could clearly be seen at the time the image was taken; see QuickBird2–28.11.2009) with snow-free images (QuickBird2-08.12.2005). This is because changes in area are detected that can be put down to the snow, rather than the actual area covered by occupied nests. This is demonstrated in particular by the fact that hardly any change in area was detected with the snow-free WorldView2 image in the same 2009/2010 season. There is also no recognisable correlation for Ardley in the comparison with the snow-free WorldView2 image. In the case of Torgersen, in contrast, a 45% decrease in area was recorded at the same time as a 35% reduction in the number of occupied nests. However, as this again involved a comparison between a snow-covered image (QuickBird2 03.12.2007) and a snow-free one, it is unclear whether the area change measured really exists or whether the snow cover is to blame.

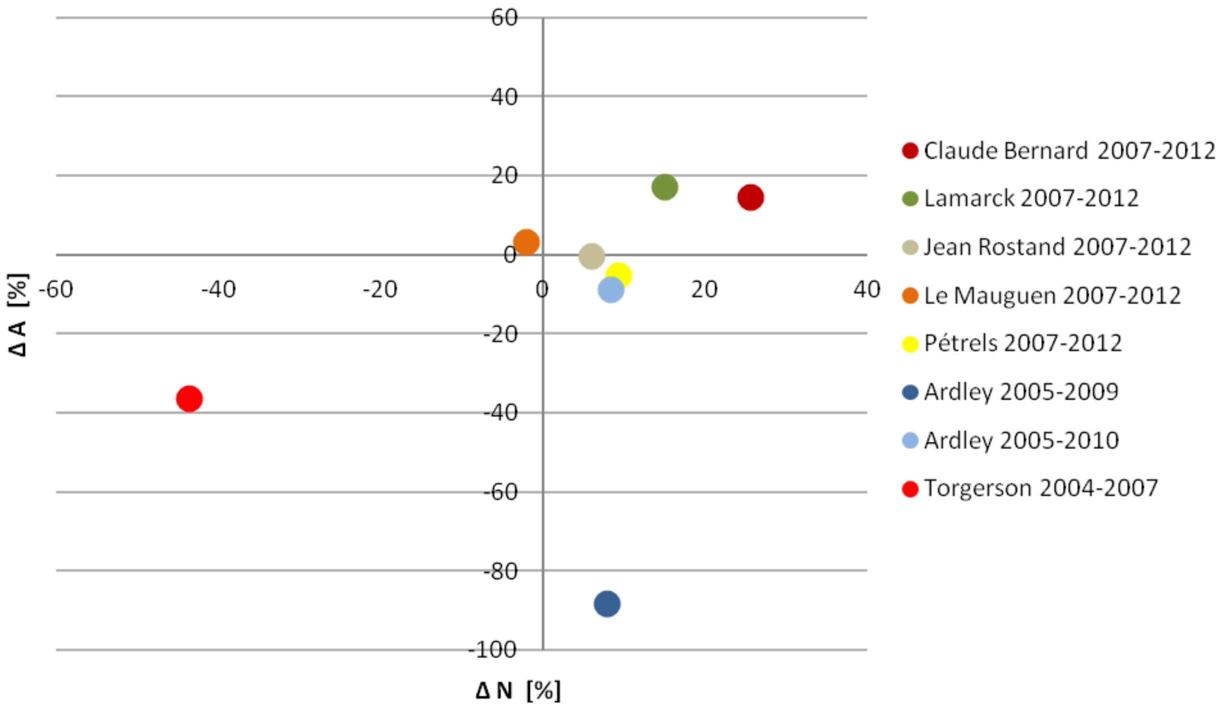


Figure 56: Relationship between area change (Δ A) and change in number of occupied nests (Δ N) for Adélie Land and Cape Bird – manual image interpretation, QuickBird2

Figure 57: QuickBird2 image 16.01.2006 (bands 312; left) and WorldView2 image 27.12.2011 (bands 532; right) – clearly visible reduction in colony size indicated by the arrows (Image © EUSI/DigitalGlobe 2012)

Decreases in area were clearly observed on Point Thomas (Figure 57). As no count data are available to use together with the image of 16.01.2006, it was not possible to check whether the decrease detected was accompanied by a reduction in the number of occupied nests. This appears plausible, however, as the number of occupied nests has more than halved in the last 20 years but precise count data are needed to verify this. The dark colouring of the guano in the WorldView2 image of 27.12.2011 (Figure 57) is probably the result of precipitation shortly before the satellite image was taken.

A clear change in area was also detected for the colony near the Pieter J. Lenie Field Station between 2006 and 2012. In particular, it was possible to identify large nest groups which could not be seen in 2006 (*cf* Figure 24). Over this period the colony area grew by 15%. Due to a lack of count data, it was not possible to check for correlation with a population change.

On Cape Bird, measurements show that there were no significant changes in area for Cape Bird N between images from 2007 and 2010, while for Cape Bird M a 10% increase was recorded. As there are no count data available for 2010, it is again impossible to check whether there is a correlation with the change in the number of occupied nests. However, the available count data show that the number of occupied nests in Cape Bird N has more or less doubled in the last 10 years. If we assume that the number also increased over the period between the two images, this would show that for Cape Bird N there is no correlation between change in the colony area and the change in the number of occupied nests.

3.4.2 Supervised classification

Landsat7

As it is assumed that manual image interpretation delivers the best results, we showed how area change arrived at through supervised classification deviates from manually measured area change (Figure 58). The less the supervised classification results deviate from manual image interpretation, the better the results. It is especially noticeable that the deviations are in some cases very large (27% on average) and that they vary greatly from one colony to another. For this reason, the results of the change analyses using supervised classification should be treated with great caution. There is also no correlation between the size of the area change worked out manually and the quality of the results from supervised classification (Figure 59). Otherwise, there would be a correlation between a clear increase or decrease in deviations and the size of the manually determined area change.

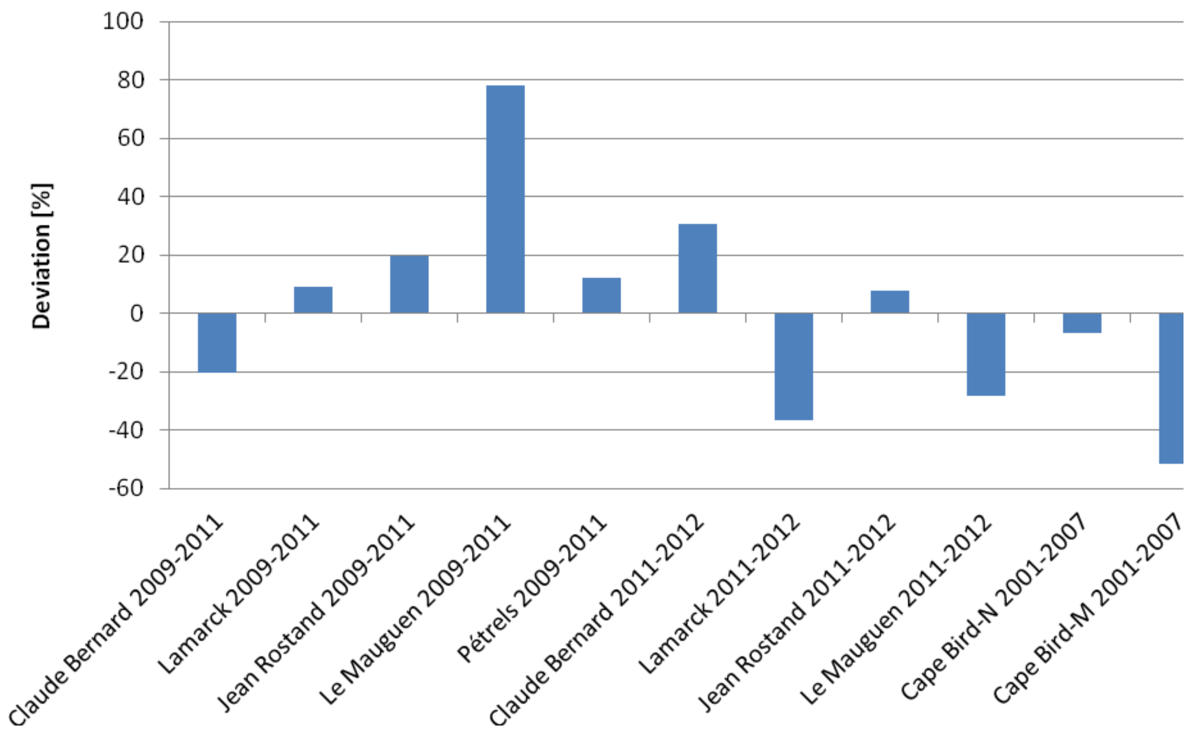


Figure 58: Deviation of colony area change determined by supervised classification from manually determined change for individual Landsat7 images

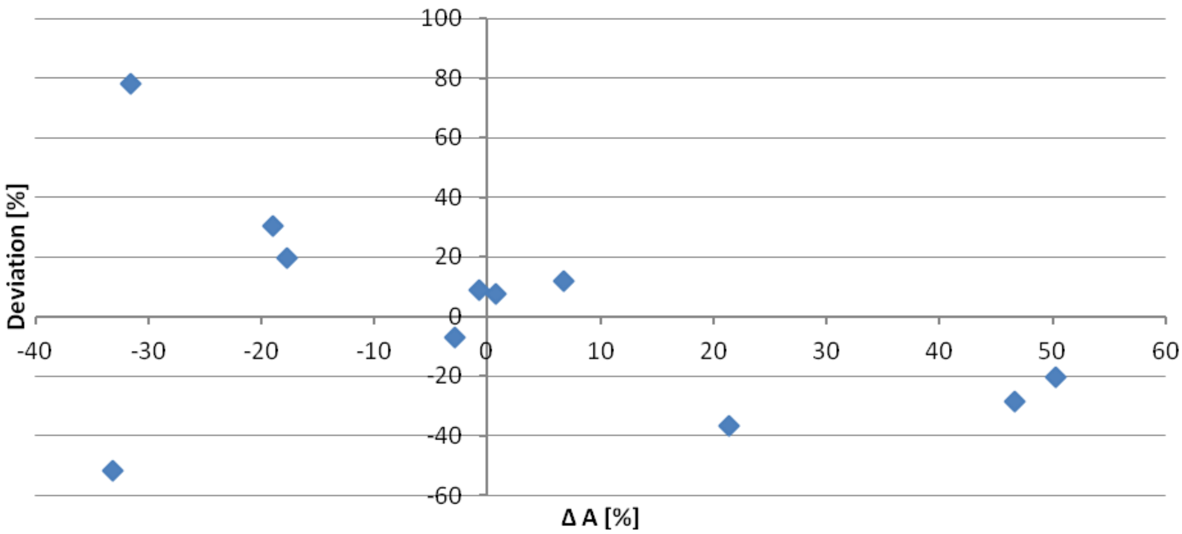


Figure 59: Deviation of colony area change determined by supervised classification from manually determined change, sorted according to manually determined changes in colony area Δ A for Landsat7 images

With supervised classification we were unable to identify a clear trend in the change in colony area over the course of a season (Figure 60). In contrast, Cape Bird N again shows an increase in colony area in December, followed by a reduction in January (Figure 61). It is once again noticeable that the area of the small Cape Bird M colony varies greatly.

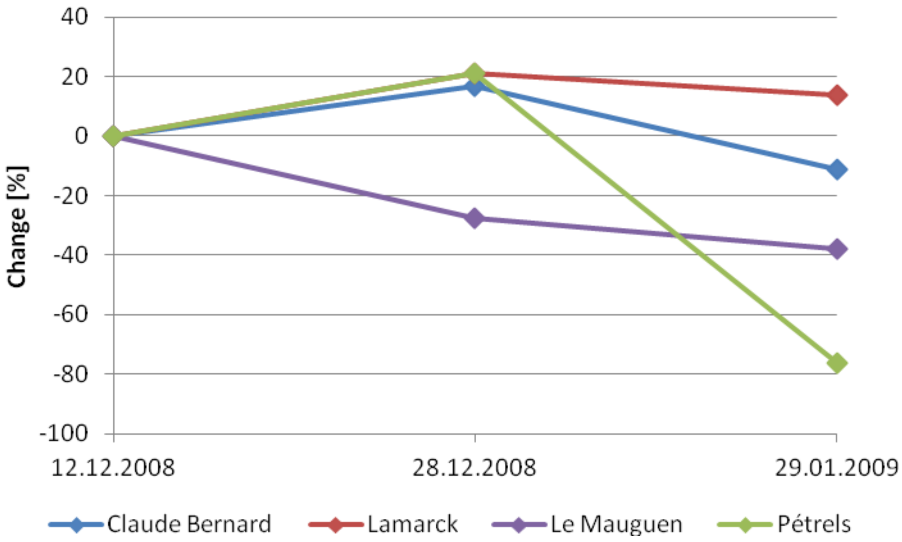


Figure 60: Percentage change in colony area over a season in relation to the start of the season in Adélie Land – supervised classification, Landsat7

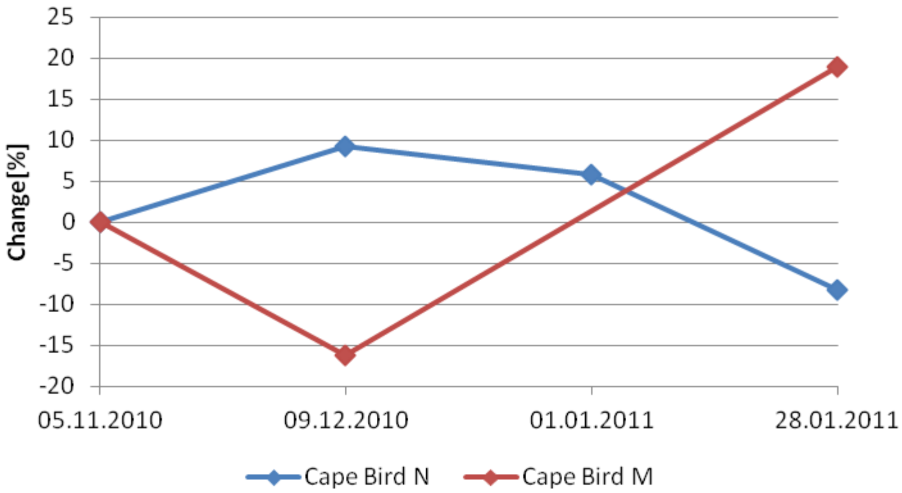


Figure 61: Percentage change in colony area over a season in relation to the start of the season on Cape Bird – supervised classification, Landsat7

As Figure 62 shows, there is no correlation between the change in the number of occupied nests and the change in area of individual colonies, either for Adélie Land or Cape Bird.

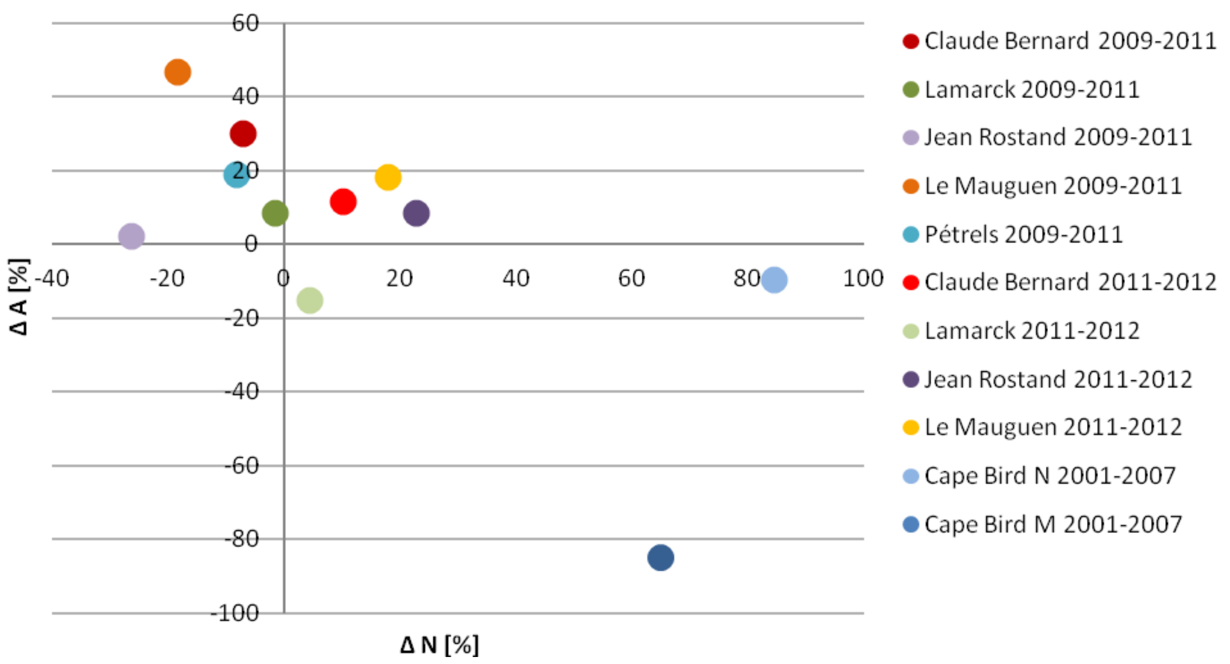


Figure 62: Relationship between area change (Δ A) and change in the number of occupied nests (Δ N) for Adélie Land and Cape Bird – supervised classification, Landsat7

QuickBird2

The results for area change deviate only to a limited extent (12% on average) from those arrived at through manual image interpretation (Figure 63). Consequently, the results of supervised classification are plausible. There is also no correlation between the size of the manually determined area change and the deviation of the results from supervised classification (Figure 64).

