Chapter 8
PALAOA: The Perennial Acoustic Observatory in the Antarctic Ocean—Real-Time Eavesdropping on the Antarctic Underwater Soundscape

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Abstract The Perennial Acoustic Observatory in the Antarctic Ocean (PALAOA) was developed to study the underwater vocal behavior of cetaceans and pinnipeds and to monitor ambient noise levels in the Southern Ocean. Establishing an autonomous long-term observatory in Antarctica is challenging mainly because of the harsh weather conditions and logistic constraints. The project goal was to build an autonomously operating, passive-acoustic observatory which allows scientists (1) to reliably and continuously record the Antarctic underwater soundscape year-round, (2) to record all vocalizations produced by marine mammals in the study area (frequency range of the recordings: 10 Hz to 96 kHz), (3) to locate vocalizing marine mammals and other underwater sound sources, (4) to obtain information on ambient noise levels in the area, and (5) to access and analyze the incoming acoustic data stream in real time at the Alfred Wegener Institute for Polar and Marine Research (AWI) located in Bremerhaven, Germany.

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8.1 Introduction and Motivation

The Southern Ocean[1] provides a nearly pristine habitat to a great variety of marine mammals, birds, fishes, invertebrates, microorganisms, and plants, of which many are endemic to this region. For most, only rudimentary information is available, as research is seriously hindered by the region's remoteness and extreme environmental conditions such as the formation of sea ice, low temperatures, and lack of daylight during polar winter. The sea ice around Antarctica covers, at its maximum extension during austral winter, approximately 20 million km^2 (Fig. 8.1).

During austral summer, when the solar radiation reaches maximum intensity, the ice-covered area shrinks to four million km^2 (Kaiser et al. 2005). Light conditions alternate between continuous daylight during summer and complete darkness for up to 5 months (depending on latitude) during winter (El-Sayed 1971).

The Southern Ocean is presumably the last refuge for the marine megafauna from anthropogenic influences (Smetacek and Nicol 2005). Yet, there are extraordinarily large gaps in our knowledge of many Antarctic marine mammal species as exemplified by our current and quite limited understanding of the distribution of Arnoux's beaked whales (*Berardius arnuxii*), which is based on sparse visual sightings (Fig. 8.2).

While even limited information is an important piece in the investigation of the impacts of environmental changes—such as those induced by global warming—in the Southern Ocean, it is not at all sufficient for any accurate assessment on the abundance and distribution of marine mammals in the region. Collecting additional data on marine mammals is essential because as top-level predators their movement patterns, abundance, and distribution are an effective reflection on the health of the larger Southern Ocean ecosystem. How can reliable data be collected in this hostile and difficult-to-access environment?

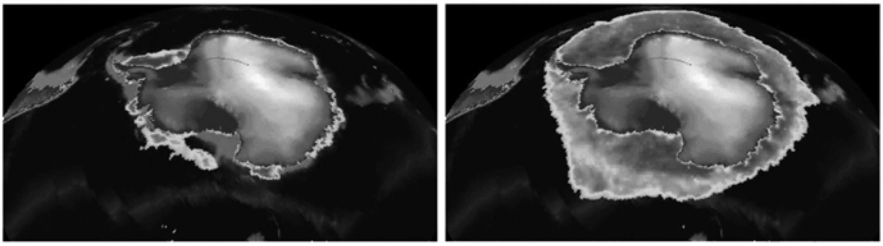

Fig. 8.1 Sea ice concentration around Antarctica in austral summer (end of February—*left side*) and winter (end of September—*right side*)—derived by satellite imagery. Image source: http://earth.rice.edu/mtpe/cryo/cryosphere/topics/sea_ice/antarctic_sea_ice.html

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[1] *Definition: The Southern Ocean, also known as the Antarctic Ocean or the South Polar Ocean, is, by definition of the International Hydrographic Organization, the oceanic division encircling Antarctica. It comprises the southern-most waters of the world's oceans south of 60° S latitude.*

