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## 6.3 First Data and Analysis Results from the New, Permanent Seismic Station TROLL, Dronning Maud Land, Antarctica

### 6.3.1 Introduction

This contribution will focus on the presentation of the first data and analysis results from NORSAR's new seismic station TROLL (Fig. 6.3.1), installed close to the Norwegian research base Troll, in Dronning Maud Land, Antarctica (for details about station installation and technical characteristics, see Schweitzer et al., 2012 in this volume).

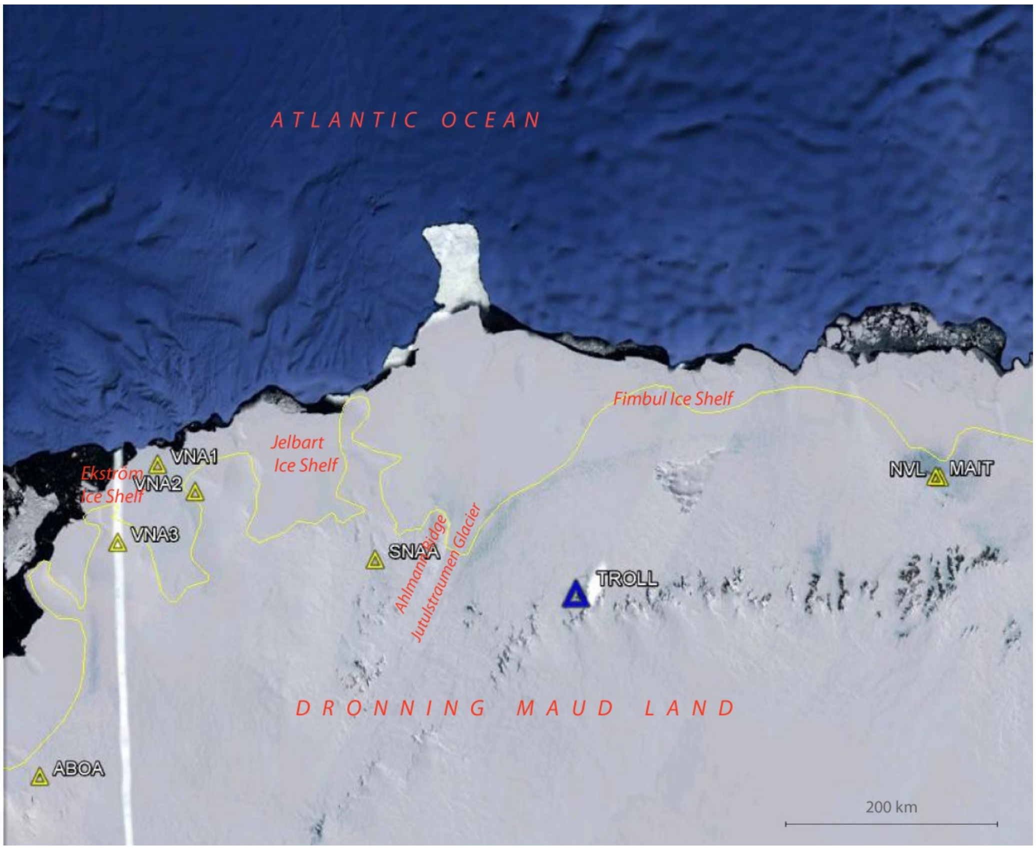


*Fig. 6.3.1 Google™ earth image of Dronning Maud Land, showing the locations of the pre-existing, international, seismic network (yellow) and the location of the new station TROLL (blue). Station ABOA is operated by Finland, station MAIT by India, station NVL by Russia, stations VNA1-3 by Germany, while SNAA is a CTBTO auxiliary station, operated in cooperation between Germany and South Africa. VNA2 is the central element of a short-period seismic array. The yellow line notes the continent – ice shelf boundary. Main ice shelves and some geomorphological units are named.*

The station targets the entire spectrum of seismological observations, from global seismicity, with emphasis on the Southern Hemisphere to Antarctic seismicity, as well as seismic signals generated by processes related to the ice sheet, such as icequakes and iceberg harmonic tremor. Each of these individual targets has its own significance:

- For NORSAR, expansion to the Southern Hemisphere is anticipated to cover gaps in its teleseismic event bulletin, thus complementing its seismicity monitoring activities. At the same time, reporting phase readings to international bulletins and databases enhances global coverage, especially when considering the sparseness of the global seismographic network in the South.