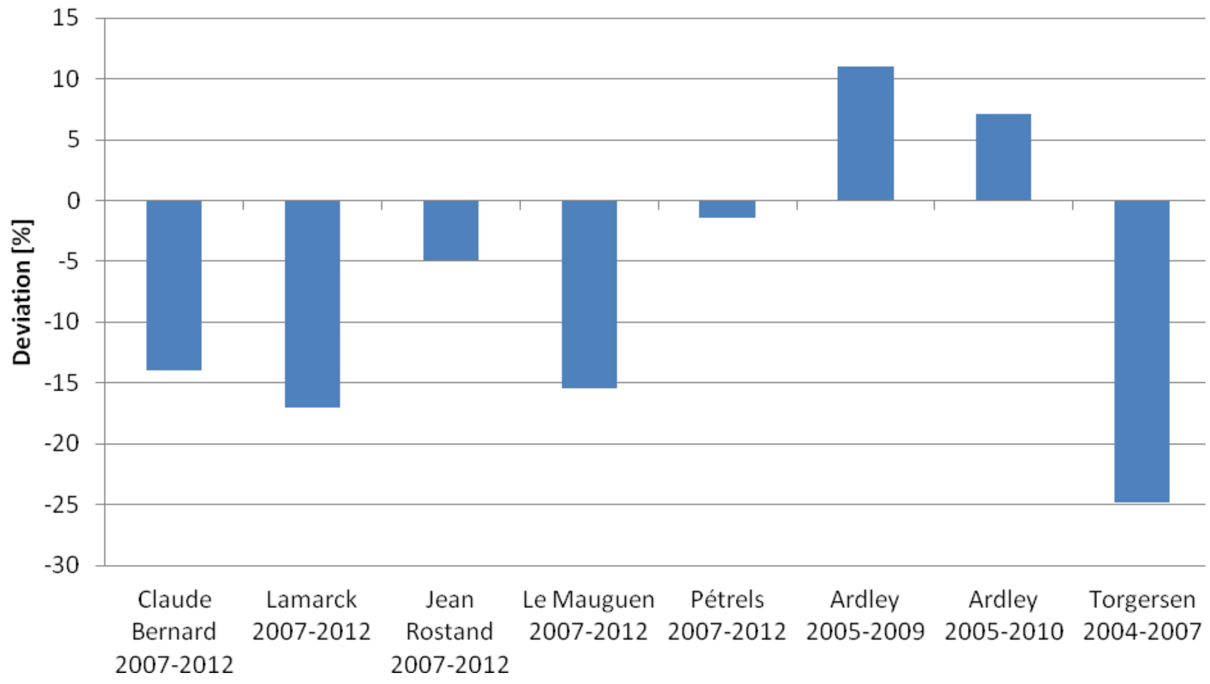


Figure 63: Deviation of colony area determined by supervised classification from the manually determined area for individual QuickBird2 images

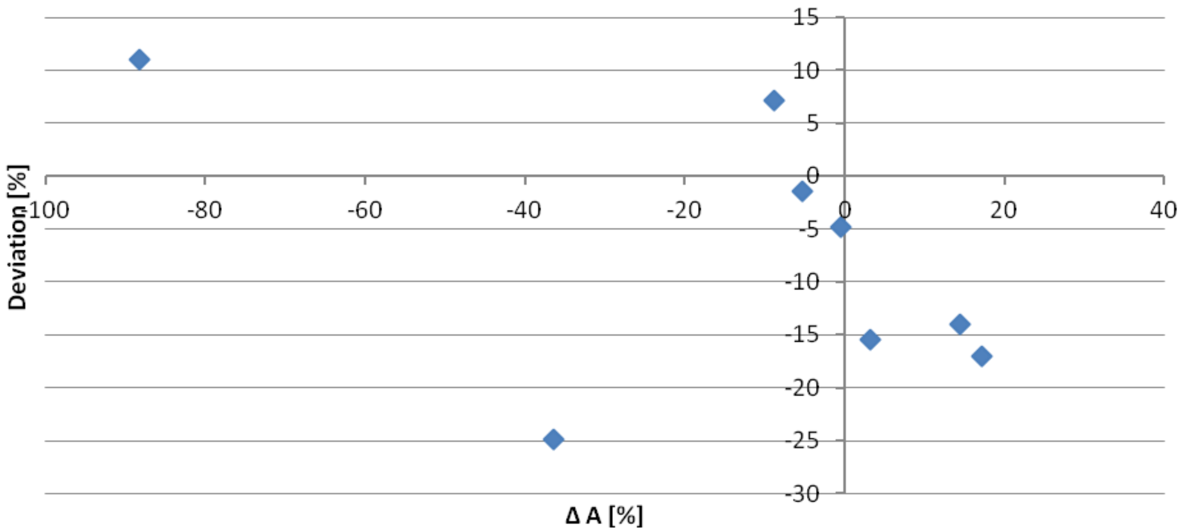


Figure 64: Deviation of colony area change determined by supervised classification from manually determined change, sorted according to manually determined changes in colony area Δ A for QuickBird2 images

Figure 65 shows clearly that for Adélie Land and Ardley Island there is no correlation between area change and the change in the number of occupied nests. In contrast, for Torgersen it was possible, also with supervised classification, to detect a reduction in the colony area and a simultaneous fall in the number of occupied nests.

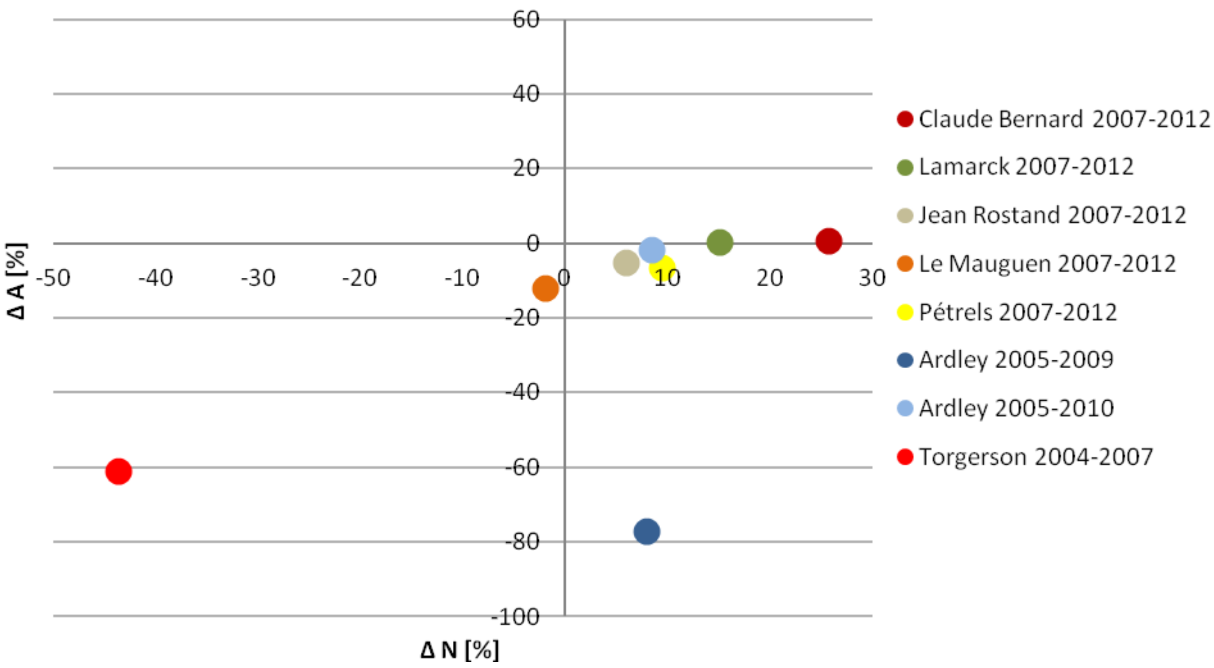


Figure 65: Relationship between area change (Δ A) and change in the number of occupied nests (Δ N) for Adélie Land and Cape Bird – supervised classification, QuickBird2

We were unable to measure a change in area for the Pieter J. Lenie Field Station, as there was light cloud cover at this location on the QuickBird2 image from 2006, with the result that manual interpretation is possible but not supervised classification.

As supervised classification of the QuickBird2 image from 2011 gave very bad results due to mist, it was necessary to compare the QuickBird2 image from 2006 with the WorldView2 image from 2011. However, the 45% reduction in area detected is unrealistically large.

For both Cape Bird colonies only limited changes in area were observed (Cape Bird N: -3.88% and Cape Bird M: +5.89%).

3.4.3 Ratio approach

Landsat7

As it is also assumed in the case of the ratio approach that manual image interpretation provides more accurate results, Figure 66 shows how area change arrived at through supervised classification deviates from manually measured area change. It can be seen that, with the exception of Cape Bird N, the deviation is very large, at 58% on average. In consequence, the results of the change analyses carried out using the ratio approach on the Landsat7 images are not plausible, except for those concerning Cape Bird N. Figure 67 shows there is no correlation between the size of the manually determined area change and the quality of the results arrived at using the ration approach. This is because deviations from the manual area measurements vary, both where there are large manually determined area changes and where these changes are small.

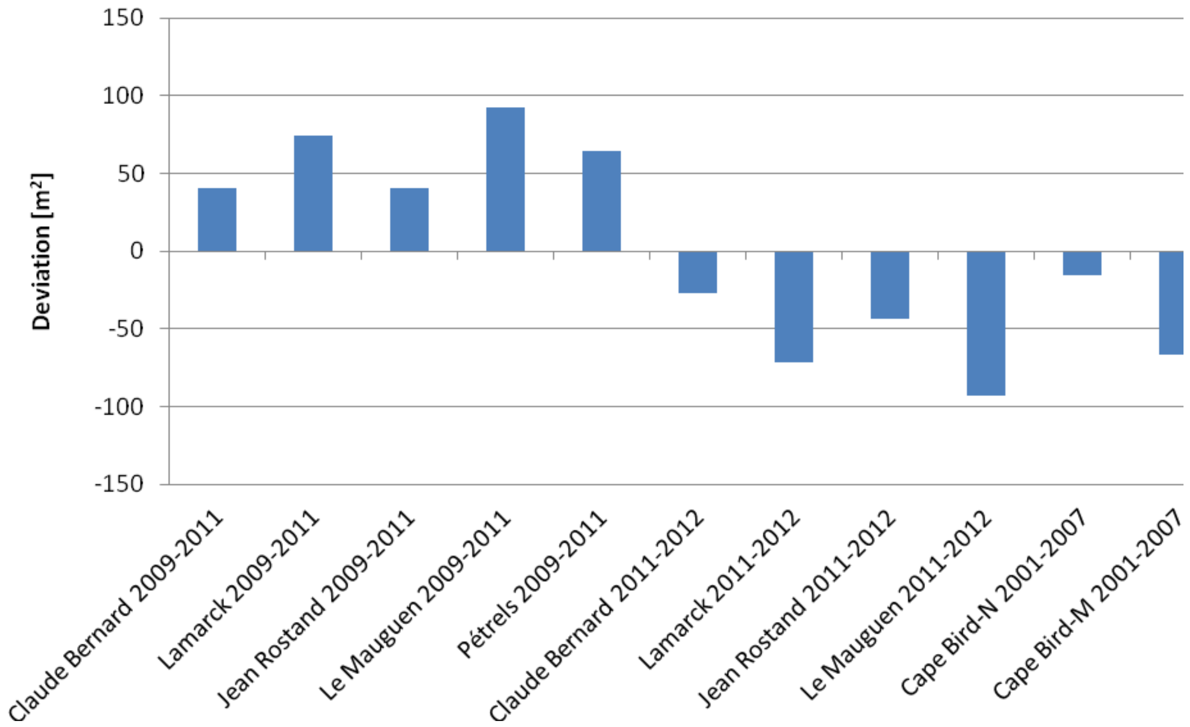


Figure 66: Deviation of colony area change classified with ratios from manually determined change for individual Landsat7 images

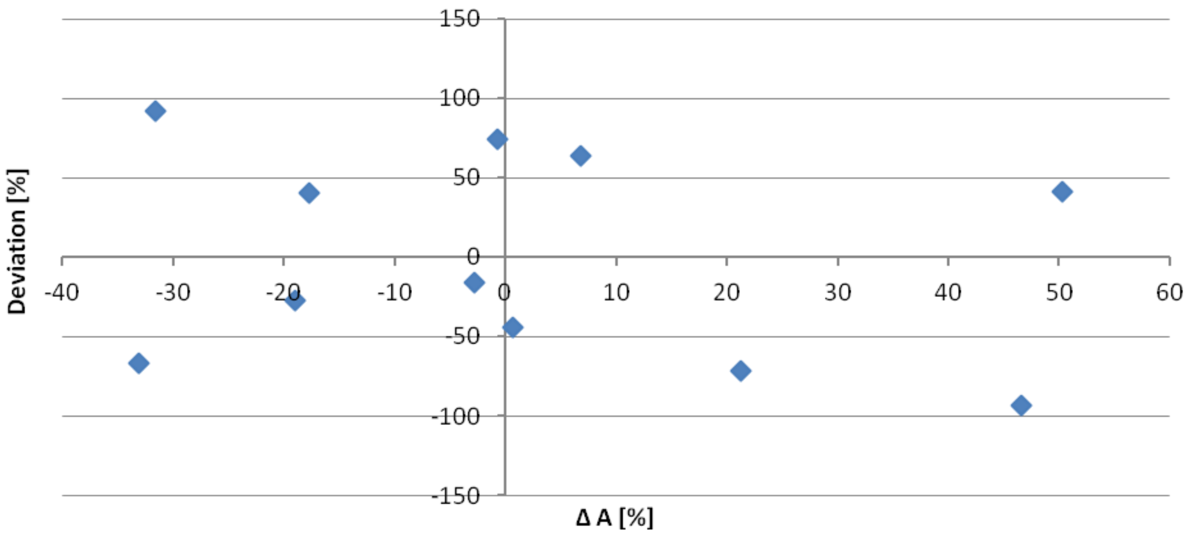


Figure 67: Deviation of colony area change classified with ratios from manually determined change, sorted according to manually determined changes in colony area Δ A for Landsat7 images

Using the ratio analysis, we detected a tendency for the Adélie Land colony area to increase towards the end of the season (Figure 68). In contrast to results with the previous methods, a decrease in the area of the Cape Bird N colony was visible in December (Figure 69).

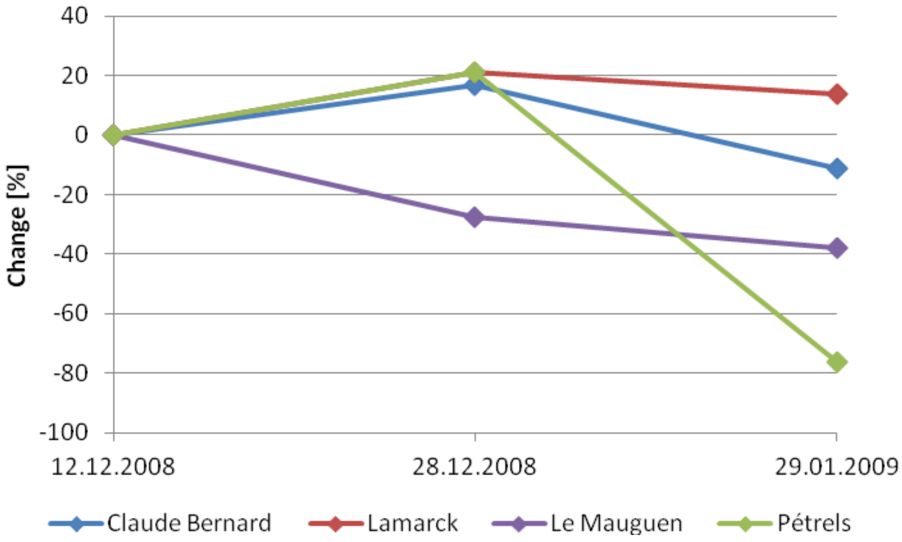


Figure 68: Percentage change in colony area over a season in relation to the start of the season in Adélie Land – ratio approach, Landsat7

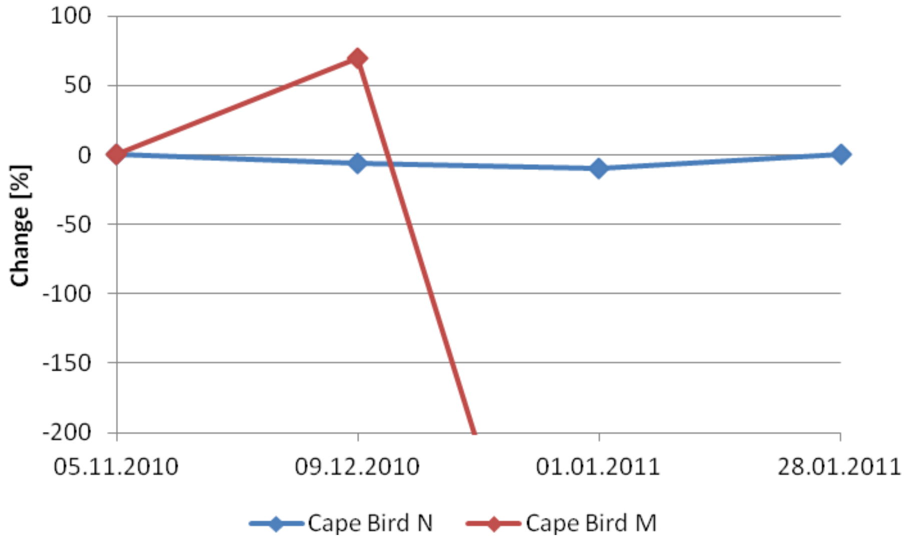


Figure 69: Percentage change in colony area over a season in relation to the start of the season in Cape Bird – ratio approach, Landsat7

Figure 70 shows that neither in Adélie Land nor on Cape Bird is there a correlation for individual colonies between the change in the number of occupied nests and the change in area.

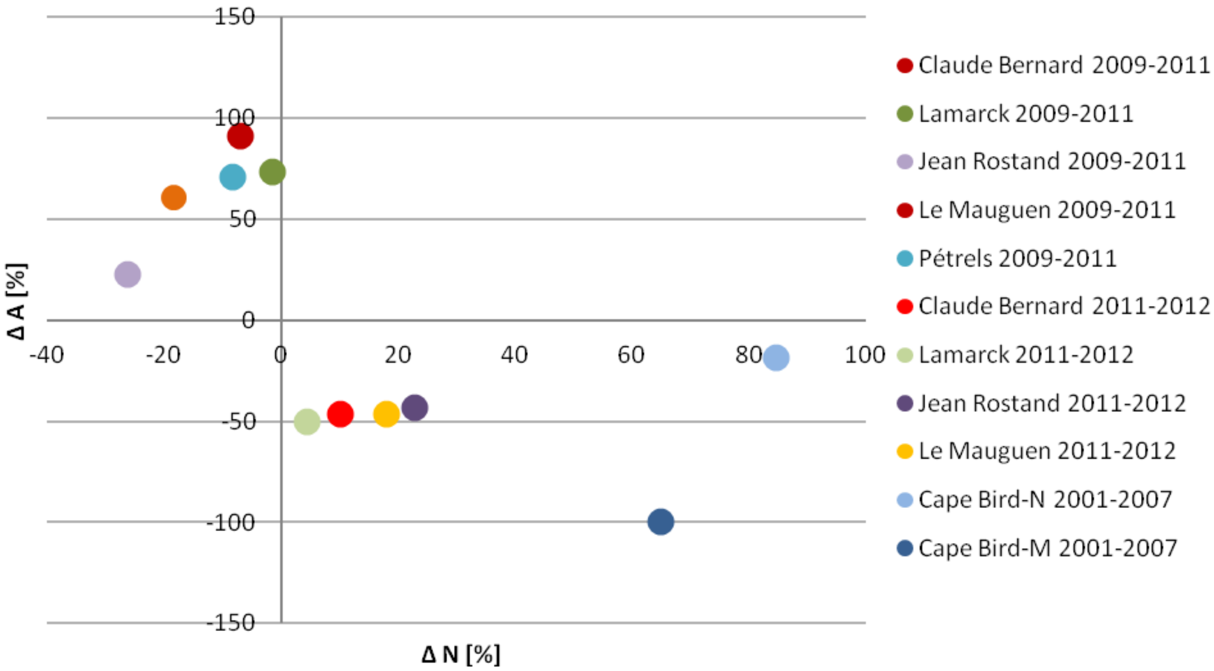


Figure 70: Relationship between area change (Δ A) and change in the number of occupied nests (Δ N) for Adélie Land and Cape Bird – ratio approach, Landsat7

QuickBird2

For QuickBird2 images, the results of ratio analysis deviate sharply from those obtained through manual determination (45% on average, Figure 71 and Figure 72). The areas detected were always significantly over-classified. For this reason, the clearly recognisable correlation in Figure 73 between a rising trend in the number of breeding pairs in Adélie Land and the increase in colony area should be treated with scepticism. The increase in colony area that was detected can be ascribed to the imprecision of the ratio analysis and not necessarily to an actual increase in area.