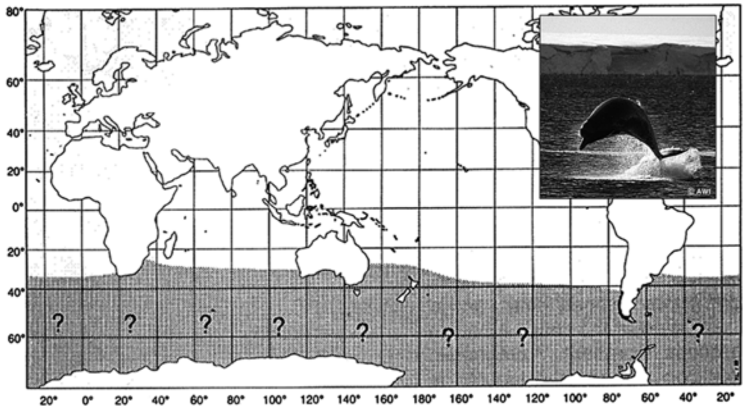

Fig. 8.2 Supposed distribution of the Arnoux's beaked whale (*Berardius arnuxii*). Map source: Jefferson et al. (1993). Image source: Dr. Joachim Ploetz, Alfred Wegener Institute

One particular research method has emerged that effectively overcomes these challenges: passive acoustic monitoring (PAM) (Tyack 1998; Richardson et al. 1995). Many marine mammals regularly use sound underwater for communication, navigation, and prey detection. Thus, PAM has the potential to provide year-round information on the presence/absence of (vocalizing) animals, independent of weather conditions and without direct visual observations (Mellinger et al. 2007). Depending on the frequency and intensity of the vocalization, the vocal behavior of marine mammals can be investigated, under favorable sound propagation conditions, within a range of up to a few kilometers (for ultrasonic vocalizations) to a few hundred kilometers (for infrasonic vocalizations) around a hydrophone (Sirovic et al. 2007). Furthermore, the use of PAM in the Southern Ocean in particular allows scientists to investigate the acoustic behavior of marine mammals and ambient noise levels in an environment almost undisturbed by humans.

In December 2005, the Alfred Wegener Institute for Polar and Marine Research (AWI), Germany, established an autonomous listening station named PALAOA[2] (*P*erenni*AL* *A*coustic *O*bservatory in the *A*ntarctic Ocean) in the eastern Weddell Sea close to the German Antarctic research base Neumayer Station. The project goal was to develop an autonomously operating observatory which records the Antarctic underwater soundscape year-round and continuously covers a frequency range between 10 Hz and 96 kHz, and allows real-time access to the acoustic data. The collected data are used to study the acoustic ecology of marine mammals as well as the ambient noise levels in this pristine environment. Additional sensors such as an AIS receiver also allow scientists to study potential impacts of human activities on the Antarctic marine environment.

[2] *PALAOA = Hawaiian; means (sperm) whale, whale tooth*

8.2 Environmental Conditions

Meteorological observations have been carried out at Neumayer Station since 1993. These are regularly contributed to the World Meteorological Organization (WMO) network Global Atmospheric Watch and provide basic weather forecast information for the DROMLAN[3] flight network. At Neumayer Station, monthly mean wind speeds at 10 m height range between 6.7 m s^{-1} in January and 10.1 m s^{-1} in August. In general, wind speeds are significantly higher during the austral winter months. However, occasional wind speeds exceeding 40 m s^{-1} (144 km h^{-1}) can occur year-round. Meteorological observations show that during the austral winter months (June to September) the mean monthly temperatures drop below −22 °C with mean monthly minimum temperatures ranging between −39.6 and −41.8 °C. The Antarctic continent is covered by an ice sheet (i.e., glacier) which reaches a thickness of more than 4000 m in central Antarctica. The ice sheet slowly floats (caused by gravity) towards the coast and into the ocean, predominantly along so-called ice streams. At the grounding line, the ice sheet detaches from the seafloor and starts to float on the ocean. This floating part of the glacier—which features a thickness between 500 and 1000 m at the grounding line (in the Dronning Maud Land Area) and several tenths of meters at its oceanic edge (Steinhage et al. 1999)—is called the ice shelf. Parts of this floating ice shelf regularly break off, a process termed calving. Thus, both small chunks of ice and icebergs measuring many hundreds of square kilometers are formed. The icebergs continue drifting with the predominant current into warmer regions where they melt. The ocean area directly adjacent to the ice shelf edge is most important for the formation of sea ice. Cold offshore winds from the high continental plateaus (so-called katabatic winds) push the sea ice offshore. Within the resulting area of open water, or polynya, intense air-sea exchange of heat leads to cooling of surface waters and formation of new sea ice. As a result, water of high density (low temperature and high salinity) is formed which contributes to the formation of Antarctic bottom water (Fahrbach and Rohardt, 2008). Figure 8.3 depicts the predominant glaciological and oceanographic processes of the Antarctic coastal ocean and ice shelf.