- Monitoring of Antarctic seismicity is of particular interest, since the Antarctic continent has long been considered rather aseismic, a view which has been gradually revised with the installation of more seismic stations (e.g., Reading, 2007 and references therein). The establishment of more, modern seismic stations will help to investigate the actual extent of the ice-cap's effect on suppressing seismicity (e.g., Johnstone, 1987). In particular for stations like TROLL, which are installed on bedrock, it is anticipated that their data help in separating this effect more concretely from the consequences of the installation of seismic stations on the ice sheet, which can reduce the quality of seismic data, especially the registration of shear waves. Furthermore, each new station constitutes a contribution in enhancing the density of the sparse, already existing network (for the seismic network at Dronning Maud Land, see Fig. 6.3.1).
- Finally, glaciogenic seismicity studies, with the information they yield on the dynamics and evolution of the ice sheet, are of interest to a much wider scientific community than that of seismologists.

### 6.3.2 Data and methods

The TROLL station has been now in operation for half a year, since 5 February 2012, with only small data outages (a total of 5½ days), related to technical problems with the Ethernet connection. The first two months of data are being used as a test dataset to set up and optimize automatic event detector schemes. These will help integrate the new station in NORSAR's routine analysis system and develop methodologies that will assist us to extract as much information as possible from TROLL records. Consequently, teleseismic activity presented herein is restricted to this two-month dataset.

The greatest challenge for setting up an efficient power detector scheme is related to the significant diversity of signals recorded at TROLL, as well as the quality of the data in terms of noise. The noise spectrum is discussed in detailed in Schweitzer et al. (2012), but icequakes and strong wind can be named here as two great contributors of noise for high frequencies (> 2 Hz), which can impair the observation of local and regional phases. At quiet intervals, TROLL is as efficient in the 1 – 10 Hz frequency range as it is at long periods (> 10 s).

Currently, the tuning of the STA/LTA detection algorithm is ongoing, results for teleseismic arrivals being compared to the listings of IDC's reviewed bulletin (IDC REB) and the readings of CTBTO station SNAA, close to the South African research base Sanae, at a distance of about 190 km from TROLL.

Regarding local and regional phases, a waveform cross-correlation detector (Gibbons and Ringdal, 2006) is employed for master templates with satisfactory signal-to-noise ratio (SNR).

For the moment, only a crude localization of local and regional events is being performed, based on backazimuth estimates and S-P arrival time differences at TROLL and SNAA. Backazimuth estimate is achieved by three-component, broadband f-k analysis (Kværna and Ringdal, 1986) for P-type phases and by three-component polarization analysis for P-type and secondary phases. The rotation of the horizontal components with the resulting backazimuth estimate is used as a control means to assess the validity of the result, as well as to improve phase picking.

### 6.3.3 Observations and results

Fig. 6.3.2 shows the IDC REB locations for the 249 teleseismic events detected at TROLL during February and March 2012 (red symbols), while NORSAR array (NAO) contributions to NORSAR's teleseismic reviewed bulletin for the same time interval are shown in blue.