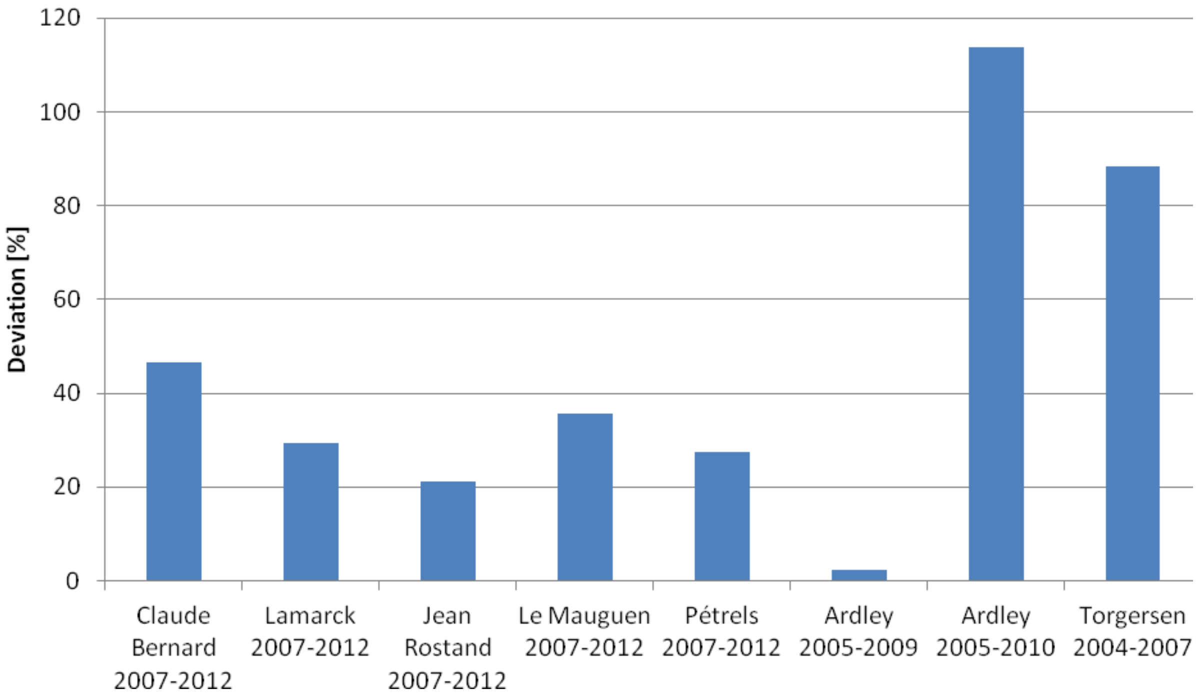


Figure 71: Deviation of colony area change classified with ratios from manually determined change for individual QuickBird2 images

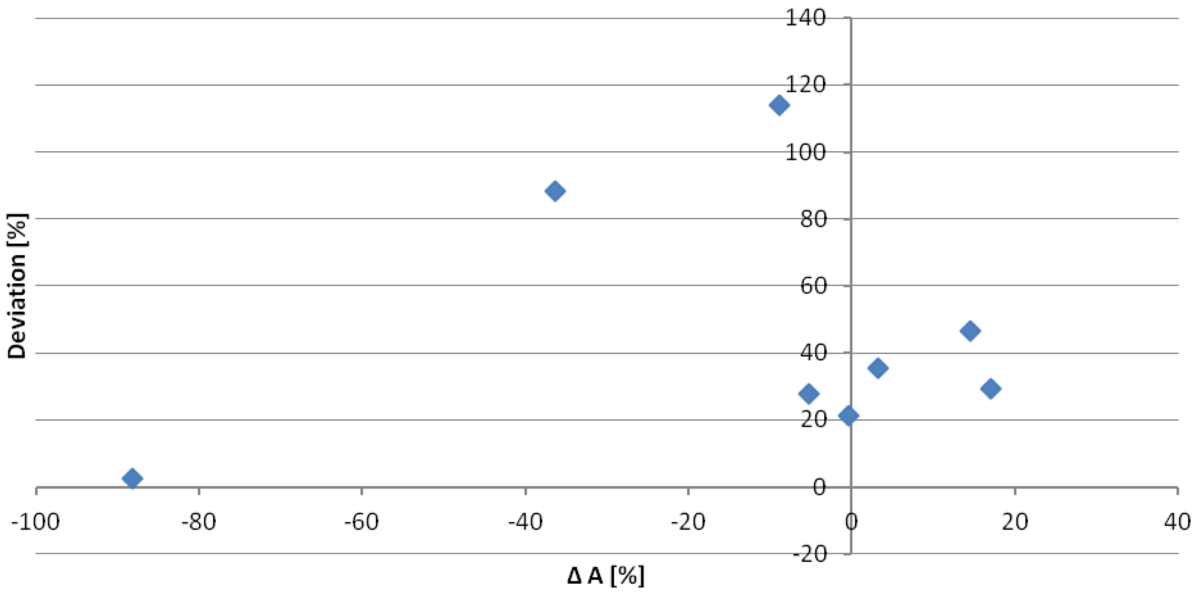


Figure 72: Deviation of colony area change classified with ratios from manually determined change, sorted according to manually determined changes in colony area Δ A for QuickBird2 images

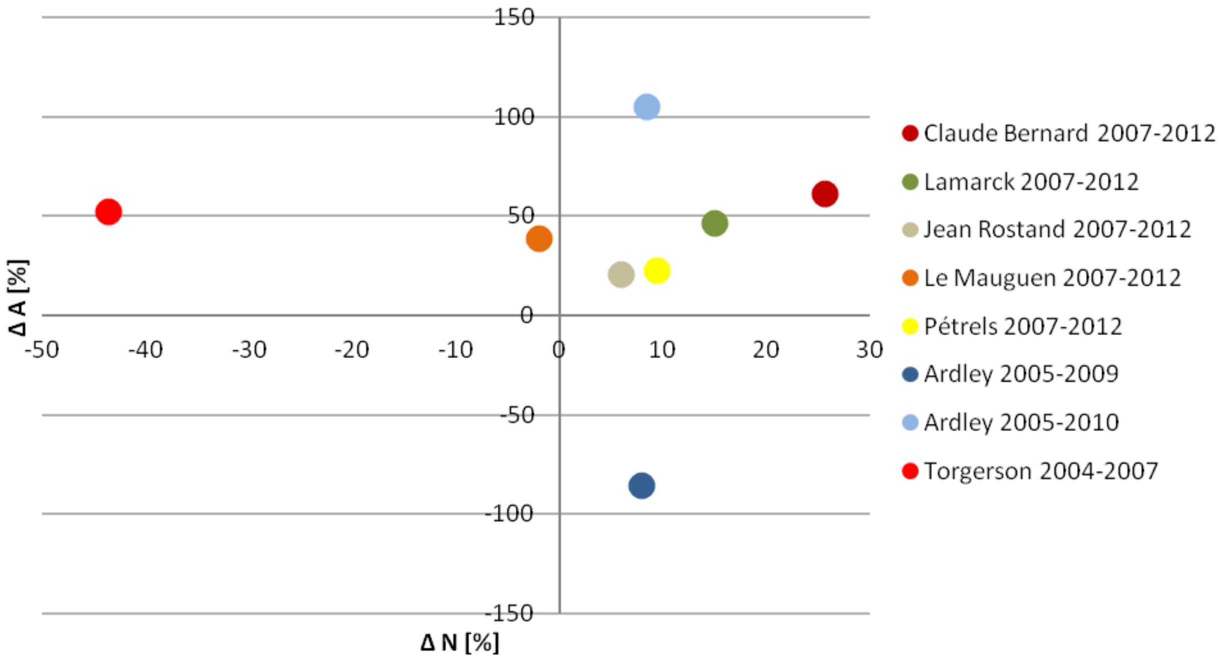


Figure 73: Relationship between area change (Δ A) and change in the number of occupied nests (Δ N) for Adélie Land and Cape Bird – ratio approach, QuickBird2

Results from the comparison of the images of Point Thomas from 2006 and 2011 show an unrealistically large reduction in the colony area of 186%. Due to cloud cover in the QuickBird2 image from 2006, ratio analysis could not be used to investigate the colonies near the Pieter J. Lenie Field Station.

Slight reductions in area were detected for both Cape Bird colonies between 2006 and 2010, although it can be assumed that over this period the number of occupied nests rose (see Section 3.4.1).

3.5 Multitemporal analysis of radar data

A multitemporal analysis was carried out of a number of consecutive SAR images, with the same imaging geometry, of Ardley Island, Point Thomas and Kopaitic Island/Schmidt Peninsula (colonies of the species *P. papua*, *P. antarctica* and *P. adeliae*). In each case there were either four or six consecutive images. The analysis provided no usable results with regard to changes in penguin colonies. For the species *A. forsteri*, data must first be collected during the next Antarctic winter, so as to be able to carry out a multitemporal analysis.

3.6 Possibility of automating the process of remote sensing data analysis

By definition, the method of manually digitalising penguin colonies by visual interpretation cannot be automated. Subpixel analysis cannot be automated either. It is possible, in principle, to automate subpixel analysis, but the results were, without exception, unusable for all sensors and colonies. This was also the case for Cape Bird, where this method provided good results as regards detectability (see Section 3.2.4). Below, we examine whether, and to what extent, supervised classification and ratio analysis can be automated.

3.6.1 Supervised classification

The difficulty facing automation of supervised classification lies in the fact that specific training areas have to be determined for each image in order to obtain a separate signature matching a specific land cover class. To get around this problem, the signatures of the supervised classifications already performed, for each land cover class and from every year, were collected in a 'signature catalogue', which was used to make supervised classifications of the individual images. For this purpose, signature catalogues compiled according to two different criteria were used.

In the first case, all signatures of all the images from one site and one sensor were put together. These 'regional signature catalogues' were then used to classify only those sites that made up the catalogue. The aim was to test whether an automated analysis of a specific site is possible using the signatures that specifically match this site. In the second case, the signatures of all available images from one sensor, showing different sites, were put together in a 'cross-regional signature catalogue'. This cross-regional signature catalogue was used to classify all the images from one sensor. The aim was to test whether a multi-site automated analysis is possible.

This automation approach presupposes that the supervised classification of the individual images from Section 3.2.2 provide good results. Furthermore, signatures from as many different images as possible are needed to obtain the broadest possible range of spectral variations of the land cover classes that appear in the images. This is because the spectral signature of guano and that of the surrounding land cover classes vary on every image. For an automated analysis to be even theoretically possible, the spectral signature of guano must not vary too much between images.

Landsat7

Figure 74 shows, by way of example, the average spectral signatures of guano for Cape Bird. It can be seen that the guano signatures are relatively similar, thus making an automated analysis at least theoretically possible.

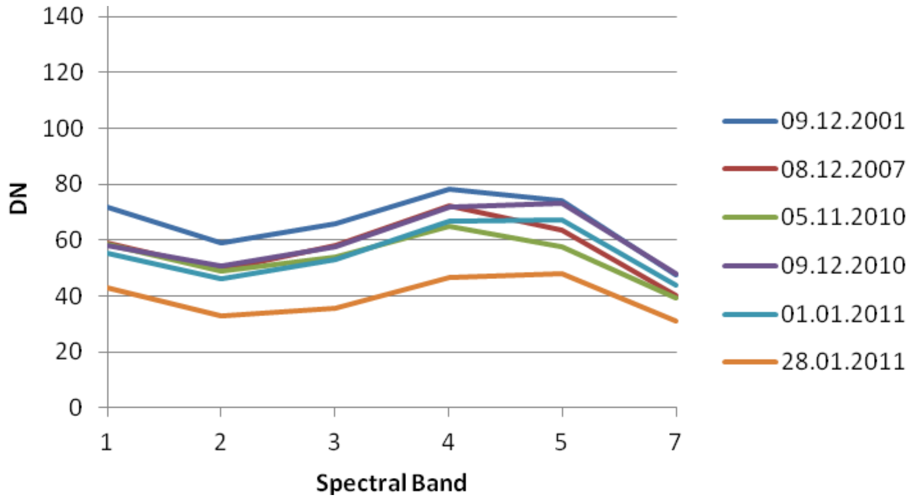


Figure 74: Spectral guano signatures from Cape Bird for Landsat7

Seven Landsat7 images were available for compiling the regional signature catalogue of Cape Bird, while for Adélie Land there were six Landsat7 images. However, as the catalogue cannot contain the signatures of the image that is to be classified, the signature catalogue of Cape Bird contained only six of seven available images and that of Adélie Land five of six images. As only two images were available for Kopaitic, each image had to be classified using the signatures of the other test site.

It was, in principle, quite possible to classify the images using the regional signature catalogue. Detailed results of the classification are shown in Figure 75. Here it can be seen that deviations from manual delineation vary considerably from one colony to another. Average deviation is 45%. Large colonies such as Pétrels and Cape Bird N show only limited deviation, while Le Mauguen in particular shows an extreme deviation of nearly 250%. There is a clear correlation between the extent of the deviation and colony area (Figure 76), with deviations declining in line with increasing colony size.

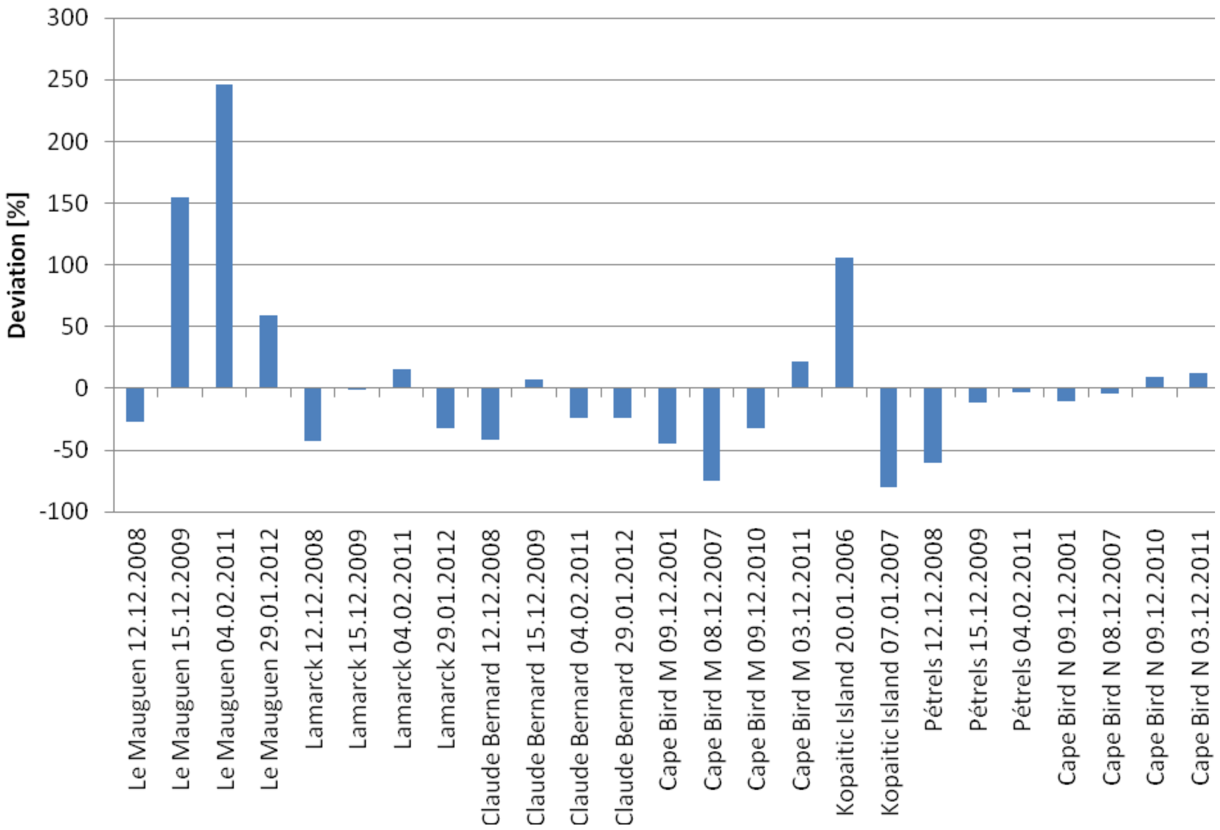


Figure 75: Deviation of colony area determined by supervised classification using regional signature catalogue from the manually determined colony area for individual Landsat7 images

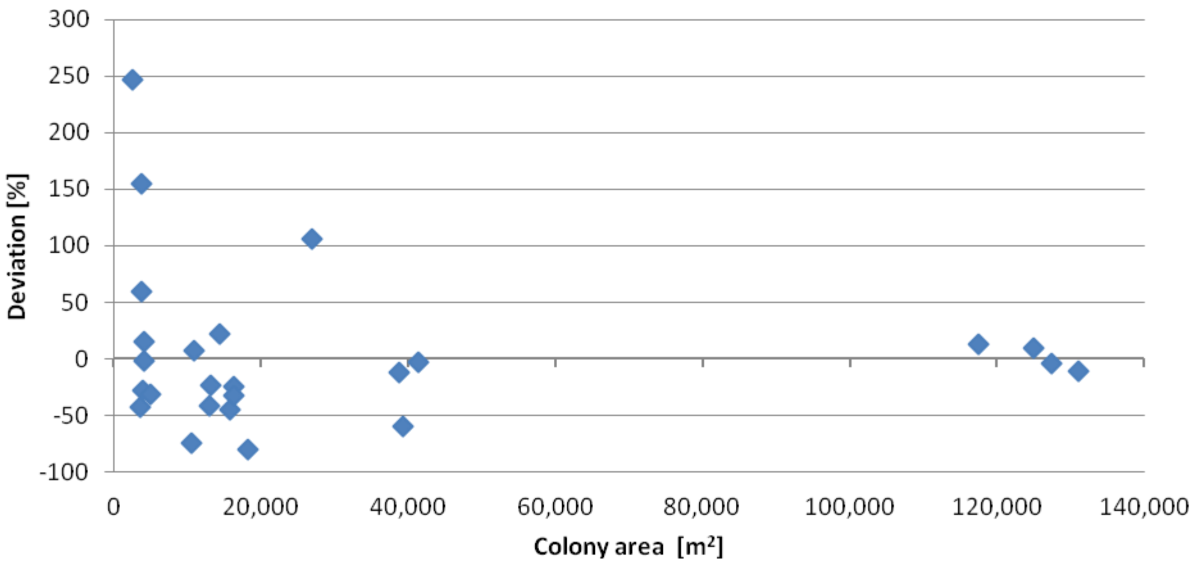


Figure 76: Deviation of colony area classified by supervised classification using regional signature catalogue from the manually determined colony area, sorted according to colony area for Landsat7 images

The cross-regional signature catalogue was compiled in exactly the same way as the regional catalogue. However, the cross-regional signature catalogue comprised 14 images.

It was also possible to classify all the images using the cross-regional signature catalogue. As can be seen in Figure 77, with some colonies there are large deviations from the manually determined colony area, while for the majority of colonies only relatively limited deviations were recorded. The average deviation is a relatively high 46%. Once again, there is a clear correlation between the extent of the deviation and the colony area (Figure 78).