8.3 Challenges and Design

To get an overview of the seasonal variation of the vocal activity of marine mammals, continuous, long-term recordings covering all seasons are essential. This requires both year-round energy supply and access to the ocean. For the power supply of PALAOA a battery bank charged by a combination of solar panels, a wind generator, and a methanol fuel cell ensures year-round operation. Because of the lack of sunlight during austral winter, PALAOA cannot be

[3] http://dromlan.org

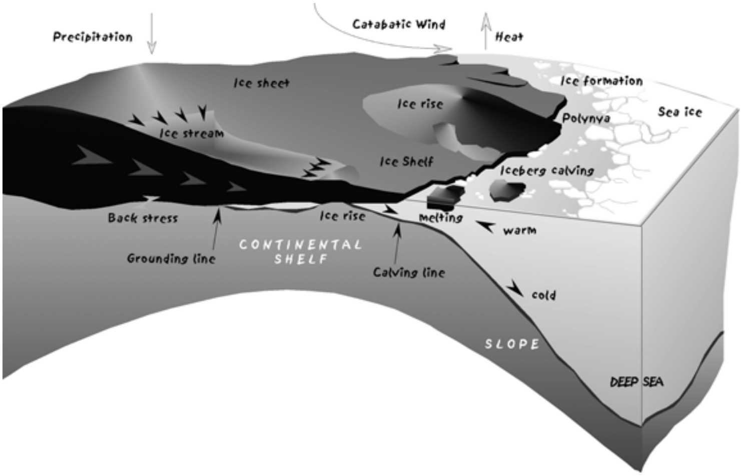

Fig. 8.3 Sketch of the Antarctic coast with glaciological and oceanographic processes. Terms are described in the main text. Image source: Dr. Hannes Grobe, Department of Geosciences, Alfred Wegener Institute

exclusively powered by solar panels. Wind generators can close this energy gap during austral winter, as meteorological conditions with high wind speeds occur more frequently during this season. Occasional gaps of low winds during wintertime darkness are bridged by the use of a methanol fuel cell. During austral winter, all electronic equipment and installations have to endure low temperatures of up to −50 °C on a regular basis. The most severe impact of these low temperatures is their influence on the battery capacity: below −30 °C the usable capacity of lead batteries will typically be less than 10 %.

Placing PALAOA close to the ice shelf edge maximized the reception probability of vocalizations because of the short distance between the hydrophones and marine mammals migrating within the coastal polynya (Figs. 8.3 and 9.4).

However, long-term hydrophone deployments over the ice shelf edge are not feasible due to the high potential of damage by calving of the ice shelf or passing icebergs. Furthermore, fast or sea ice deployments would not sustain year-round observations due to summer melting and autonomous recording units moored at the seafloor do not provide real-time access and are threatened by grounding icebergs. Therefore, we decided to place the infrastructure of PALAOA inside a container on top of the ice shelf, and drill holes through the ice to install hydrophones in the water below. To reduce the risk of losing the station due to break-off—the steady advance of the Ekstrom Ice Shelf results in break-offs of ~150 m per year on average—data from previous airborne radio-echo sounding surveys were consulted. These indicated an ice thickness between 80 and 200 m on the ice shelf north of Neumayer Station (Fig. 8.4). Satellite interferometric imagery indicated that the northernmost protrusion of the ice shelf exhibited little shear—a favorable condition for long-term stability without putting stress on the cables inside the ice.

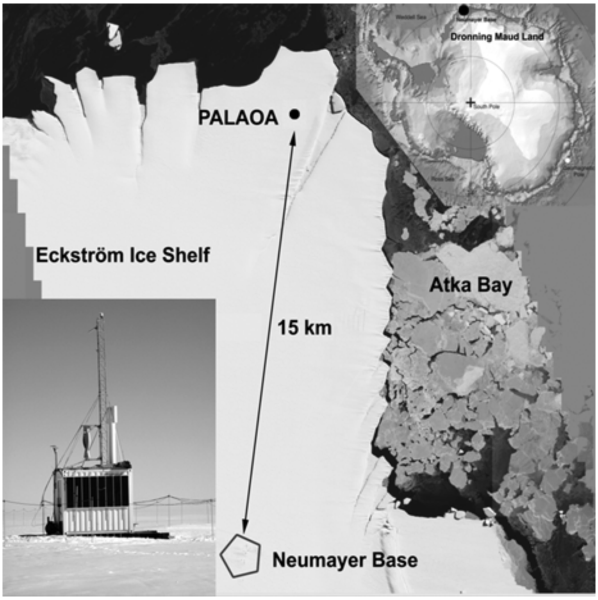

Fig. 8.4 Location and picture of PALAOA. Source of satellite image: Google Earth. The satellite image was taken 14 March 2006