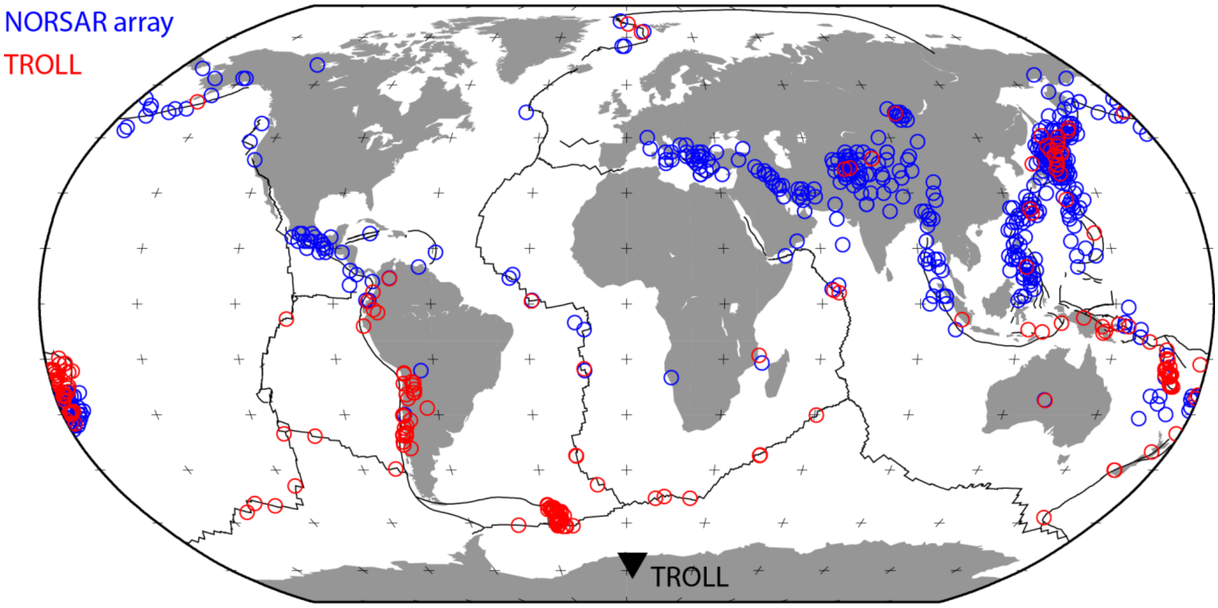


*Fig. 6.3.2 Distribution of events in NORSAR's teleseismic reviewed bulletin (blue) and events detected at TROLL (red) for the time interval 5 February – 31 March 2012. TROLL detections are mapped according to corresponding IDC REB locations. The location of TROLL is noted with a black, inverted triangle.*

The vast majority of the detected phases are P onsets from the events along the plate boundaries in the southern oceans, as well as South America and the island chains of the South Pacific (e.g., Fiji, Solomon, Tonga, Vanuatu and Loyalty Islands), while a significant number of PKP onsets has been detected, predominantly from Japan, but also the European Arctic. The latter is of particular interest, since it opens possibilities for focal depth determination of larger magnitude events in regions such as the Knipovich Ridge and Svalbard. Regarding the magnitude of the detected events, the global threshold for P phases for this particular dataset and the current capability of the detector is mb 3.8 (determined by IDC), while for PKP it is mb 4.5. Slightly lower thresholds are observed for the Fiji Islands region (mb 3.5) and Japan (mb 4.2), suggestive of a path effect, which however needs to be further investigated when the detector is properly tuned and a larger dataset is available. A special case, due to its relevant proximity to Dronning Maud Land, which places it in the far-regional distance for TROLL, is the South Sandwich Islands region. The inclusion in the IDC REB mainly of larger magnitude events from this region (mb > 4) highlights the difficulties involved in seismicity monitoring. Several events were detected at TROLL which are only reported by other stations in Antarctica (e.g., the Neumayer stations operated by AWI), according to the ISC On-line Bulletin (ISC, 2010). The figure illustrates clearly the gain for NORSAR from the establishment of the TROLL station, in particular when considering the fundamentally different detection capabilities of a single station and an array of the size of NORSAR.