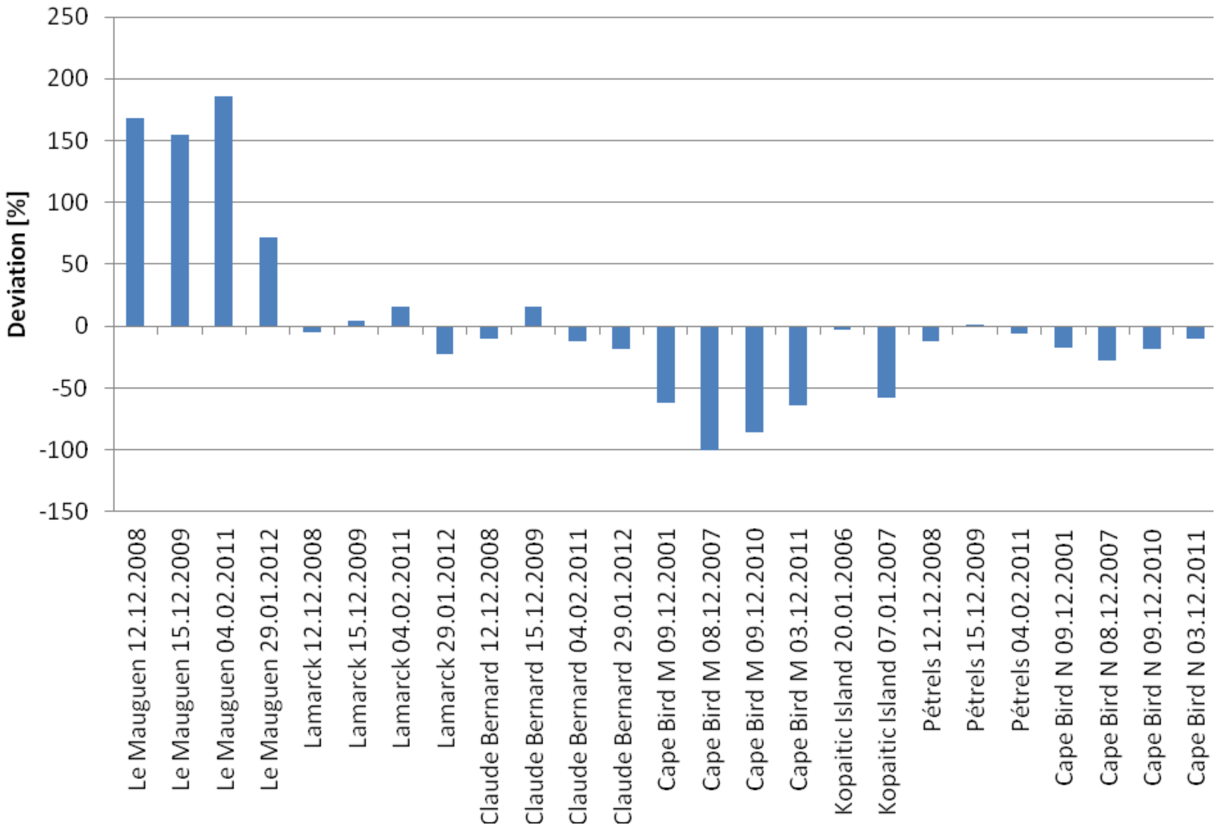


Figure 77: Deviation of colony area determined by supervised classification using cross-regional signature catalogue from the manually determined colony area for individual Landsat7 images

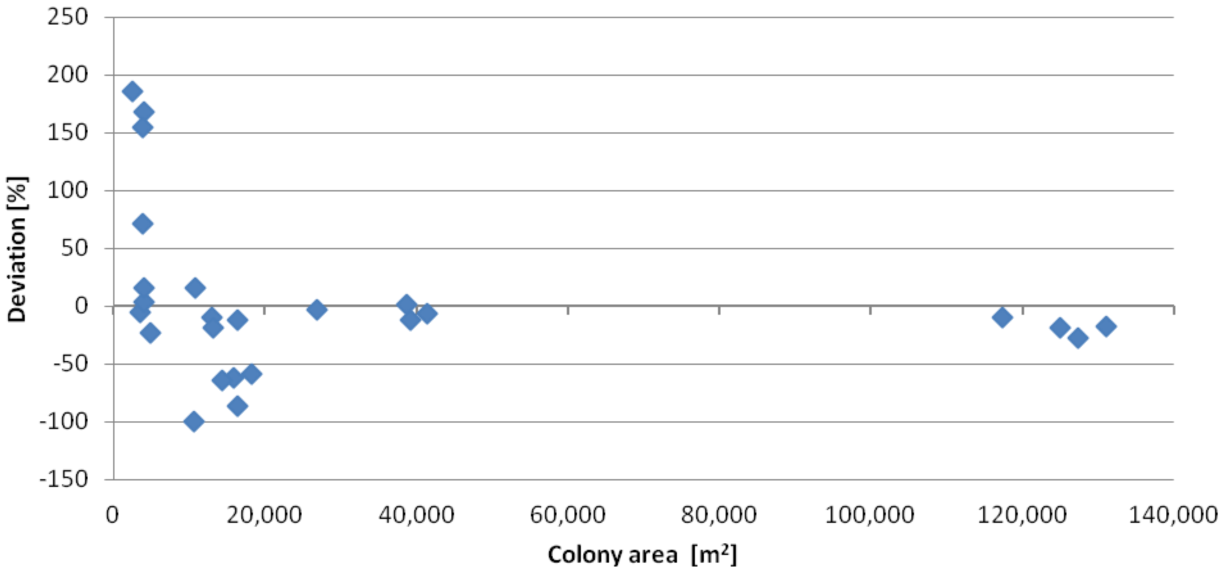


Figure 78: Deviation of colony area classified by supervised classification using cross-regional signature catalogue from the manually determined colony area, sorted according to colony area for Landsat7 images

QuickBird2 & WorldView2

The analysis of QuickBird2 images faced the problem that only a maximum of two images per colony were available. This made it impossible to compile a regional signature catalogue for the individual sites. In order to get at least an indication of whether regional classification is possible with QuickBird2 images, one image was classified in each case using the signatures of the other. For WorldView2 there was only one image per colony, making regional classification impossible. Moreover, it makes no sense to combine QuickBird2 and WorldView2 images because of the difference in their spectral bands.

Classification results are given (Figures 79 to 82). The only plausible results were for the Cape Bird and Adélie Land images. Among other things, this is because for the other colonies the images varied too much with respect to the weather conditions at the time (mist, snow, etc.). Although the results varied considerably, they did indicate that a regional classification can deliver good results if there are enough historical images available. As with the change analysis in Section 3.4.2, there was no correlation here between deviation and colony area, including with the high-resolution sensors, due to the high spatial resolution (Figures 80 and 82).

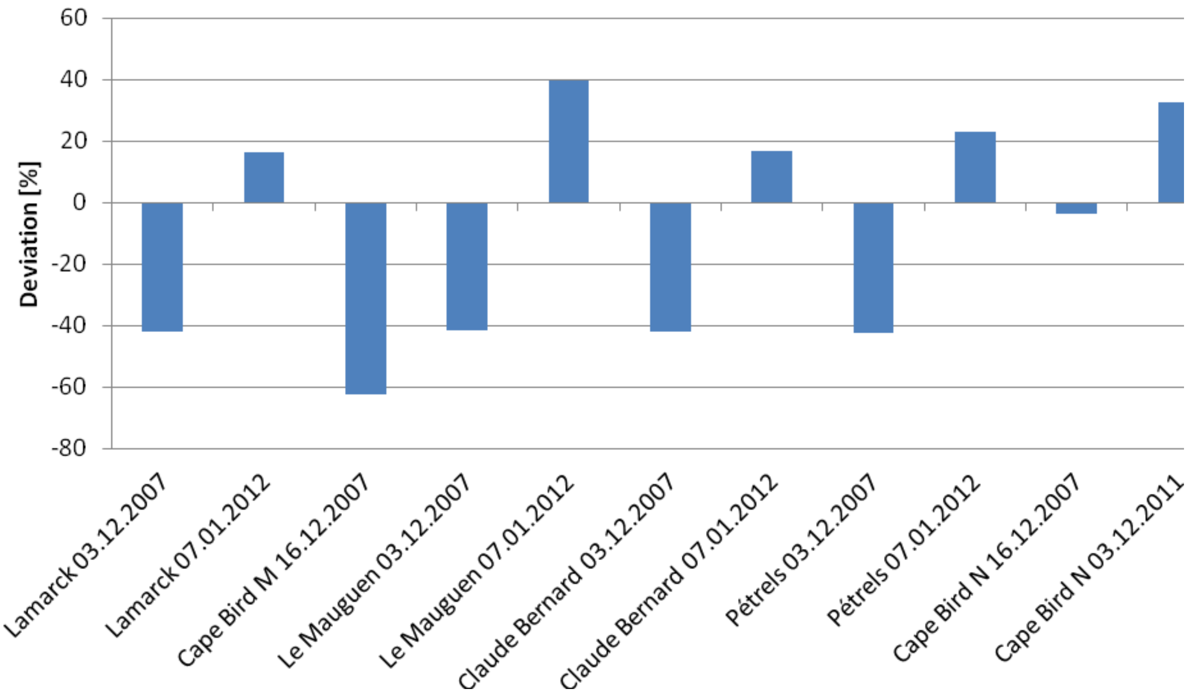


Figure 79: Deviation of colony area determined by supervised classification using regional signature catalogue from the manually determined colony area for individual QuickBird2 images

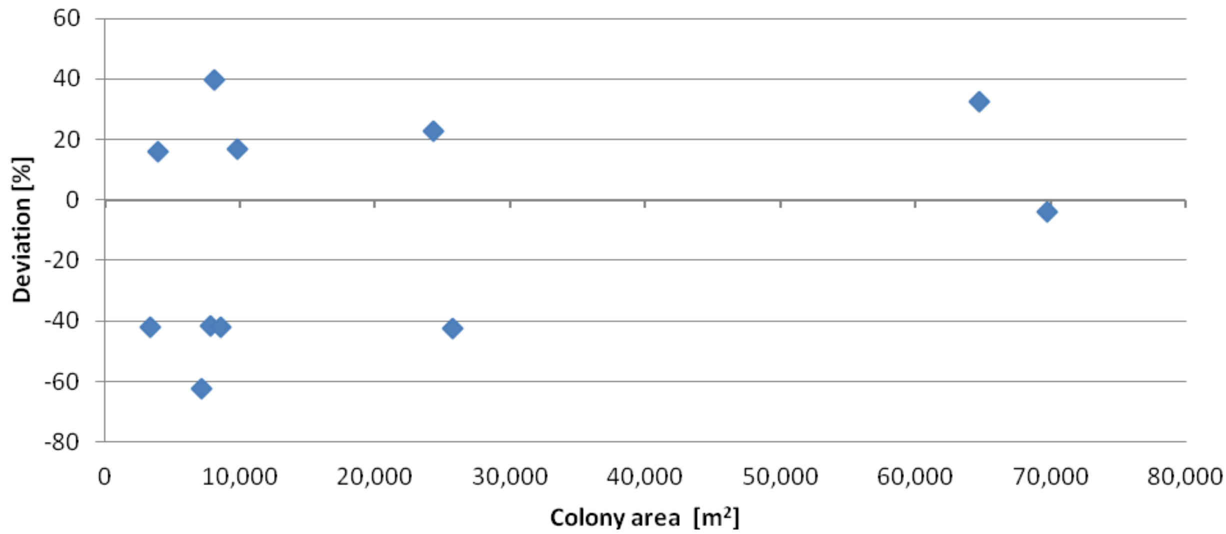


Figure 80: Deviation of colony area classified by supervised classification using regional signature catalogue from the manually determined colony area, sorted according to colony area for QuickBird2 images

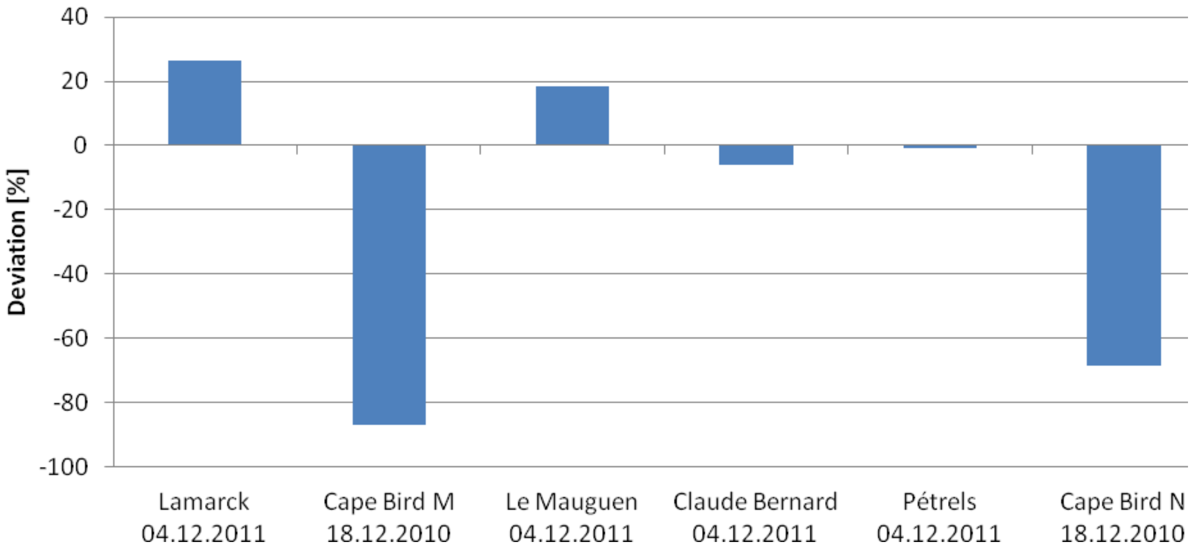


Figure 81: Deviation of colony area determined by supervised classification using regional signature catalogue from the manually determined colony area for individual WorldView2 images

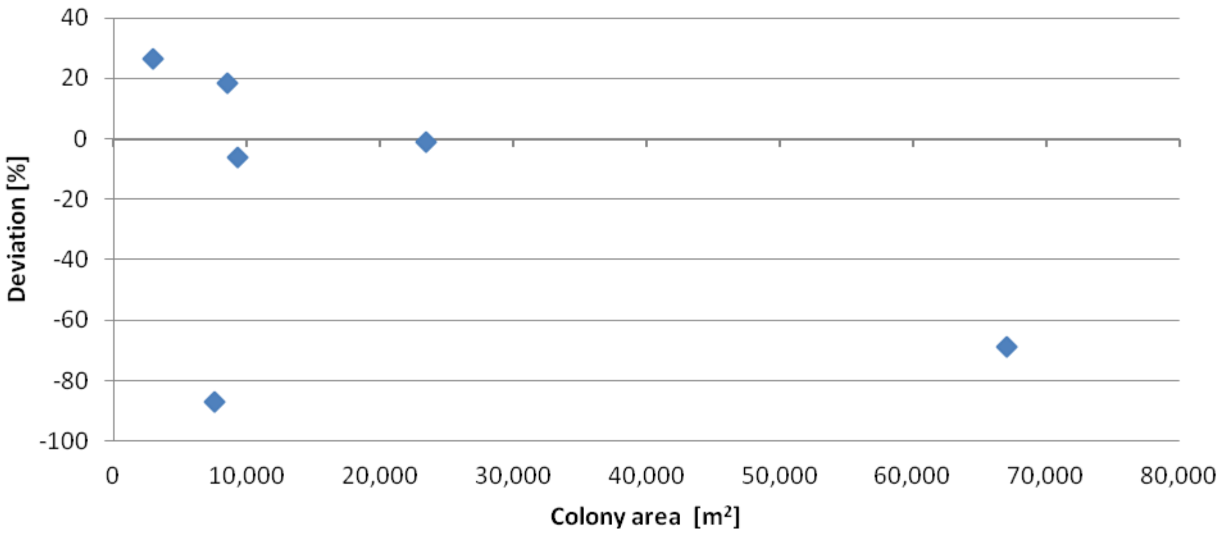


Figure 82: Deviation of colony area classified by supervised classification using regional signature catalogue from the manually determined colony area, sorted according to colony area for WorldView2 images

The cross-regional supervised classification, with a signature catalogue that included all images, gave only unusable results for all colonies for QuickBird2 and WorldView2. For this reason, diverse signature combinations were tested. The outcome was that only the cross-regional classification with the Cape Bird and Adélie Land images provided usable results (Figures 83 to 86). These results, though very variable, indicate that a cross-regional classification made up of a large number of signatures can provide good results as only limited deviations were detected for Adélie Land. There was no correlation between the extent of the deviations and colony area with any of the sensors.

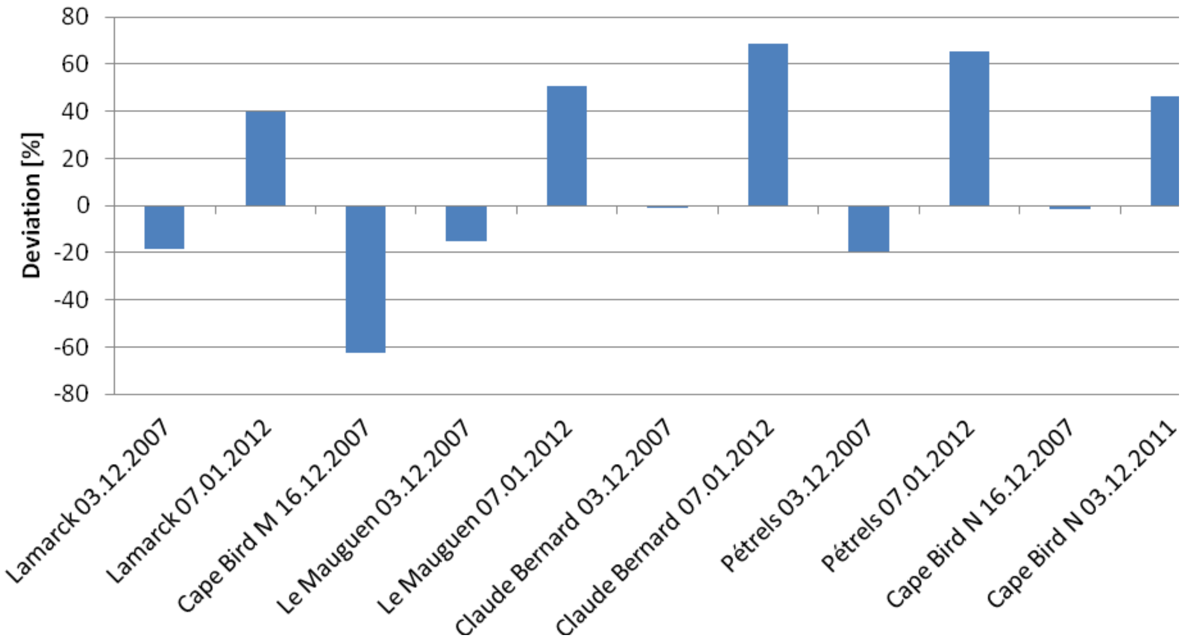


Figure 83: Deviation of colony area determined by supervised classification using cross-regional signature catalogue from the manually determined colony area for individual QuickBird2 images

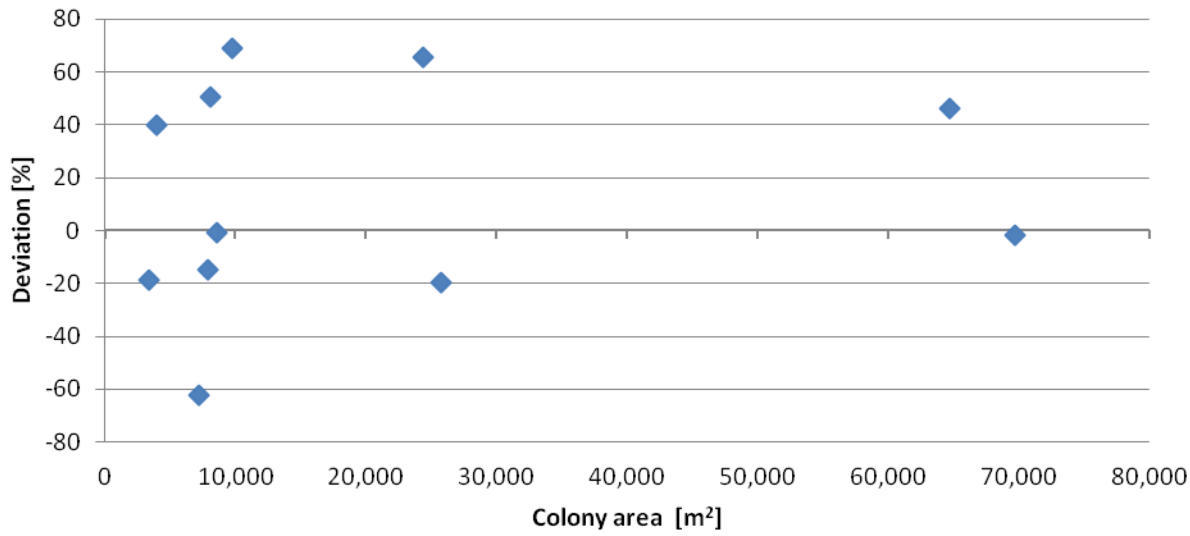


Figure 84: Deviation of colony area classified by supervised classification using cross-regional signature catalogue from the manually determined colony area, sorted according to colony area for QuickBird2 images