Anticipating the need of regular maintenance of the observatory, particularly during its first few years of operation, feasible access from Neumayer Station at 70°40′S and 8°16′W using a snow crawler, was considered a necessary constraint on PALAOA's possible location.

To transmit the data in real time from the ice shelf edge to Neumayer Station (distance ~15 km), a radio link was established. The topography of this area is flat and the stations are within sight. This allows for a point-to-point connection without the need of a relay station. Real-time access allows the analysis of acoustic data (quasi) instantaneously and year-round without the need of retrieving physical data storage units. Most importantly, the real-time connection permits continuous monitoring of the station, alerting service personal at Neumayer Station to malfunctions.

To deploy the hydrophones in the water body below the ice shelf, a hot water drilling operation was conducted to penetrate the 100 m thick ice shelf. The hot water drilling system was designed by the AWI and first used in 1993 (Nixdorf et al. 1994). Drilling a single hole took around 12 h of continuous operation.

In the original setup, the PALAOA array consisted of four hydrophones arranged in a flattened tetrahedron configuration with a 500 m baseline. However, during the first 6 months of operation, two hydrophones failed for unknown reasons. The remaining two hydrophones (type Reson TC4032 and Reson TC4033; each connected to a Reson VP2000 amplifier/filter) are spaced 300 m apart. A 3D sketch of the PALAOA hydrophone array is presented in Fig. 8.5. In addition a CTD sensor measuring conductivity, temperature, and depth was deployed to obtain information on ocean currents and sound propagation conditions.

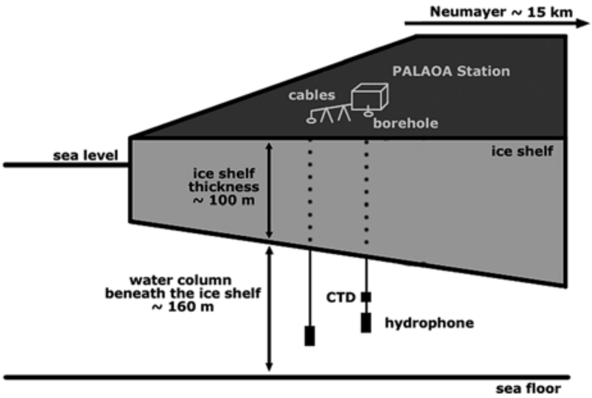

Fig. 8.5 3D sketch of the PALAOA hydrophone array

To be able to control the station remotely from Germany, a microcontroller (type BARIX Barionet 100), equipped with relays and I/O modules, was installed. This device is freely programmable (in BASIC) and allows an operator to turn on/off all devices in the observatory remotely from Germany. This is very useful as the station's energy consumption can be adjusted according to the available supply. For real-time data access a WLAN point-to-point connection between PALAOA and Neumayer Station was established. Maximum bandwidth of the WLAN radio link is around 2.5 Mbit/s.

The design goal for the acoustic module was to acquire continuous, long-term, and broadband (frequency range usually 10 Hz to 15 kHz, up to 96 kHz on demand) recordings of the Antarctic underwater soundscape. However, because of the energy shortage during austral winter and the limited bandwidth of the WLAN radio link, two acoustic systems are operated in parallel.

The high-quality digitizing system consists of an industrial PC with an external FireWire studio-grade soundcard (MOTU Traveler). This enables sampling of the two hydrophone signals at rates of up to 192 kHz at 24 bit. In parallel a 1 pps signal provided by a GPS receiver is recorded on a third channel for accurate time stamping of the audio files. The MOTU data are recorded on a PC with software specifically developed for the PALAOA project. This program (called AsioRecorder) is a stable recording software supporting audio stream input/output (ASIO) multichannel drivers. The recorded, high-quality data are stored locally on an exchangeable high-capacity hard disk which is sent to Germany once a year via ship or airplane. Selected files of interest can be accessed via FTP (file transfer protocol) from PALAOA to Neumayer Station receptively the AWI in Germany at any time.