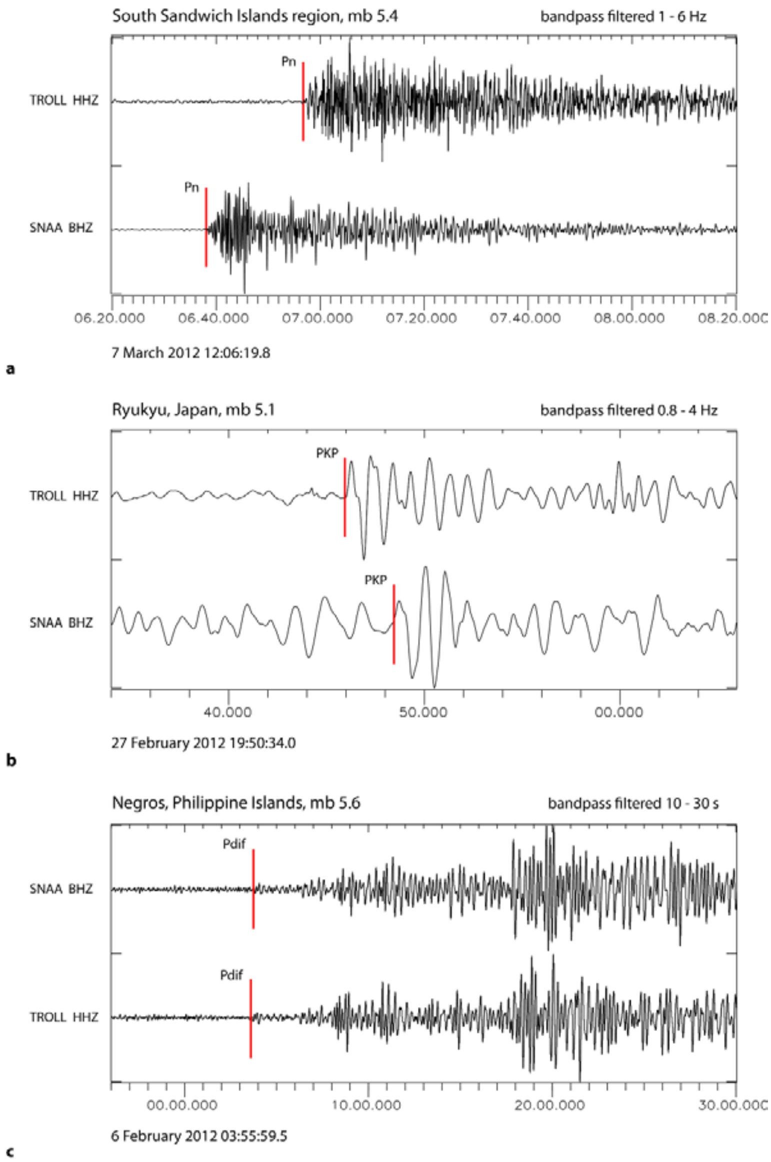


*Fig. 6.3.3 Examples of waveforms of far-regional and teleseismic events recorded at TROLL and SNAA. Only the vertical component is shown. (a) P-wavetrain from a far-regional event with mb 5.4 from the South Sandwich Islands region (IDC REB solution: origin time 12:02:43.72, location -58.0158°N, -25.3964°E, focal depth 0), (b) A teleseismic PKP onset from an event in Ryukyu, Japan (IDC REB solution: origin time 19:31.51.04, location 25.6087°N, 127.1991°E, focal depth 38 km), and (c) The first 25 min of a teleseismic event from the Philippine Islands (IDC REB solution: origin time 03:49:10.79, location 9.9404°N, 123.1064°E, focal depth 0).*

Figure 6.3.3 offers waveform examples from (a) an mb 5.4 event from the South Sandwich Islands, (b) an mb 5.1 event from Ryukyu, Japan, and (c) an mb 5.6 event from the Philippines, as recorded at TROLL and SNAA. Only in the case of the South Sandwich Islands event does SNAA show a better SNR than TROLL, whereas for frequencies lower than about 1 Hz, TROLL has better SNR than SNAA. This is consistent with the TROLL station's good performance in the low frequency and long period range (see Schweitzer et al., 2012).

As mentioned in the Introduction, the monitoring and analysis of Antarctic seismicity is one of the main targets of the TROLL seismic station. Fig. 6.3.4 shows approximate locations of seismic events in the region around TROLL.