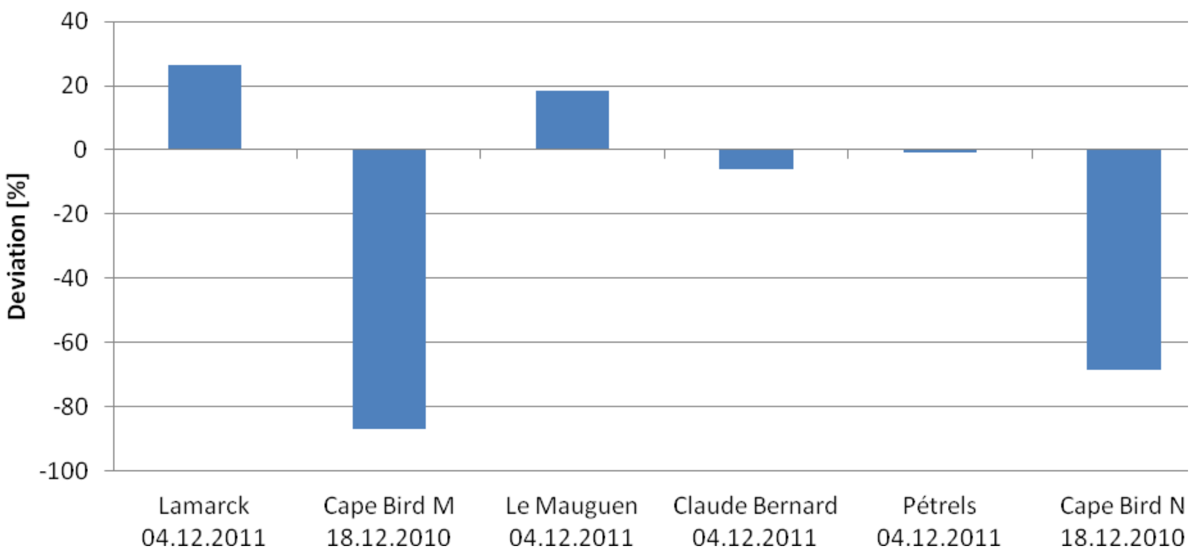


Figure 85: Deviation of colony area determined by supervised classification using cross-regional signature catalogue from the manually determined colony area for individual WorldView2 images

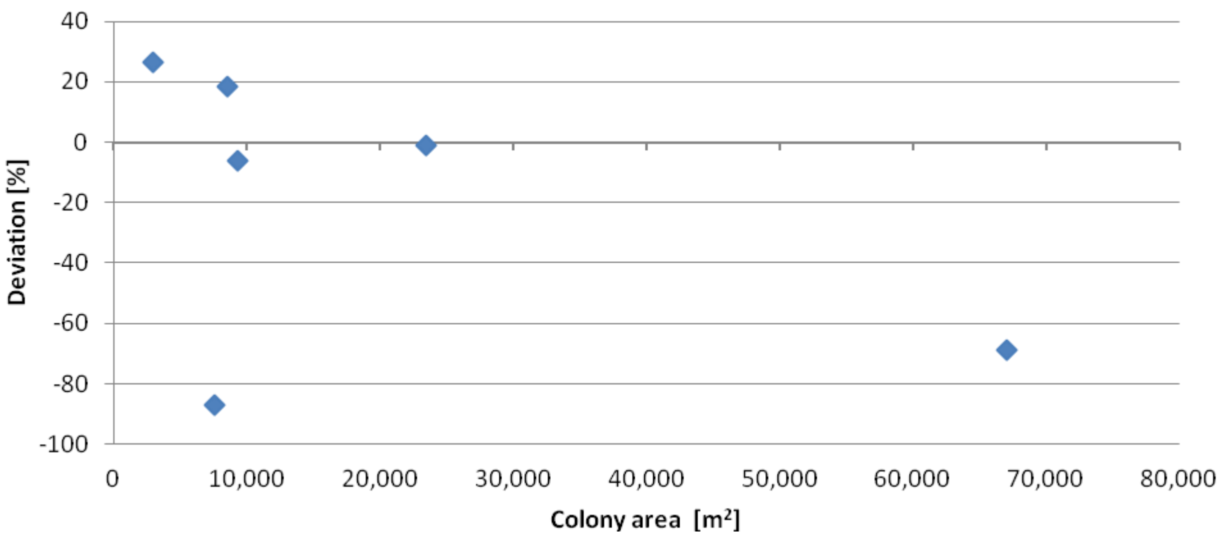


Figure 86: Deviation of colony area classified by supervised classification using cross-regional signature catalogue from the manually determined colony area, sorted according to colony area for WorldView2 images

3.6.2 Ratio approach

A universally valid ratio combination is needed in order to use an automated ratio analysis to detect penguin colonies in different images. This combination must contain ratios with which it is possible to distinguish between guano and the surrounding land cover classes at all desired sites. To find such a universally valid ratio combination with the corresponding threshold value, the minimum and maximum ratios for guano were calculated for all the historical images of each sensor. These were then compared with each other and combined to form a common signature for guano. Figure 87 shows, by way of example, the average ratios for guano of six historical images of Cape Bird. Finally, the minima and maxima of the surrounding land cover classes were used to derive the threshold value for distinguishing the penguin colonies. As with supervised classification, a regionally valid ratio combination was sought which was valid for all the images of a site. Furthermore, a cross-regional ratio combination was sought which could also be used to detect penguin colonies in images from different sites. The largest possible number of images is needed to obtain a ratio combination that is as universally valid as possible.

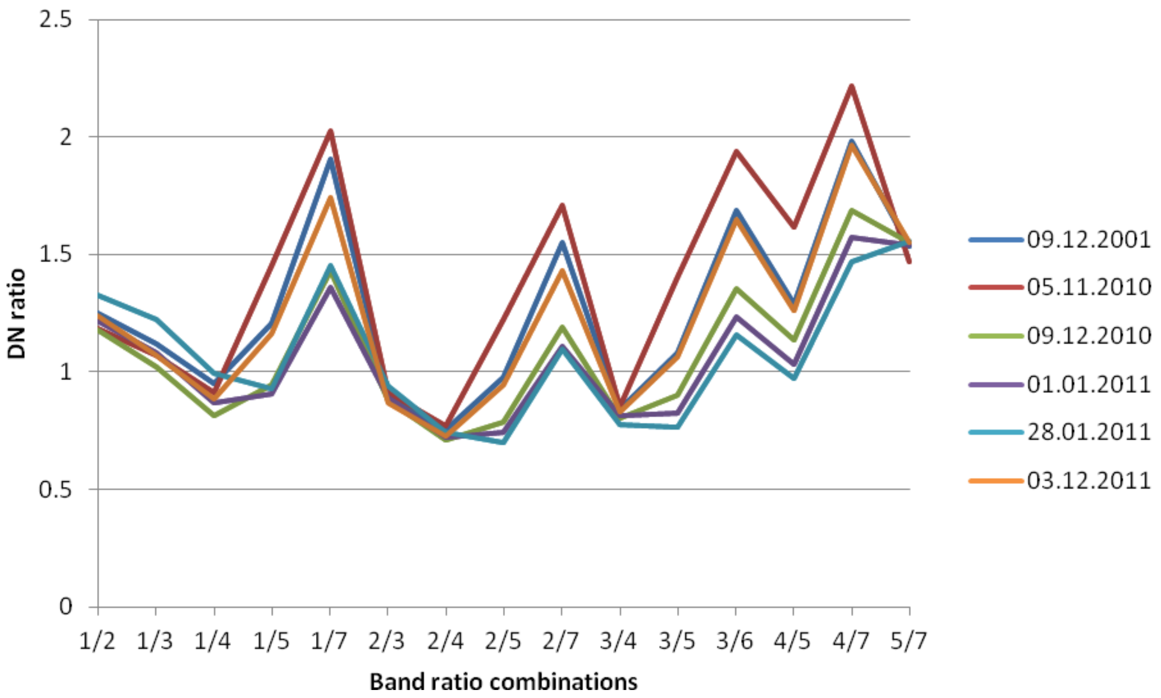


Figure 87: Variability of the average ratios for guano in diverse images of Cape Bird for Landsat7

Landsat7

For the regional and cross-regional analysis of the individual colonies, the same number of images was available as for supervised classification (see Section 3.6.1). As a result, a suitable regional ratio combination could be found for all the colonies under investigation (Cape Bird, Adélie Land and Kopaitic). We also succeeded in distinguishing the penguin colonies in all images using a cross-regional ratio combination. Comparison of the results with manual delineation showed that there were again extreme deviations in some colonies, while others only deviated to a limited extent (Figures 88 and 91). Once again, there was a clear reduction in deviation as colony area increased in size.

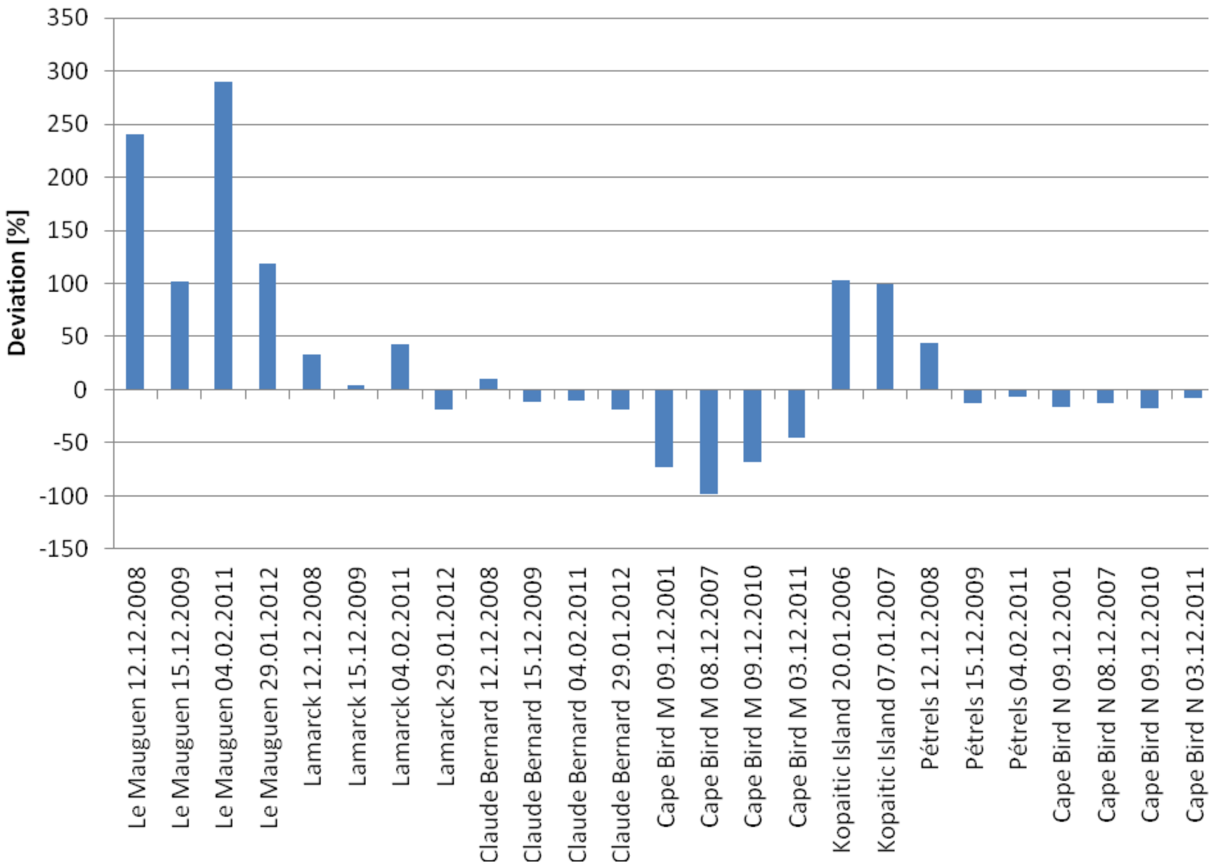


Figure 88: Deviation of colony area classified using regional ratio combination from the manually determined colony area for individual Landsat7 images

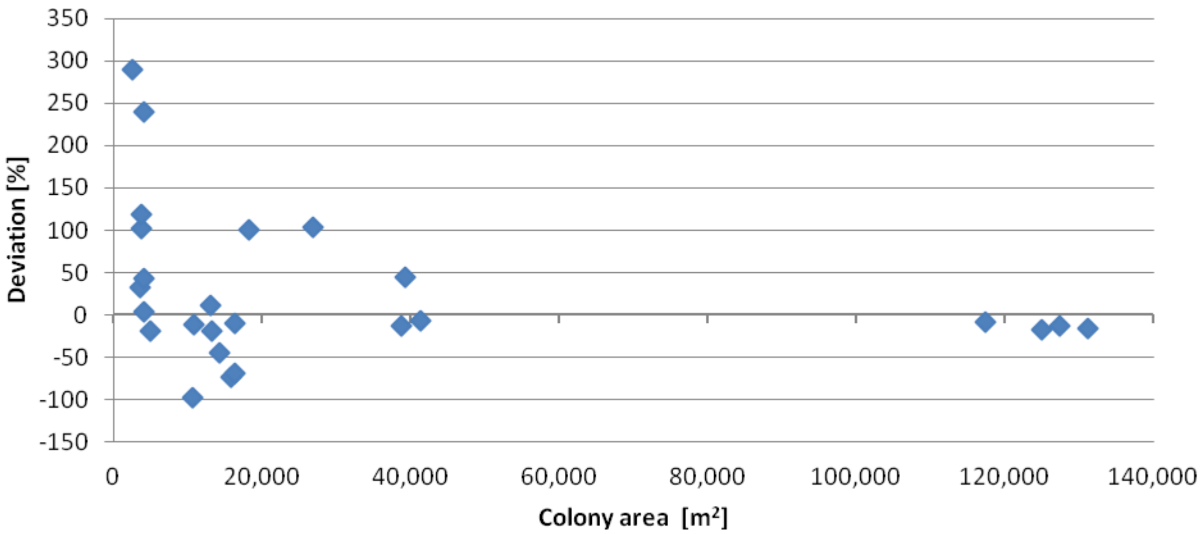


Figure 89: Deviation of colony area classified using regional ratio combination from the manually determined colony, sorted according to colony area for Landsat7 images

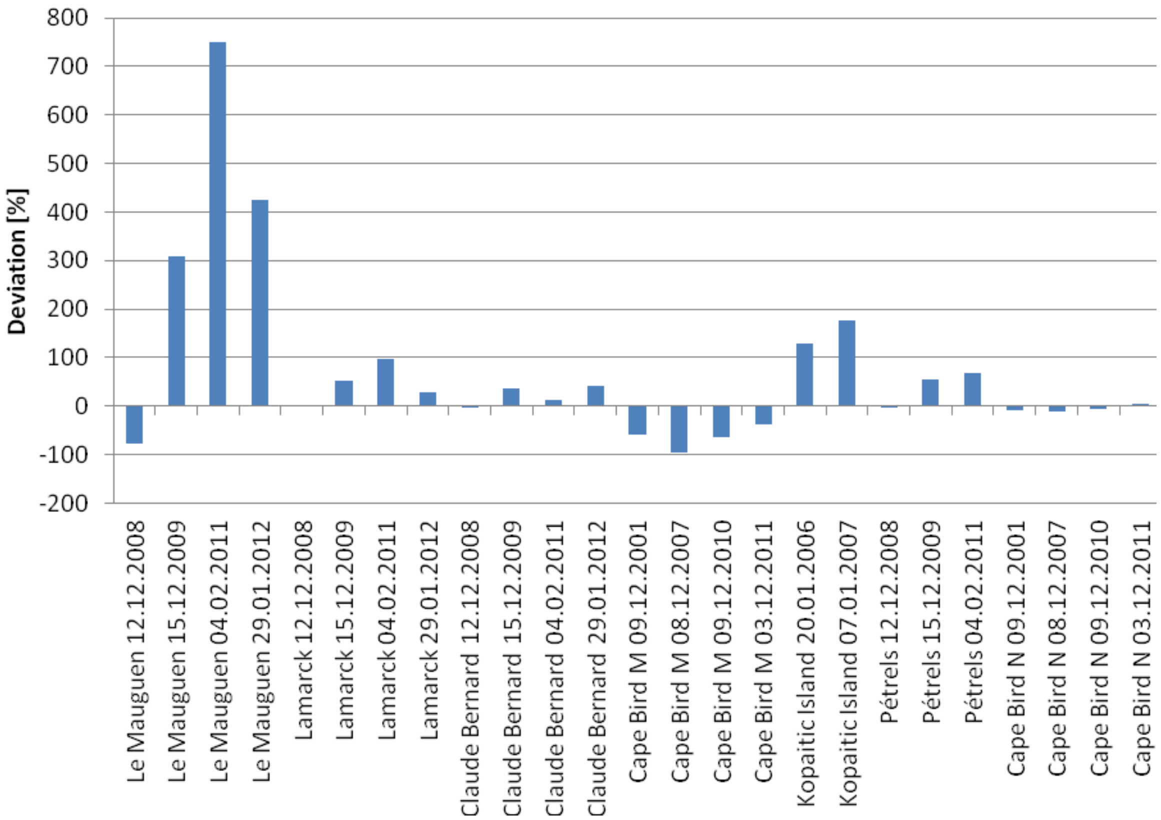


Figure 90: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area for individual Landsat7 images

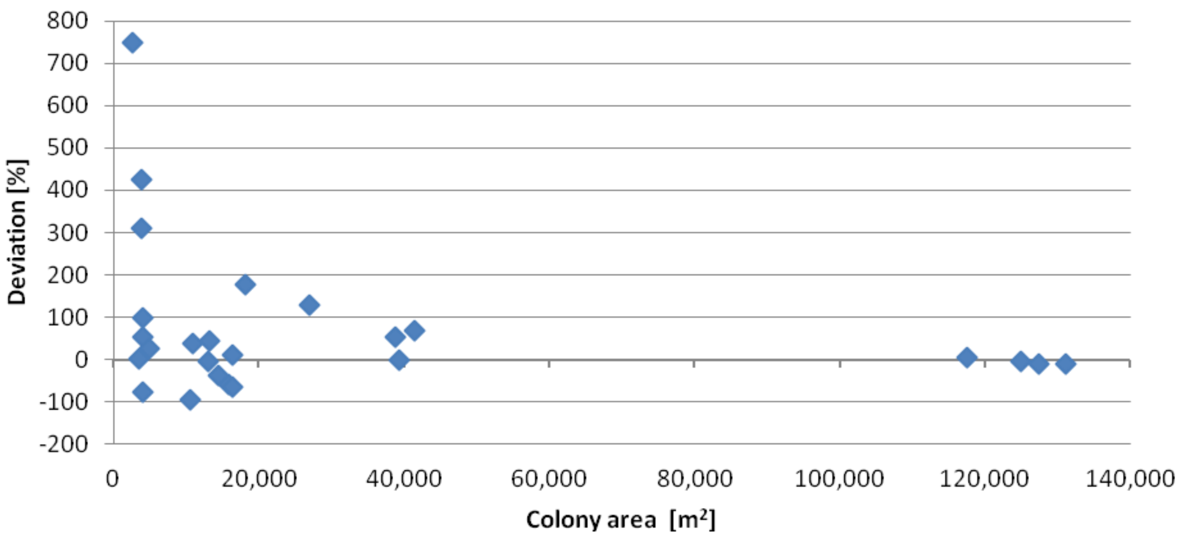


Figure 91: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area, sorted according to colony area for Landsat7 images

QuickBird2 & WorldView2

As with the supervised classification (see Section 3.6.1), the analysis of the QuickBird2 and WorldView2 images faced the problem that there were only at most two images of the same colony. For this reason each QuickBird2 image was classified only with the ratio combination of the second image available for the same colony. No regional analysis was possible for WorldView2 due to a lack of historical images. The analysis for Ardley, Point Thomas and Torgersen provided no usable results because the differences between the images were too great and the ratios that had been specially determined to fit the individual images gave unsatisfactory results (see Section 3.2.3). Figure 92 gives the results of the regional ratio analysis for Cape Bird and Adélie Land. These show only moderate deviations from manual delineation and there is no correlation between colony area and deviation (Figure 93).