This system (incl. WLAN link etc.) consumes about 53 W in total, which often exceeds the power limitations of the energy module during wintertime. For this reason, a second low-power audio module was installed in parallel. Signals of the two hydrophones are additionally routed into a stream encoder (type BARIX Instreamer 100), which provides a compressed 192 kBit/s MP3 stream of reduced bandwidth (10 Hz–15 kHz). This approach minimizes the power consumption of the entire system to about 15 W. The MP3 data stream is transmitted continuously

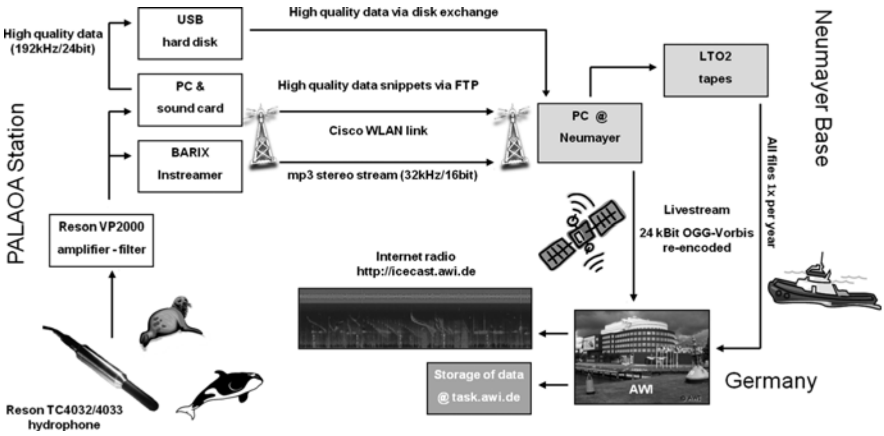

Fig. 8.6 Flowchart PALAOA acoustic data streams

via the established WLAN link to Neumayer Station. At Neumayer Station, these data are saved as time-stamped 1-min files for later shipment to Germany, and additionally re-sampled to an OGG-Vorbis compressed audio stream (24 kBit/s) and transmitted in real time via IntelSat satellite link to the AWI in Germany. This allows scientists to monitor and analyze the data almost instantaneously in the lab. An overview of the PALAOA data streams is given in Fig. 8.6.

8.4 Data Management and Analysis

PALAOA was intended to continuously record the Antarctic underwater soundscape. Consequently, the station is producing large amounts of data. As described, the PALAOA recordings are being sent continuously via IntelSat satellite link to the AWI in Germany. The highly compressed OGG-Vorbis audio stream is segmented and stored as time-stamped, 1-min files on a server located at the AWI. Once a year, this extremely compressed audio data are replaced by the MP3 files, which are stored on hard disks and shipped from Neumayer Station to Germany.

MP3 files of 1-min duration have an approximate file size of about 1.25 MB. Thus, during 1 day (year) of continuous operation 1440 files (525,600 files) and 1.7 GB (620 GB) of data are generated. This estimation is for the MP3 stream data only. Broadband data recorded with the high-quality digitizing system during polar summer (high biotic activity and no power constraints) are not included in this budget. The amount of additional data (webcam pictures, CTD data, GPS data, AIS data, operating data, meteorological data, and network statistics) is about 300 MB (110 GB) per day (year). Additionally, spectrograms covering 1 min, 5 min, 1 h, and 1 day of acoustic data are generated continuously using the Spectrum Lab[4] software

[4] http://www.qsl.net/dl4yhf/spectra1.html

and stored as jpeg images to allow for fast visual screening of the incoming data. Since start of operation in December 2005 a total of ~10 TB of data were collected and stored in the AWI data silo.

All PALAOA recordings consist of standard multimedia files (.wav, .flac, .mp3, and .ogg). They are kept transparent on a network drive and can easily be accessed/viewed with standard audio software. However, the sheer amount of files makes it hard to analyze longer periods as no commercially available software can load a million sound files at once. An application called PALAOAdb was developed in Matlab™ to allow users easy access to the dataset from a timeline- or event-oriented view. PALAOAdb periodically updates its database by analyzing the most recent recordings to provide an up-to-date display. The initial view is a plot of several selectable parameters for the entire recording period. Available are sound-specific measures like RMS or peak sound level, and other environmental observations like air and water temperature or tidal current. Also, the results of analyses like pattern recognition algorithms can be selected. Users can zoom in and click on the timelines to open single files, either with a built-in player and spectrogram viewer or via any external program like Ishmael,[5] XBAT,[6] or Triton.[7] PALAOAdb provides displays to visualize parameters and results from the entire data set. It takes about 1 s to load and process a single MP3 file with the basic procedures. Thus an off-line analysis can be done in up to 60 times real-time speed. PALAOAdb is easily extendable as new algorithms can be implemented as Matlab functions. Also, PALAOAdb will create timeline views from the results of the analyses.