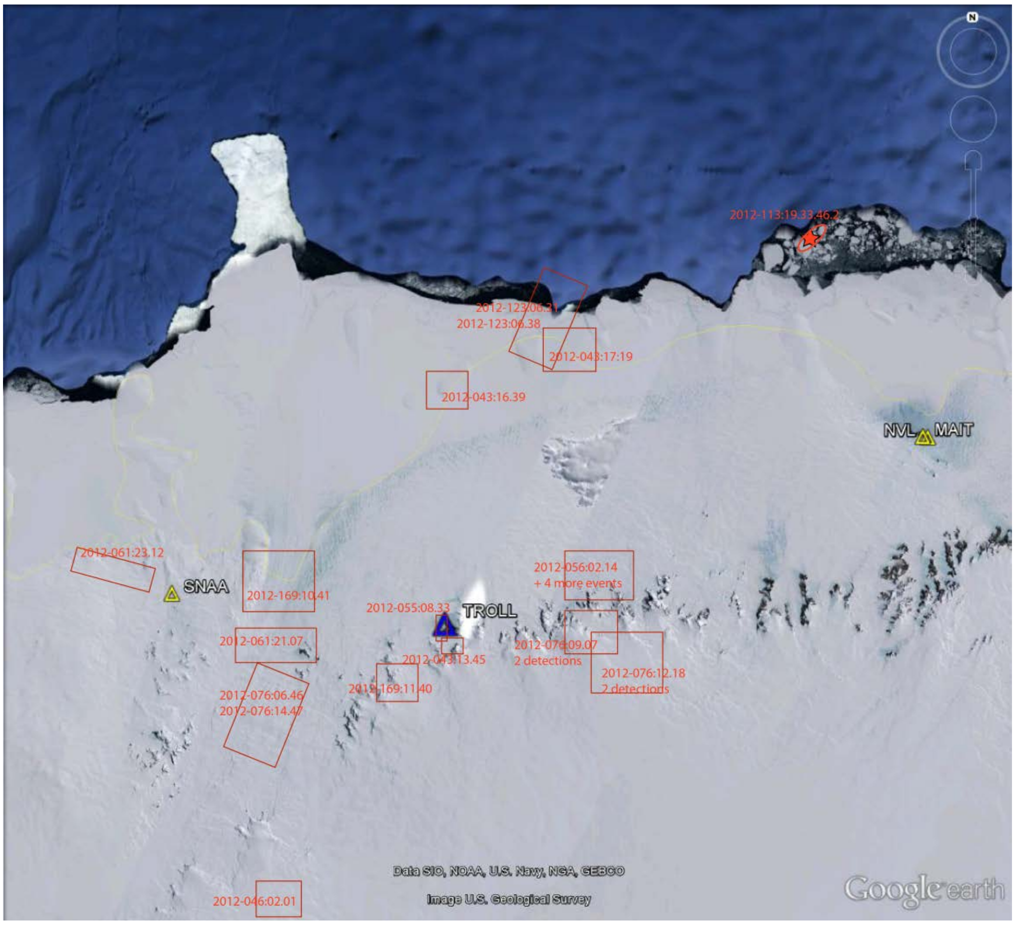


*Fig. 6.3.4 Google™ earth image of the region of Dronning Maud Land around TROLL, showing areas of seismic activity recorded at TROLL. The time of each event and number of detections based on waveform similarity, where available, are noted. Rectangles correspond to crude location estimates with only TROLL and SNAA data, their size indicating backazimuth and S-P arrival time difference uncertainty. One event (red star) is located with three stations (TROLL, NVL and SNAA). The 95% confidence level error ellipse is shown.*

Most of the approximate locations mapped in the figure are based on backazimuth and S-P arrival time differences measured at TROLL and SNAA, and only one event is located with the use of data from three stations. An effort has been made to give an impression of the uncertainty involved in these measurements, shown by the size of the rectangles denoting the areas of activity. In two cases, the application of the waveform cross-correlation detector has yielded a couple of detections associated with the located events. Most of the events are observed close to the mountain chain including the Jutulsessen nunatak, where TROLL is located, while others are observed at the boundary between the continental shelf and the ice shelf, and at major glaciers, such as Jutulstraumen. Many more small events have been identified in TROLL records, but most of them are very weak and cannot be picked at any other station in the region.

Whether these seismic events are attributed to tectonic activity or to processes within the ice sheet is a question to be investigated further. Although these events cannot be categorized as icequakes just at face value, an abundance of icequakes has been recorded at TROLL. These are events from the immediate vicinity of the station, with a strong Rg character. Their occurrence follows a clear temporal pattern, showing a strong correlation to the coldest time of day, between midnight and the early morning hours. A characteristic example is shown in Fig. 6.3.5. This particular case highlights also the difficulties that coinciding icequakes create in picking and detecting regional phases, since it shows quite clearly that they share the same frequency range with local and regional seismic events.