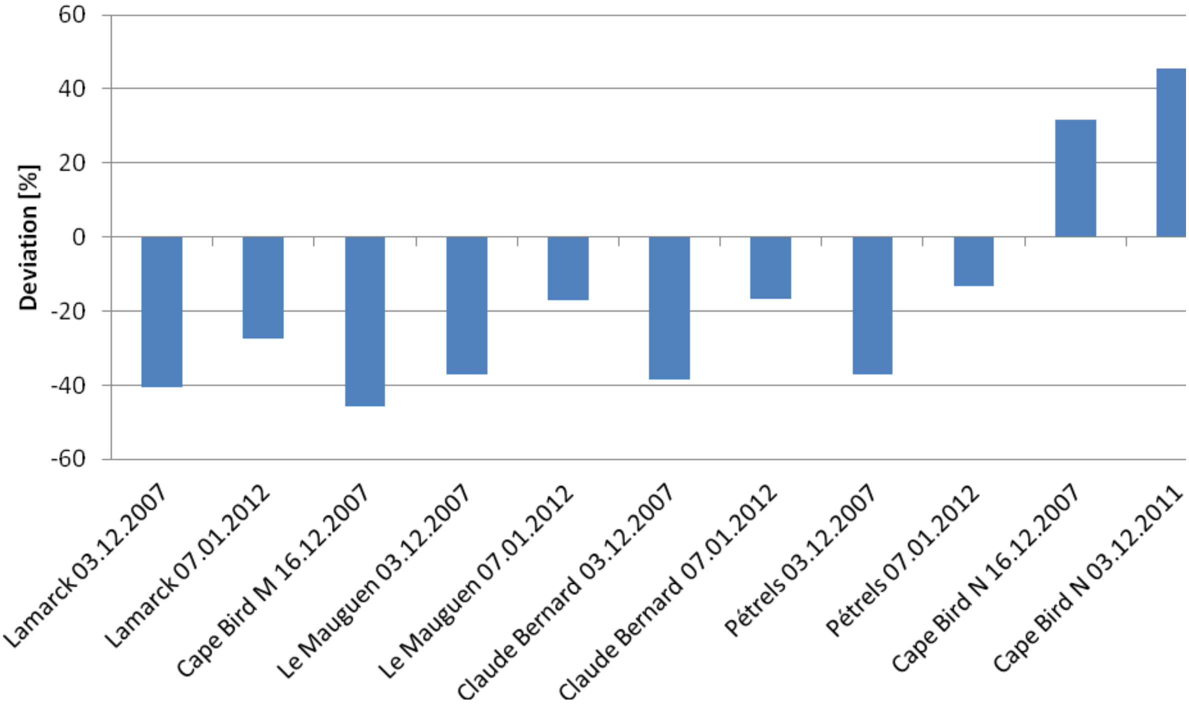


Figure 92: Deviation of colony area classified using regional ratio combination from the manually determined colony area for individual Quickbird2 images

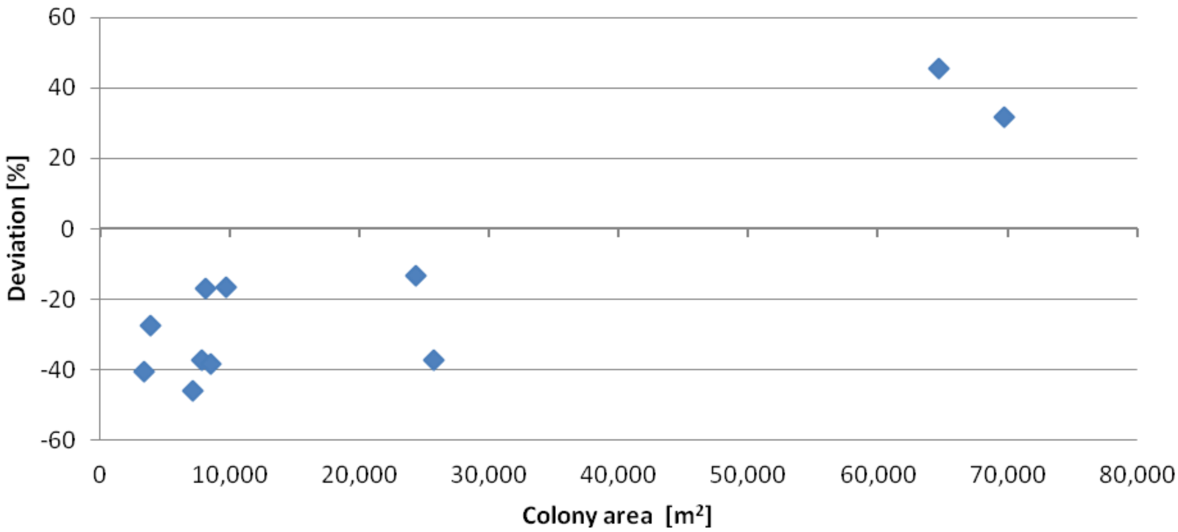


Figure 93: Deviation of colony area classified using regional ratio combination from the manually determined colony, sorted according to colony area for Quickbird2 images

No cross-regional ratio combination could be found that provided usable results for all available QuickBird2 and WorldView2 images, because the differences between the images were too great. The only cross-regional ratio combination that it was possible to analyse was between the images of Cape Bird and Adélie Land. Deviations were relatively small (Figures 94 and 97). As with all the other investigations with these sensors, there was no correlation between deviation and colony area.

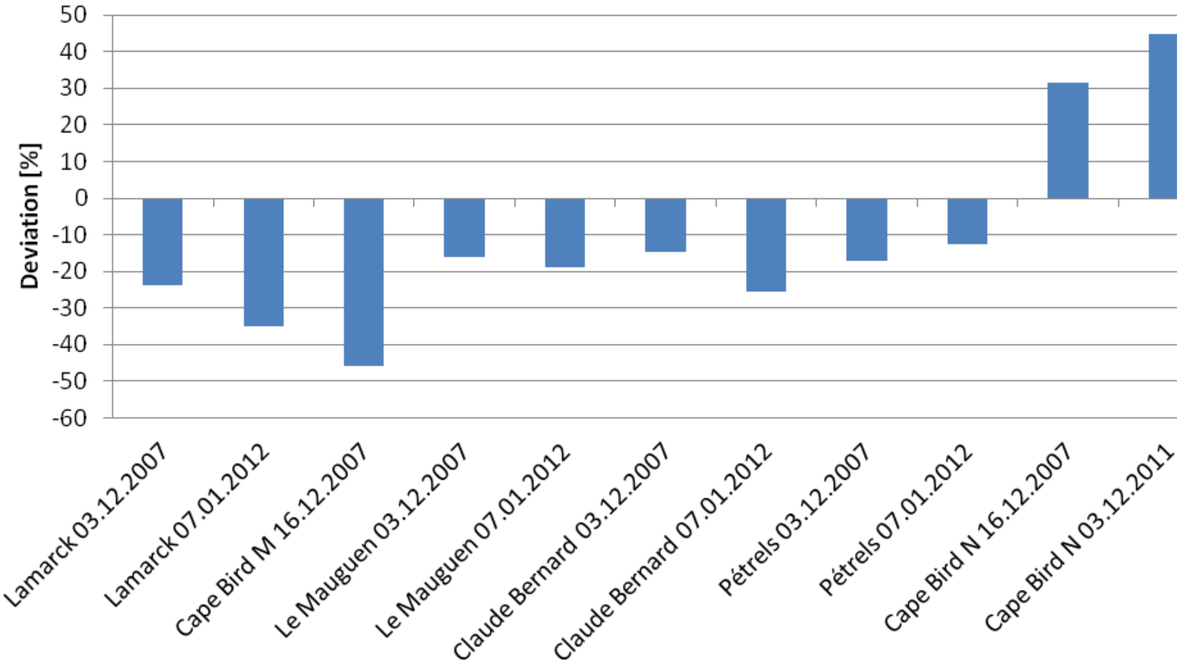


Figure 94: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area for individual Quickbird2 images

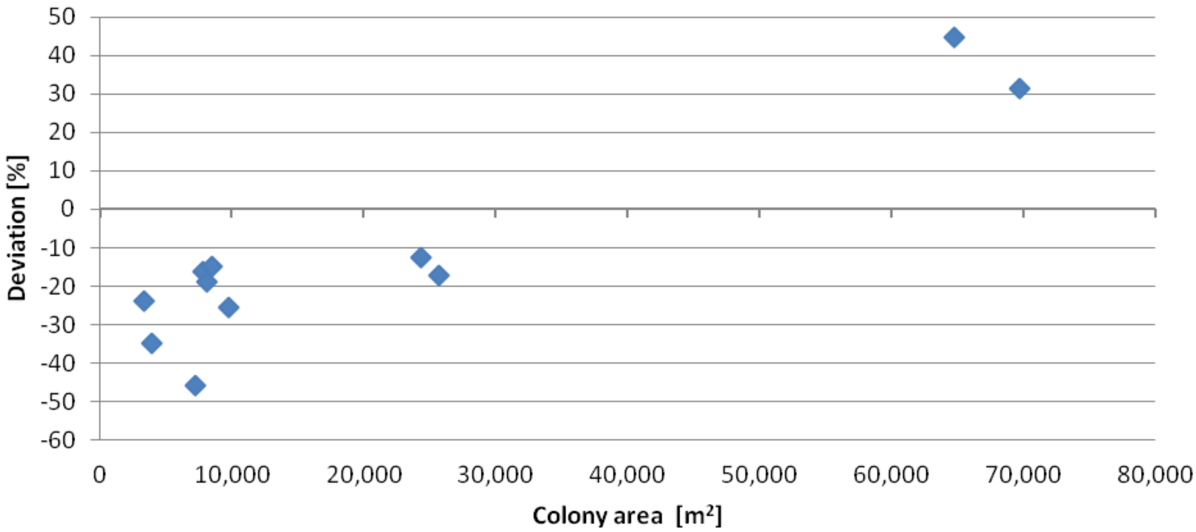


Figure 95: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area, sorted according to colony area for Quickbird2 images

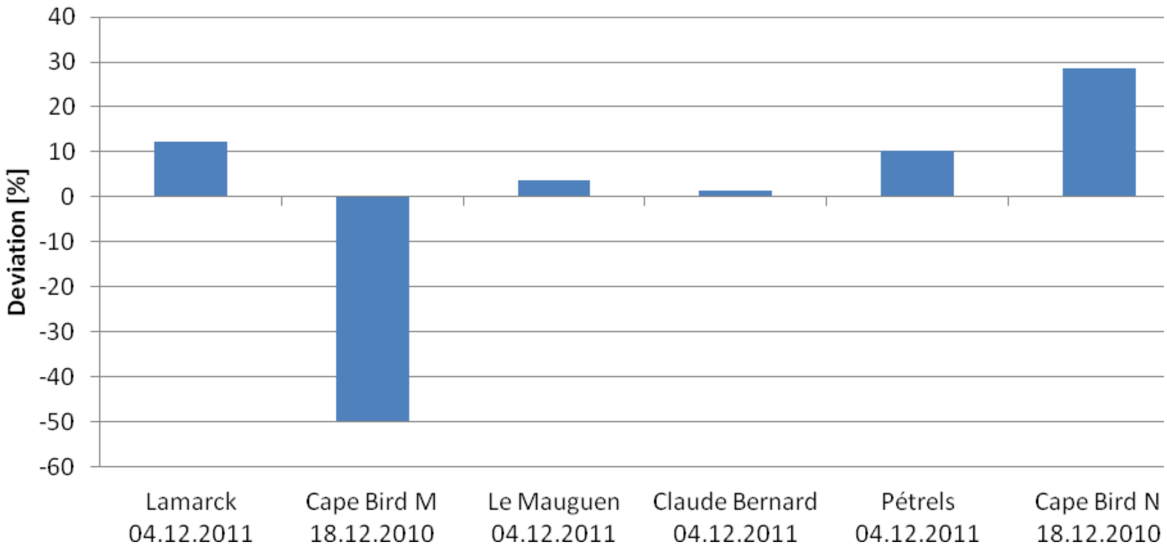


Figure 96: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area for individual WorldView2 images

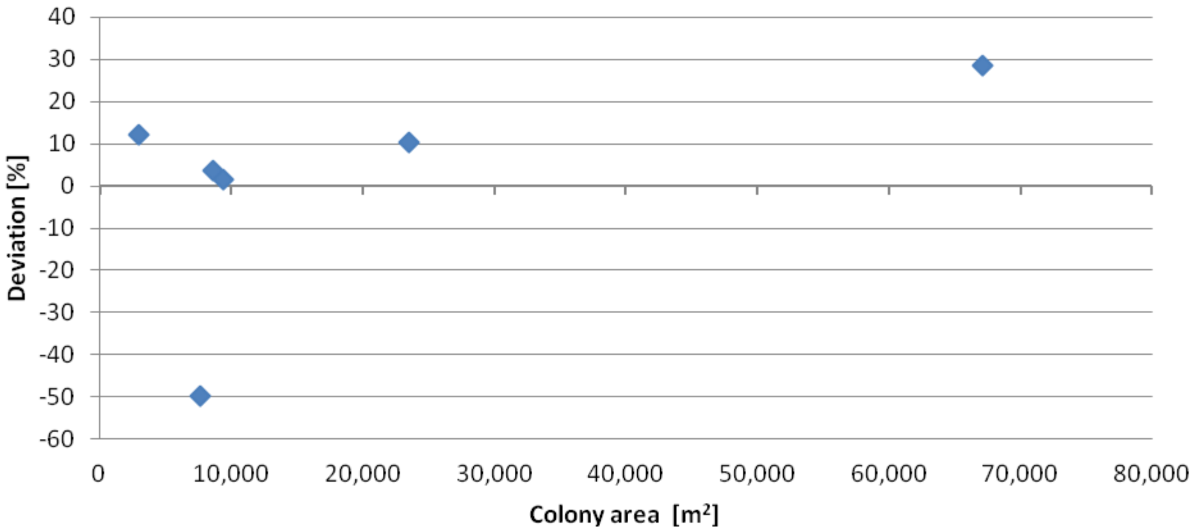


Figure 97: Deviation of colony area classified using cross-regional ratio combination from the manually determined colony area, sorted according to colony area for WorldView2 images

3.7 Possibility of automating radar data analysis

We were unable to detect penguin colonies of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins) using TerraSAR-X SAR data, so that the question of automation does not arise. A larger body of data is necessary to reach a conclusion regarding the possibility of automating the analysis process for the species *A. forsteri* (emperor penguin). However, the analysis of further SAR images is only planned for the coming Antarctic winter during the emperor penguin breeding season.

4 Synthesis of the investigations

4.1 Assessment of the possibilities and limitations of the diverse image recording systems

The possibilities and limitations of the individual image recording systems were determined on the one hand by their availability and on the other hand by their ability to detect penguins or guano.

4.1.1 Availability

For the Antarctic, the availability of usable optical satellite data is restricted mainly by weather conditions and the lack of light during the Antarctic winter. Particularly in the northern part of the Antarctic Peninsula, the most important factor that limits availability is the frequent cloud cover (Figure 4). In contrast, in the continental coastal areas, weather conditions are much more suitable for obtaining optical images. Images taken shortly before or shortly after the Antarctic winter have the disadvantage that, depending on the topography of the site, they are likely to contain hard shadows and this makes any analysis more difficult, or even impossible.

Landsat7

The Landsat7 platform has the advantage that the images are available to anyone promptly and without cost. There is comprehensive spatial coverage of the Antarctic coastal areas. In addition, there are incomplete but free archive data available for Landsat7 going back to 1999 and for Landsat4 going back to 1982. Landsat7 only flies over the same spot every 16 days. However, in theory the temporal coverage by Landsat7 is greater because the edges of the image swaths overlap. This overlapping increases towards the South Pole, so that the more southerly colonies are theoretically recorded more often. However, the Scan Line Corrector Failure (NASA 2011), that effects all Landsat7 images after 2003, becomes increasingly large towards the edge of the image. This results in images where a colony is at the edge being only very rarely usable, which again greatly restricts availability. In practice, this means that in some years, where bad weather conditions are more frequent, there may be no usable images, or only images that are hard to analyse, during the period from December to February, which is normally the ideal time for detecting colonies of rock-breeding penguins. In our experience, for instance, there are four times as many usable images per season for Cape Bird than for the more northern Ardley Island.

WorldView1, WorldView2 & QuickBird2

In contrast to Landsat7, these satellites only record images of the Antarctic to order. Although they face the same restrictions such as weather and lack of daylight, due to their swivelling sensor they achieve much greater coverage, taking many more images in a short period. Thus, even limited periods with cloud-free skies can be used to obtain images. Even so, it is possible that, in a particular season, no usable images of certain colonies can be made. Due to weather conditions, it was not possible to obtain any images of Ardley und Torgersen Island for the 2011/2012 season, although over a period of just under two months these colonies were overflown a number of times by WorldView1, WorldView2 and QuickBird2. There are a lot of gaps in the records of historical images, both in time and place. In practice this means that for some penguin colonies there are no historical data available at all. Another disadvantage is the relatively high purchase cost (at least 1,800 US$ per current image).

4.1.2 Detectability

Detectability is linked to the spectral and spatial resolution of the sensor and to the methods employed in each case. Therefore, we give a summary below of these two aspects. Subpixel analysis provided no usable results and for this reason it is not discussed further. No penguin colonies of the species *P. papua*, *P. antarctica* and *P. adliae* (gentoo, chinstrap and Adélie penguins) could be detected by means of TerraSAR-X SAR data.

Landsat7

The analysis of the Landsat7 images showed that not all penguin colonies studied could be detected equally easily. For colonies to be detectable with certainty, the area of the colony covered with guano had to measure at least 3,000m^2 and contain more than 1,000–5,000 occupied nests (Figure 98). A further decisive factor was the density of nest groups within the colony. If the individual nest groups were spread over a wide area, as on Ardley Island, then detection was impossible. Thus, colonies with a density lower than 0.12 occupied nests per m^2 of the occupied colony sector (the area bounded by nest groups) could not be detected by Landsat7 (Table 13). The shape of the colony and the classes of land cover surrounding it also influenced detectability, especially if the above-mentioned parameters were around the minimum values given. Colonies with the same area and number of nests were easier to detect with Landsat7 if they were compact (e.g. Lamarck Island) than if they were long and sinuous in form. Colonies situated on ground that offered a strong contrast (e.g. dark volcanic rock on Cape Bird) were significantly easier to detect than colonies where the area was partly covered with or surrounded by vegetation, which is spectrally similar to guano (e.g. Point Thomas). It was not possible to distinguish between different rock-breeding penguin species with the Landsat7 images.