To speed up processing of long-term data sets (e.g., several years of recordings), PALAOAdb was extended with a parallel computing system that allows users to distribute the analysis across multiple computers. An executable program called PALAOAdb-worker—which contains, for example, a detection algorithm for a specific marine mammal call—can be compiled in PALAOAdb. PALAOAdb-worker is a stand-alone application which can run on any computer. There is no Matlab installation necessary. PALAOAdb generates a to-do list which contains a list of all files to analyze. The to-do list and the data sets are located on a server (or multiple servers) within a local area network. The principal configuration of the parallel computing system is given in Fig. 8.7.

Any computer in the local area network running PALAOAdb worker is repeatedly connecting to the central server and checking the to-do list for open jobs. Once an open job is detected, the corresponding data set is transferred to the worker which conducts the analysis and sends the results back to the central server. In a final step, PALAOAdb collects all results and compiles them for further analysis.

[5] http://www.bioacoustics.us/ishmael.html

[6] http://www.birds.cornell.edu/brp

[7] http://cetus.ucsd.edu/technologies_Software.html

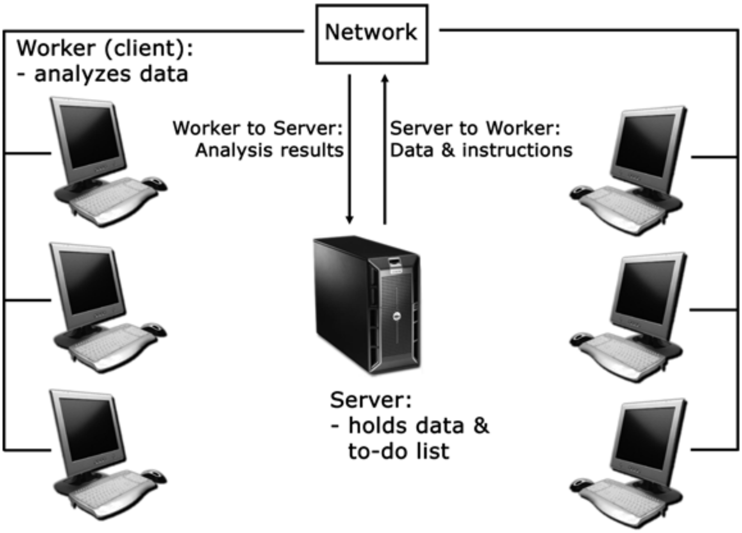

Fig. 8.7 PALAOAdb—a parallel computing system

As there is no inter-process communication between the workers, the speed scales linearly with the number of nodes, as long as the network and the file server are not saturated by fetching the audio files. With a size of 1.25 MB per 1-min MP3 file, a 100 MBit/s network can handle up to ten files per second. Thus, it is possible to scan a year of data with basic detectors in less than a day by running ten clients in parallel. This, of course, scales with the complexity of the conducted analysis.

8.5 Results

As of October 2013 PALAOA has recorded more than 50,000 h of multichannel audio data. The PALAOA recordings have revealed a high degree of biotic and abiotic acoustic activity in the Southern Ocean during all seasons, dominated by the vocalizations of Weddell seals (*Leptonychotes weddellii*), Ross seals (*Ommatophoca rossii*), crabeater seals (*Lobodon carcinophaga*), and leopard seals (*Hydrurga leptonyx*), as well as various cetaceans (blue whales, *Balaenoptera musculus*; fin whales, *Balaenoptera physalus*; humpback whales, *Megaptera novaeangliae*; Antarctic minke whales, *Balaenoptera bonaerensis*; and killer whales, *Orcinus orca*) and ice-generated noise. Figure 8.8 shows a typical spectrogram recorded with the PALAOA observatory in December 2007.