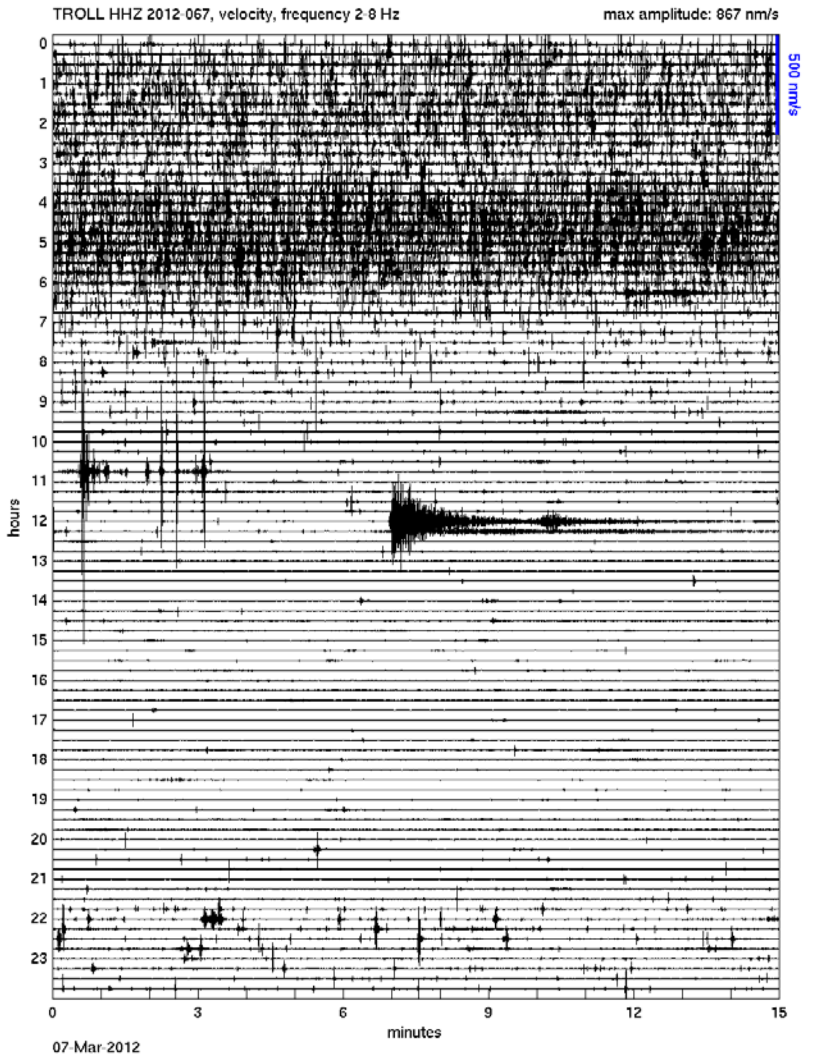


*Fig. 6.3.5 "Helicorder plot" of the vertical component of TROLL for 7 March 2012, bandpass filtered between 2 and 8 Hz. The record is dominated by very local icequakes for the time interval between midnight and 07:00 in the morning. Regional events, such as the South Sandwich Islands earth-quake of Fig. 6.3.3(a), can also be seen on the same day's records.*

A different category of cryosignals recorded at seismic stations are those related to the evolution and drifting of icebergs. Processes include calving, collision and scraping against the ocean floor, the ice shelf or against other icebergs, etc. (e.g., Müller et al., 2005; MacAyeal et al., 2008; 2009; Martin et al., 2010). More than 100 such signals have been recorded at TROLL during its first six months of operation. They exhibit a wide variety of forms and variation in frequency structure, from harmonic overtones to signals of completely chaotic character, but their vast majority has in common a frequency content of 0.6 to 12 Hz. The strength of the signals is also very variable and the weaker ones can be mistaken for noise due to weather or weak teleseisms. The most secure way to identify them as such is through the inspection of their spectrograms. The correspondence with particular icebergs drifting along the shoreline is achieved through the spatiotemporal correlation of signals and their backazimuth estimates with satellite images (e.g., http://rapidfire.sci.gsfc.nasa.gov/imagery/subsets/?mosaic=Antarctica) and/or iceberg tracking databases (e.g., http://www.scp.byu.edu/data/iceberg/database1.html). This correlation is supported by the records of other stations at Dronning Maud Land, such as SNAA, NVL and VNA1-3.