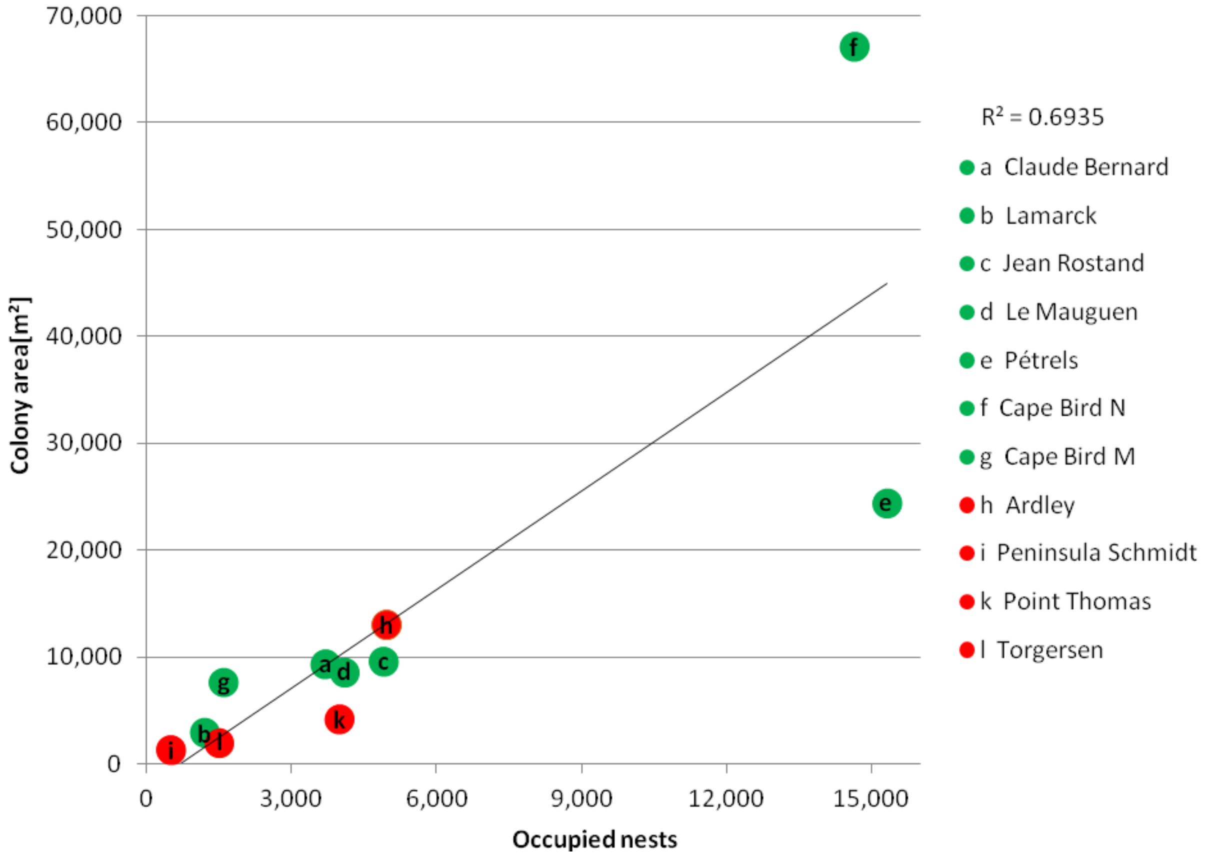


Figure 98: Relationship between colony area and number of occupied nests - Green = visible, Red = not visible, and linear correlation gradient with $R^2 = 0.693$

Table 13: Density expressed in occupied nests per m² of occupied sector of the colony area for Landsat7 - Green = visible, Red = not visible

Colony	Density of occupied colony sector [nests / m²]
a Claude Bernard	0.18
b Lamarck	0.19
c Jean Rostand	0.23
d Le Mauguen	0.18
e Pétrels	0.24
f Cape Bird N	0.27
g Cape Bird M	0.23
h Ardley	0.08
i Schmidt Peninsula	0.04
k Point Thomas	0.30
l Torgersen	0.12

Due to the restrictions mentioned above, we only succeeded in detecting the colonies of Cape Bird, Adélie Land and Kopaitic Island. Experience gained from the analyses showed that manual delineation provided the best results on colony area. The drawback of manual delineation is, among other things, that it is very time-consuming if large areas need to be examined. However, as the colonies are all relatively small in relation to the resolution of Landsat7, time was not an important factor. On the contrary, manual delineation was the fastest method for analysing individual images. One disadvantage was that manual interpretation is very subjective and it was possible for colony boundaries to be interpreted very differently by different individuals.

We were also able to detect penguin colonies using supervised classification and the ratio approach. Figures 99 and 100 show the results obtained with both methods, giving the percentage deviations of colony areas determined through classification from manually determined colony areas. Manual delineation was chosen as the benchmark for the quality of results. It can be seen that the results of area determination vary greatly between the individual colonies. The extreme deviations for Le Mauguen can be attributed to the specific distribution of nest groups in the island colony. The colony consists of a large, compact nest group in the north and many small groups spread over a wide area in the south. Manual delineation only detected the clearly recognisable northern part, whereas pixel-based classification methods (supervised classification and ratio approach) also picked up parts of the southern colony. It can also be seen that the classification results of both methods worsen considerably in line with a decline in colony area (Figure 100). The minimum threshold of the colony area for results that can still be used for a quantitative analysis is around 40,000m^2. Altogether, both methods gave comparable results.

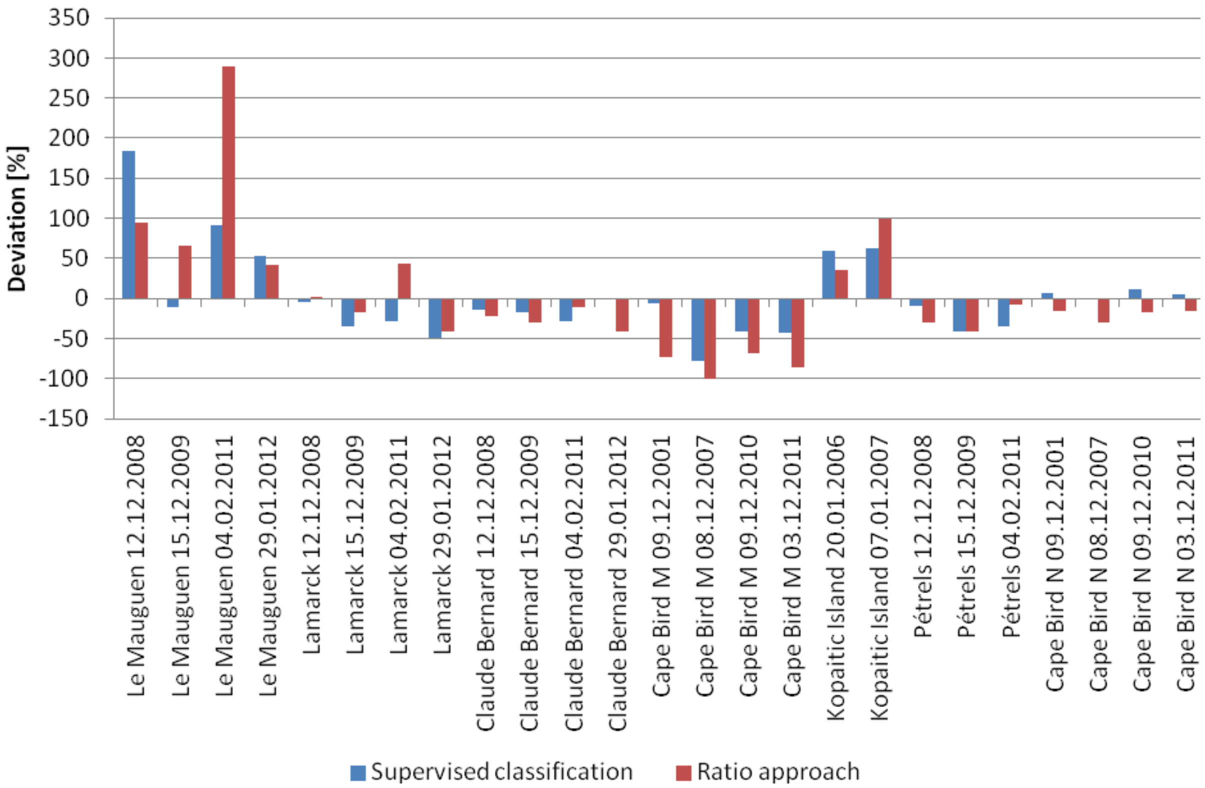


Figure 99: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, for individual Landsat7 images

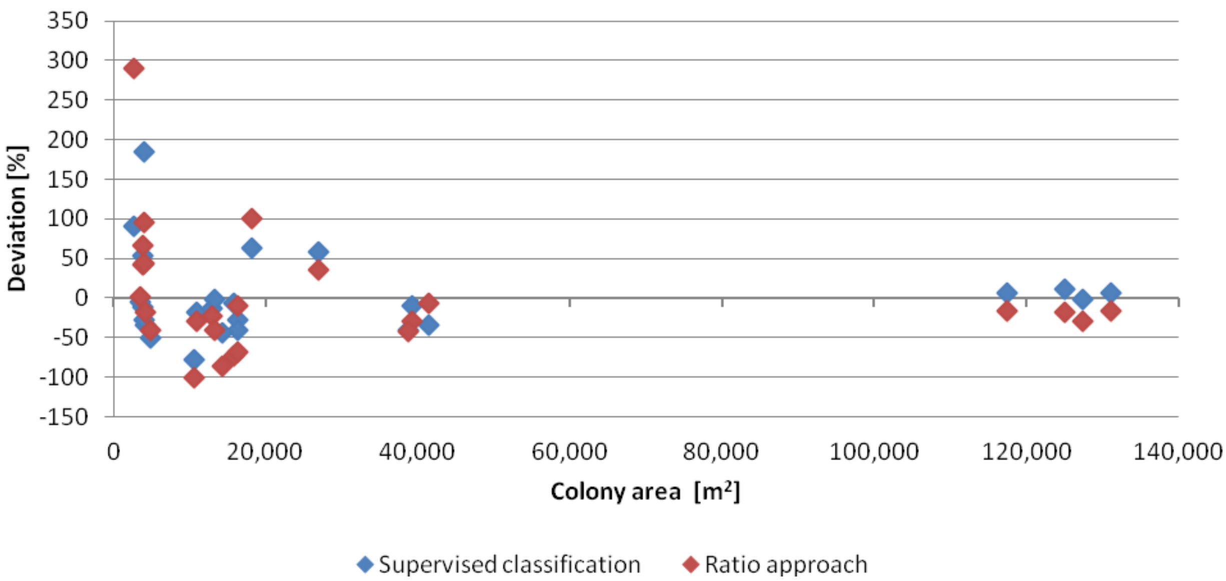


Figure 100: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, sorted according to colony area for Landsat7 image

WorldView1

The analysis of the panchromatic WorldView1 images showed that it is relatively difficult to detect penguin colonies on rocky surfaces and that it is only possible at all under certain conditions. The approximate location and size of the colony to be detected must be known and its brightness value must be clearly distinguishable from its surroundings. Only manual image interpretation was able to give usable results under these special conditions.

QuickBird2 & WorldView2

For QuickBird2 and WorldView2, no minimum threshold could be found for the detectability of colonies or their nest groups. In fact, we detected all the colonies, including the smallest. With the help of manual image interpretation, we were even able to recognise single nests and larger groups of penguins. However, despite the high spatial resolution of 50-60cm, no single penguins standing on rocks were detectable. There were problems above all with images taken at the start of the breeding season and in which the colony was under a considerable covering of snow. On the one hand, snow covered the lower-lying potential nesting places and on the other hand, it can be assumed that at the beginning of the breeding season insufficient guano had accumulated to be detectable.

Figures 101 to 104 compare the results of supervised classification with those of the ratio approach. It was also possible to detect all colonies with these methods, though with significant variations in quality between the individual images. The largest variations were in snow-covered images (Torgersen 2007 and Ardley Island 2009), and also those with mist (Point Thomas 2011). The apparent increase in deviation accompanying a decline in colony area in the QuickBird2 images in Figure 102 can be ascribed to the fact that 5 of 11 QuickBird2 images were not made under optimum conditions. In contrast, the four WorldView2 images were made under the best possible conditions. No correlation can be seen between deviation and colony area (Figure 104). If this is taken into account, no qualitative differences can be seen between the QuickBird2 and WorldView2 images. It can also be recognised that supervised classification gives better results under bad conditions than the ratio approach.

With the QuickBird2 and WorldView2 images no definitive distinction between penguin species could be made. Only at the colony near the Pieter J. Lenie Field Station was it possible to surmise that Adélie penguin nests in an area otherwise dominated by gentoo penguins could be distinguished. Due to a lack of up-to-date count data and mapping data, it was not possible to reach a definitive conclusion as to whether these really were Adélie penguins.

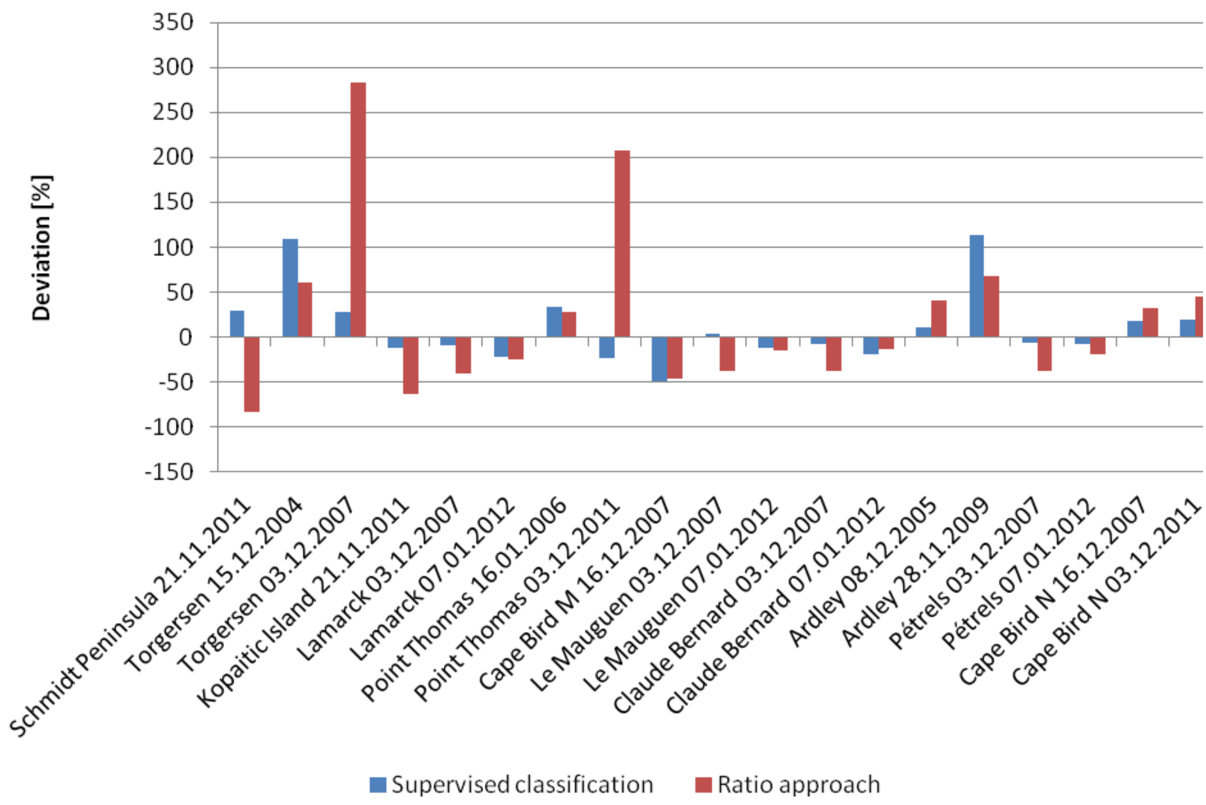


Figure 101: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, for individual QuickBird2 images

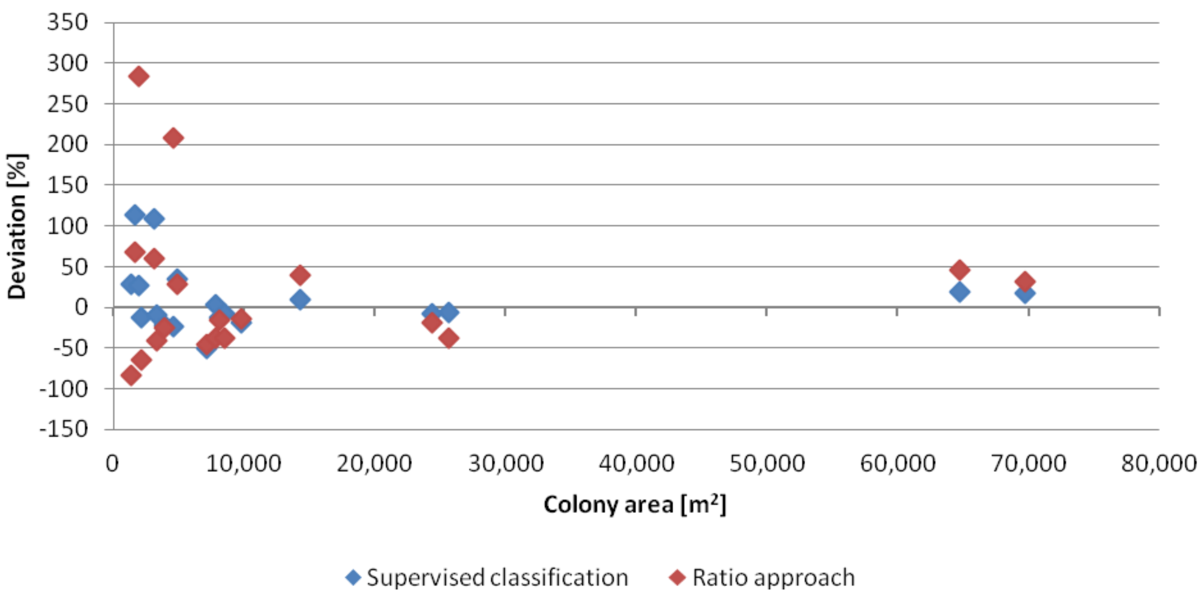


Figure 102: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, sorted according to colony area for QuickBird2 images

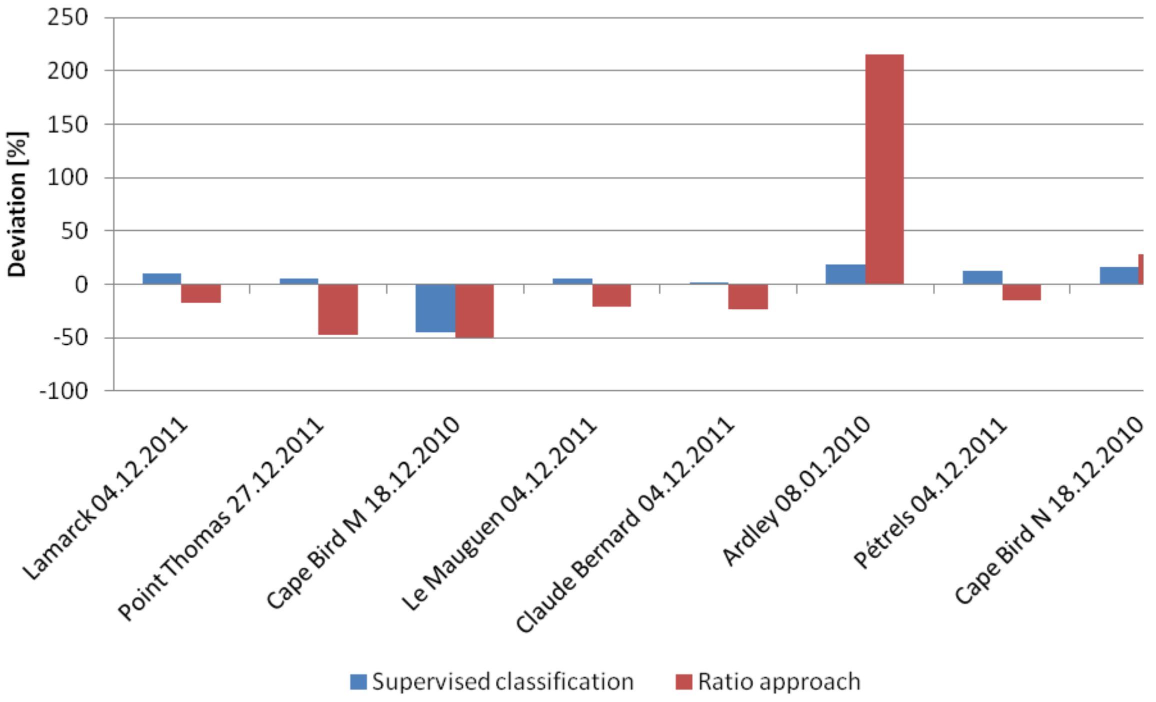


Figure 103: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, for individual WorldView2 images