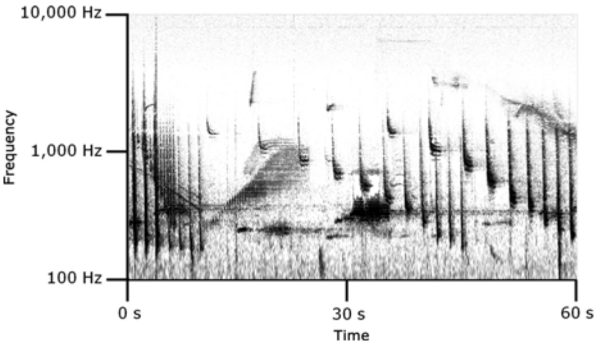

Fig. 8.8 Typical spectrogram of the underwater soundscape recorded with the PALAOA observatory in December 2007. Spectrogram shows various call types produced by Weddell seals and leopard seals

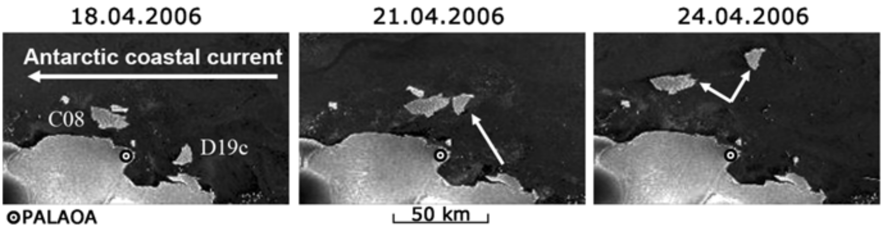

Fig. 8.9 Collision of two icebergs (C08 and D19c) close to the PALAOA observatory, Antarctica. Source of satellite images: European Space Agency, ENVISAT-ASAR

8.5.1 Selected Research Highlights: Ambient Noise

In April 2006 PALAOA recorded the collision of a grounded iceberg (C08) and an iceberg drifting (D19c) with the Antarctic coastal current (ACC), concurrent with supporting satellite imagery (Fig. 8.9).

The estimated source level and sound exposure level (at the source) of the acoustic event (10-min duration) were approximately 200 dB re. 1 μPa at 1 m and 228 dB re. 1 $\mu Pa^2 s$, respectively. This observation revealed that iceberg collisions are one of the loudest acoustic events in the Southern Ocean (Boebel et al. 2008).

8.5.2 Leopard Seals

Previous studies (on other leopard seal populations around Antarctica) reported that leopard seals predominately reside in the vicinity of penguin colonies during January and February when the inexperienced chicks enter the water for the first time (Lowry et al. 1988; Siniff 1991). However, the results of the acoustic observations made with PALAOA suggest that they migrate towards our study area as early as September, possibly to feed on adult foraging emperor penguins. The period of observed vocalizations is surprisingly well matched with the period when both penguin parents start to undertake regular foraging trips and move between the colony and their oceanic feeding areas to feed their chicks (unpublished data by Dr. J. Ploetz, AWI). The continuous presence of a substantial number of birds in the ocean is likely to provide an attractive feeding spot for leopard seals in the nearby vicinity of PALAOA (Klinck 2008).

8.5.3 Pinniped Vocal Behavior

The timing of vocal activity of the four ice-breeding pinniped species that occur near PALAOA (leopard seals, Weddell seals, Ross seals, and crabeater seals) shows a strong seasonal cycle with little interannual variation (Van Opzeeland et al. 2010). Furthermore the PALAOA continuous long-term recordings revealed quasi-permanent bioacoustic activity during the species-specific periods of peak vocal activity (Van Opzeeland et al. 2010).

8.5.4 Pinniped Vocal Repertoire

The PALAOA recordings made possible the first detailed description of the long-range vocal repertoire and acoustic behavior of the crabeater seal (Klinck et al. 2010) and Ross seal (Seibert 2007).

8.5.5 Cetacean Presence

A recent study by Van Opzeeland et al. (2013) focused on the acoustic presence of humpback whales in the vicinity of PALAOA in 2008 and 2009. Results indicated that calls were recorded during 9 and 11 months of 2008 and 2009, respectively. In 2008, humpback whale vocalizations were present in January through April, June through August, November and December, whereas in 2009, calls were present throughout the year, except in September. The detection radius of the recorded calls was estimated to be in the order of 100 km. The presence of vocalizations during austral winter demonstrates that the year-round ice-free polynyas near the Antarctic continent are likely of greater importance to humpback whales than previously assumed.

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