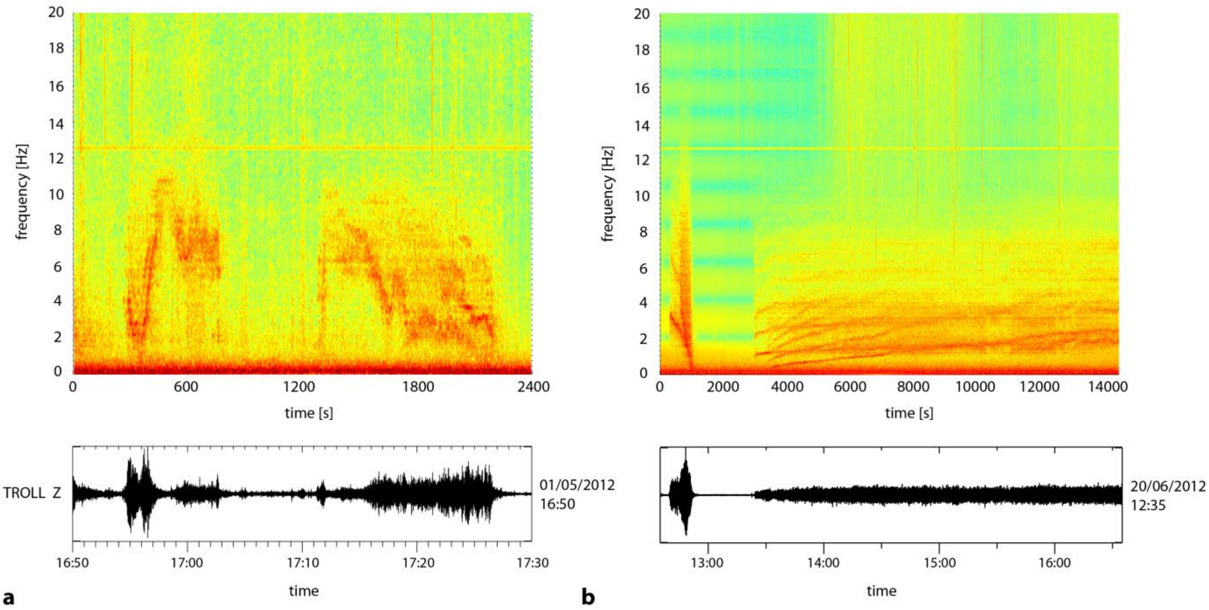


*Fig. 6.3.6 Spectrograms (top row) and corresponding waveforms of TROLL's vertical component for two examples of iceberg generated signals. (a) A 40 min record containing two signals associated with an iceberg NE of TROLL. The spectrogram is computed from raw data, while the waveform has been bandpass filtered between 2 and 6 Hz. (b) A 4 hour record containing two signals associated with an iceberg NNE of TROLL. In this case, the waveform has been bandpass filtered between 1 and 6 Hz. Only the first 3 hours of the 1 day long harmonic tremor are shown.*

Fig. 6.3.6 shows two waveform and corresponding spectrogram examples of such incidents, composed by signals of structured (non-chaotic), but quite different character. The spectrograms are computed for unfiltered data, but have been truncated to 20 Hz to enable detailed observation. The corresponding waveforms are bandpass filtered to the frequency band of optimum SNR. The first example (a) constitutes a complex of two signals whose main characteristic is intense and arbitrary frequency gliding. The two signals, separated by an aseismic interval of about 7 min, exhibit reverse dispersion patterns, while the second one has towards its end two well-defined overtones in addition to the dominant frequency band. The second example (b) is composed by a strong signal that lasts about 14 min followed by harmonic tremor of total duration of approximately 1 day, although only the first 3 hours are shown in Fig. 6.3.6. The first signal is composed by a strong dominant frequency band with two easily distinguishable overtones gliding from higher to lower frequencies in a parabolic manner, as well as a more chaotic and lower energy content part reaching up to 14 Hz towards its end. The tremor signal is composed by two different sets of harmonics, each set reaching up to 10 overtones, not easily visible at this scale.

The exact mechanisms behind the generation of these iceberg related signals are subject to further study. Several mechanisms have been proposed until now for iceberg harmonic tremor, including the superposition of a rapid succession of strike-slip events generated by stick-slip motion in the case of colliding icebergs (MacAyeal et al., 2008) and the flow of water through crevasses inside the drifting iceberg in a similar mechanism to that of volcanic tremor (Müller et al., 2005).

### 6.3.4 Summary

A wide variety of seismic signals have been recorded during the first half year of operation of NORSAR's new station TROLL in Antarctica. The first data and results of their preliminary analysis are indicative of the station's contribution both to global and Antarctic seismicity monitoring, as well as a source of data and information on the dynamics of the Antarctic ice sheet.

A more robust image of the station's performance is anticipated when it is fully integrated to NORSAR's routine processing and the necessary schemes have been developed to exploit fully the information contained in its records.

***Acknowledgements***

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