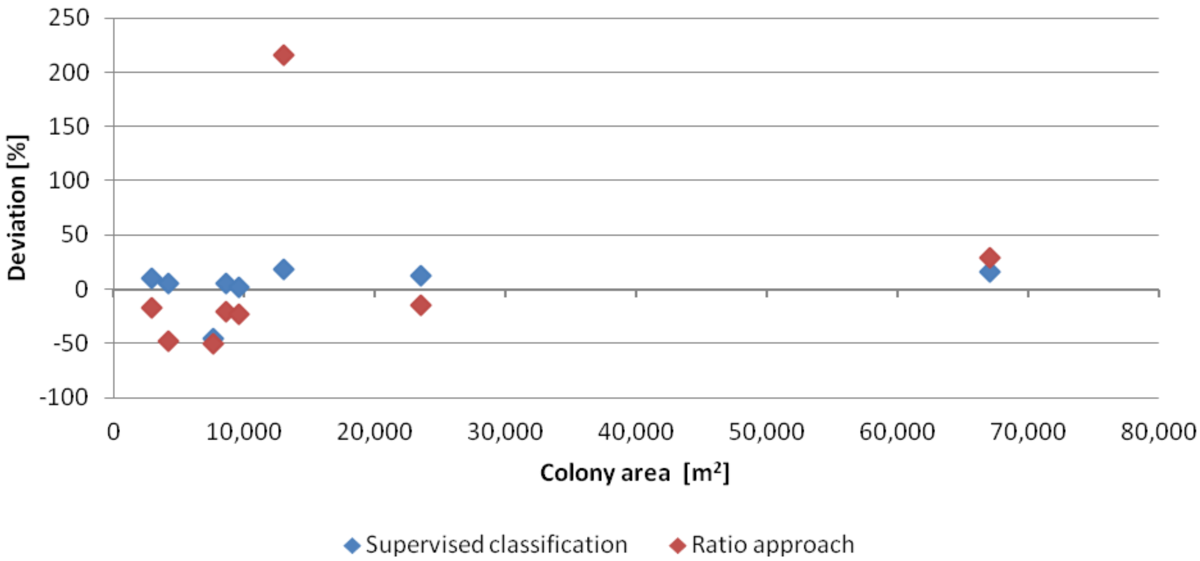


Figure 104: Comparison between deviation of colony area determined by supervised classification and deviation of colony area classified using ratios, both in relation to manually determined colony area, sorted according to colony area for WorldView2 images

If all the results from QuickBird2 and WorldView2 images are compared, it becomes clear that the images from WorldView2, with a maximum 10cm higher spatial resolution and equipped with four additional spectral bands, had no significant advantage over the QuickBird2 images when it came to detecting penguin colonies. The difference in the maximum spatial resolution is qualified in practice by the fact that an increase of 20° (max. 45° possible) in the off-nadir angle (look angle) results in a worsening of the spatial resolution of approximately 10%. High off-nadir angles must be accepted if high temporal coverage of the colonies are to be achieved. The additional multispectral bands also offered no advantages in practice, because they are all in the visible spectrum or the near-infrared region where the reflection of guano does not differ significantly from that of the land cover classes that are to be distinguished.

4.2 Assessment of the detectability of changes in colonies

In order to detect changes between different seasons, we first had to determine the extent of changes in the detectable area over one year. We needed to exclude the possibility that area changes detected in images from different years might be attributable to variability within a single year. We were then able to investigate whether, and to what extent, it was possible to detect changes in the size of those parts of the colony that are covered with guano. Based on these results, we were able to analyse whether there is any correlation between changes in area detected and changes in the number of breeding pairs from one season to another.

4.2.1 Area changes in the course of a season

Four Landsat7 images of Cape Bird (2010/2011 season) and three of Adélie Land (2008/2009 season) were available to use as examples for detecting area changes within a season. For both sites it was established that the detectable area increased towards the end of the season and, in the case of Cape Bird, the area decreased again after the actual breeding season. It is assumed that one reason for this is an increasing accumulation of guano during the course of the breeding season. Another reason is that there is usually snow on the ground in images from the start of the season and this snow covers the lower lying breeding sites. The maximum area changes within one season for each colony are listed in Table 14. With all methods, the changes measured are relatively large, although the changes detected by manual interpretation are the smallest. It is also noteworthy that only in the case of Cape Bird N were moderate changes recorded for all methods. With Landsat7 it appeared that for large colonies, area changes from one year to another could only be detected by manual interpretation if they were greater than 13% and with supervised classification or the ratio approach if they were greater than 17%. In contrast, in the smaller colonies only changes of between 20% and 105% could be detected, which raises doubts about the practical use of such methods for detecting changes in small colonies with Landsat7 images. However, as this analysis only considered one season and two colonies, the results are not representative and should be tested with additional time series analyses.

Table 14: Maximum area change measured within one season for Landsat7

	Claude Bernard [%]	Lamarck [%]	Le Mauguen [%]	Pétrels [%]	Cape Bird N [%]	Cape Bird M [%]
Manual image interpretation	11	17	24	3	13	67
Supervised classification	20	47	76	55	17	23
Ratio approach	40	69	34	39	16	105

4.2.2 Detectability of changes in the number of breeding pairs

The basis assumption for detecting changes in the number of occupied nests is that they correlate with area changes in the colonies. This roundabout way using area change is necessary as individual penguins brooding on rocks cannot be comprehensively detected with any certainty. For this reason the area changes detected in Landsat7 and QuickBird2 images from different years were compared with changes in numbers of occupied nests. As the only ground-based area and population measurements available were those of Ardley Island that corresponded to a QuickBird2 image from the 2005/2006 season, the area changes measured could not be verified but could only be evaluated as to their plausibility. No usable results on changes in penguin colonies could be obtained using multitemporal analysis of a number of consecutive SAR images, with the same imaging geometry, of Ardley Island, Point Thomas and Kopaitic Island/Schmidt Peninsula (colonies of the species *P. papua*, *P. antarctica* and *P. adeliae*).

Landsat7

For Adélie Land, we examined the differences between four Landsat7 images from different seasons and for Cape Bird we compared two Landsat7 images. The analyses of the Adélie Land and Cape Bird M colonies gave predominantly implausible results. The reason for this can be found in the limited spatial resolution of Landsat7 and the small size of the colonies. The implausible area changes detected are too strongly influenced by the imprecision resulting from the methods used rather than being the result of actual changes in colony area. In contrast, for the large Cape Bird N colony it was established that there was no correlation between area change and a change in the number of occupied nests. In the period from 2001 to 2007, the absolute number of occupied nests doubled, but no significant change in colony area was recorded. This is probably because there is first an increase in density of the nest groups and only when all the best nesting sites are taken and penguins have to seek space elsewhere is there an increase in area (Mustafa et al. 2005). Thus, it is only when a specific threshold value has been exceeded that the colony increases in area. Woehler and Riddle (1998) have shown that nest density can vary greatly, from 0.1 to 3.1 breeding pairs per m^2.

The results of area measurements using supervised classification and the ratio method deviated significantly from those obtained by manual determination (50-80%), with the result that in practice, with these methods, only very large area changes could be detected with certainty.

QuickBird2 & WorldView2

Multitemporal analysis for QuickBird2 images was possible for three colonies at each of two different dates. With manual interpretation of Adélie Land images it was only when there were large changes in area (>26%) and large changes in the number of occupied nests (>15 %) that a correlation could be established between the two. On the one hand, this could be because small changes in area could not be detected due to the imprecision of measurements with this method. On the other hand, it could also mean that changes in area only occur once a specific increase in the density of occupied nests per m^2 has been reached. For Ardley Island, however, no correlation could be established (*cf.* Mustafa et al. 2005). For Torgersen Island it was not absolutely clear whether the correlation we found could be ascribed to actual area changes or was due to factors related to the images. It was possible to establish, without any doubt, a decrease in area at Point Thomas and an increase near the Pieter J. Lenie Field Station situated a few kilometres south of Point Thomas. Due to a lack of count data, we could not reach any conclusion regarding a correlation with a possible change in the number of occupied nests. The investigations of Cape Bird N supported the observations made with Landsat7 because no area change could be measured with the QuickBird2 images either. However, there were also no count data of occupied nests for these QuickBird2 images.

Also with the QuickBird2 images, supervised classification and the ratio analysis produced relatively large deviations from manual determination. Supervised classification, with a maximum deviation of 27%, gave significantly more accurate results than the ratio analysis with its maximum deviation of 45% from manual delineation.

WorldView1

Due to the absence of historical images, we could not reach any clear conclusions on the suitability of WorldView1 images for change analysis. However, examination of the individual images and the results of Guinet et al. (1995) indicate that changes in colony area can be detected using panchromatic images provided that the approximate area is known *a priori* and the colony is situated on a substrate that offers a strong contrast.

4.3 Assessment of the efficiency of the method and the possibility of automation

The possibility of automation of analysis was tested for supervised classification and ratio analysis for Landsat7, QuickBird2 and WorldView2. To this end, regional (matched to colonies from one region with similar land cover classes) and cross-regional (matched to all colonies of different regions) signature catalogues and ratio combinations were created in each case and tested with supervised classification and ratio analysis. The question of automation does not arise with TerraSAR-X SAR data because using these data we were unable to detect penguin colonies of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins).

Landsat7

There were only enough images available from Landsat7 to test automation of the analysis methods adequately. We were able to use a total of seven images to create regional signature catalogues and up to 15 images to create cross-regional signature catalogues or ratio combinations. This is important as the automated analysis methods applied in this project require the broadest possible range of spectral variations of the land cover classes that occur in the images.

Both supervised classification and ratio analysis provided usable results for all the colonies tested. The colonies were detected on all the images of Cape Bird, Adélie Land and Kopaitic Island. In this process, it made no difference whether regional or cross-regional analyses were carried out. The quality of both analysis methods depended greatly on the area size of the colonies to be detected. Thus, once again it was only with Cape Bird N that the deviations from manual delineation were so small that minor changes in colony area could be detected with certainty. It was not possible to test detectability in the vicinity of sites with large areas of vegetation. The problems in detecting the Point Thomas colony suggest that vegetation near colonies can hamper automation. Vegetation is also an important factor in differentiating between the two analysis methods. In one test the ratio approach failed to distinguish between guano from Cape Bird and the vegetation of Point Thomas. In contrast, our experiences using supervised classification in this project indicated that such a distinction is possible. When the cross-regional signature catalogue created using the images from Cape Bird, Adélie Land and Kopaitic Island was applied to King George Island, the results were not promising. In principle, however, the Antarctic lends itself to automation due to the comparatively limited variability of the land cover classes. For test purposes, therefore, further images of the Cape Bird region, which had not previously been examined, were classified with the cross-regional signature catalogue using supervised classification and ratio analysis. As a result, two further colonies were detected – on Beaufort Island and Cape Crozier – which were previously unknown to the person processing the images. However, the process also highlighted the problem of false classifications, as the ratio method falsely classified light-toned stone as guano in the Antarctic Dry Valleys. In order to minimise such errors, it would be sensible to classify only the coastal strips and islands, rather than the totality of the Landsat7 images.

QuickBird2 & WorldView2

For the assessment of QuickBird2 there were only at most two images of the same colony available and, for WorldView2, only one. As a result, we were unable to carry out a conclusive regional analysis using supervised classification and ratio analysis. For the cross-regional analysis there were also too few images recorded under comparable conditions for us to reach a definitive conclusion regarding the possibility of automation. The analyses performed in spite of this problem showed that automated analyses seem to be possible, at least for the images of Cape Bird and Adélie Land. In contrast, an automated ratio analysis of Ardley and Torgersen Island can be completely ruled out because at those sites guano could not be distinguished from other land cover classes without significant false classifications. In summary, it appears much more difficult to achieve automation with the methods tested in this project when using QuickBird2 and WorldView2 images than with the Landsat7 images. The QuickBird2 and

WorldView2 images gave rise to many more false classifications. The reason for this lies in the high spatial resolution, which means that there are a wide variety of land cover classes in a small area.

5 Proposals for implementing an international monitoring project

In order to establish monitoring of penguin populations throughout the Antarctic, it is essential that there be cooperation between science (Scientific Committee on Antarctic Research - SCAR) and politics (Antarctic Treaty Consultative Meeting - ATCM), with the additional involvement of other players (e.g. Convention on the Conservation of Antarctic Marine Living Resources - CCAMLR). As well as the political will, other crucial elements are communication (the willingness to exchange data), secure funding and, not least, the drive and energy of the relevant scientists. For this reason, this initiative should be discussed jointly by the above-mentioned bodies and aims and methods should be worked out which can meet with the approval of all concerned.

Complete long-term data sets for Antarctic bird populations are rarely available, and the penguin species that breed in the Antarctic are no exception. Until the present, Antarctic-wide comprehensive records have only been created for the emperor penguin (Fretwell et al. 2012). The essential prerequisite for creating Antarctic-wide records of the three *Pygoscelis* species (Adélie, chinstrap and gentoo penguins), and of the macaroni penguin (*Eudyptes chrysolophus*), is that the Antarctic bodies above work together and provide mutual support.

The SCAR 'Expert Group on Birds and Marine Mammals' (SCAR EG-BAMM) is seen as the most suitable body for the coordination of data collection. This expert group belongs to the 'Standing Scientific Group on Life Sciences' (SSG-LS). According to its constitution, the SCAR EG-BAMM brings together expert knowledge in the fields of Antarctic ornithology and mammalogy and supports research that sheds light on the role of birds and seals in the marine and terrestrial ecosystems of Antarctica (see http://www.egbamm.scar.org). The group also applies and interprets available scientific data to contribute to the protection and management of Antarctic birds and mammals. For example, SCAR EG-BAMM collects information about the population status and population trends of individual species in the Antarctic Treaty Area. Since the 1980s, the former SCAR 'Bird Biology Subcommittee' (BBS) of the 'Working Group on Biology' has collected and published information. However, the last overview is more than 10 years old (Woehler et al. 2001). The 'Australian Antarctic Data Centre (AADC)' has developed and administers a password-protected database, and its long-term data formed the basis for the analysis for this publication.

The plan is to present the results of this project at the XXXII 'SCAR and Open Science Conference', which takes place in Portland, Oregon, USA, in July 2012, and to discuss them within the EG-BAMM. The results of the EG-BAMM meeting will be taken up by the SCAR SSG-LS.

Parallel to this, Germany plans to introduce the project results at the next Antarctic Treaty Consultative Meeting (ATCM) and to its Committee for Environmental Protection (CEP). In advance of the project, the Federal Environment Agency has made contact with CEP representatives of other Treaty Parties in order to prepare the monitoring initiative connected with the project and to try and attract support.

An agreement with representatives of the Convention of the Conservation of Antarctic Marine Living Resources (CCAMLR) is also desirable. This is seen as important as the CCAMLR, in its 'Ecosystem Monitoring Program' (CEMP), collects data on penguin populations in the Antarctic and therefore has relevant experience and has drawn up standards in this regard (CEMP Standard Methods).

6 Outlook

The previous sections described the possibilities and limitations of using satellites to monitor penguin colonies in the Antarctic.

What methodology could be applied to creating a programme to monitor penguin populations throughout the Antarctic? For future investigation, the present study suggests a process comprising three levels of research, to be conducted in parallel:

Level 1

We were able to show that Landsat7 images could be used to detect large colonies of penguins that do not breed on ice (>1,000–5,000 occupied nests), although the accuracy of results was limited due to the relatively low spatial resolution. On the positive side, the data are available free of charge and provide comprehensive coverage. Images are available of the whole of Antarctica from 1999 onwards and they can be analysed very efficiently with a high degree of automation. We therefore propose that Landsat7 images, which comprehensively cover all ice-free coastal areas of the Antarctic, be taken on an annual basis. This is, in particular, to detect large colonies of Adélie penguins, but also chinstrap, gentoo and macaroni penguins south of 60° south. At the same time, data available from the literature should be collected and compared with these satellite data. In order to minimise the area of uncertainty, for example where there is interference from vegetation (especially in the Antarctic Peninsula region), the open questions with respect to detectability need to be resolved (see Section 4). It would also be interesting to investigate Landsat7 images from previous years in order to detect changes in colony size from that period.

Level 2

In order to obtain quantitative records of changes in colony area, it is also necessary to order images from high-resolution sensors (e.g. QuickBird2 or WorldView2), which have to be paid for. These could be used, in particular, in the Antarctic Peninsula region – where there are in some cases major changes in Adélie penguin populations – to obtain selected detailed data (in comparison to the Landsat7 images) of approximately 30 representative colonies. These could be analysed, at an acceptable cost, through manual image interpretation. In parallel, these colonies should be visited and counted at least once during the period of the study, and information relevant to remote sensing (e.g. relief structure, vegetation cover and rock type) recorded. This could be done through arrangements with the countries involved, for example by organising national supply ships to collect data on their way to research stations. In this respect, too, international cooperation would be necessary and sensible.

Level 3

At 10 selected colonies or connected groups of nests, in parallel to the high-resolution satellite images (*cf.* Level 2), species composition and density (adults with juveniles, where appropriate up to crèche age) should be recorded on the ground in the course of the breeding season. This includes mapping the colony borders using accurate satellite navigation (GPS/GLONASS) as well as recording the number of individual birds, where necessary with the help of aerial photographs (e.g. photographs taken from gas-filled balloons). The purpose of creating a more comprehensive data base than that achieved in this study is to reach a better correlation between the colony areas determined using the satellite images and the number of occupied nests (see Section 4.1). This would also include investigation of population changes over the years and within a single season, and also research on identifying and determining species. We should like to point out here that chinstrap and gentoo penguins played a subordinate role in this pilot study due to a comparative lack of data. These species should be taken into consideration in a future project, as should macaroni penguins. Finally, we would expect the futer work done on these issues to lead to improved automation of the process.

Cost estimates for satellite images

If a monitoring programme as proposed here were carried out over three years, we estimate that the costs of obtaining satellite data would total approximately US$250,000 (Level 1: no costs, Level 2: US$170,000 and Level 3: US$80,000).

Further investigations

Further investigations should be carried out to improve the accuracy of semi-automatic and automatic image analysis, both for Landsat7 images and images with high spatial resolution (e.g. QuickBird2 or WorldView2). Among other things, object-based approaches to complement the pixel-based classification investigated in this project are considered to be particularly promising. In order specifically to improve automatic image analysis, more satellite images (time series) of a colony will be needed (*cf.* Level 3).

The present study will be extended in September 2012 by the results of research on emperor penguins which breed during the Antarctic winter. For this, satellite images will be taken with WorldView2 and RapidEye of the emperor penguin colonies in the vicinity of Neumayer Station III and Dumont d'Urville, shortly before the breeding season in April to May and shortly after the breeding season in July to September. Furthermore, Terra-SAR-X images of the same colonies will be taken during the breeding season in July. Ground counts are also planned there for the 2012 season.

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