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The Array Analyzing of the High Quality Glacial Seismic Events Active in Greenland Using Long-Period Surface (Rayleigh) Wave Detection by the German Regional Seismic Network

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ABSTRACT

This study reports on four high quality glacial events in Greenland, M 4.9, 2007-07-04; M 4.8, 2007-07-09; M 4.7, 2007-07-09; M 4.7, 2007-07-20 detected using the long-period surface waves (Rayleigh wave) recorded at the stations of the German Regional Seismic Network (GRSN) array (German-GR and Geofon-GE programs). The waveform patterns of the detected slow events for Greenland updated through 2008 were monitored to analyze this new class of low-frequency earthquakes in the context of the array processing technique and array parameters using the software Seismic Handler Motif (SHM). The array geometry of GRSN was defined by seven stations and processed to associate seismic phase arrivals to define glacial events. Two stations of GRSN were assigned the role of reference sites. The long-period surface wave characteristics of the event signals with magnitudes M 4.9, M 4.8, M 4.7, and M 4.7 were detected using filtering, beamforming, and location-relocation steps; then, the results were updated using SHM. The event data were filtered with a Butterworth band pass filter of 35s-70s with a common amplification. Using the array-beamforming technique, the beam traces were computed to calculate the beam-slowness (the apparent velocity) and the beam-azimuth of incoming wavefronts for particular time intervals to further analyze the observed glacial events. Then, the detected event signals were relocated and used to estimate array parameters; beam-slowness and beam-azimuth. Finally, in this study, the array processing technique was used with array parameters computed from the SHM to detect and analyze the slow glacial events using the array installation data from GRSN.

Keywords:
Greenland; Glacial Events; Surface Waves; Waveform Patterns; Beamforming

INTRODUCTION

The worldwide recorded long-period signals from events in Greenland display the high amplitude of the event signals at long ways [1]. These signals from glacial earthquakes observed in Greenland are different from those of tectonic events; thus, standard techniques of seismic monitoring are not used to detect or locate them [1]. The existence of glacial earthquakes was not known until 2003 [2-3]. These largest events in Greenland cause long-period (T>30 s) signals and are similar in magnitude to those caused by tectonic earthquakes with a moment-magnitude of Mw = 5.

The Greenland events are not appeared in regular earthquake catalogs which are based on the radiation of the high frequency components [1, 3]. The glacial events are consistent with slow processes and depletion of high-frequencies [2]. The longer source duration periods of glacial events result in the depletion of radiated high frequencies [1]. Long time glacial events can radiate little high frequencies and can elude detection since event signals with low amplitudes-high frequencies are buried in noises. The well-known standard techniques of event detection and relocation depend on the high-frequency (1s) P-waves in seismogram data [1].

Glacial events were initially observed from the development of a new algorithm [1, 3]. The 252 glacial earthquakes in Greenland for the period 1993–2008 were detected and located using a surface-wave detection algorithm [1, 4] (The full list of events for 1993–2008, as well as recent updates, is available at http://www.globalcmt.org.). This algorithm was designed to identify seismic sources in relation to their generation of long-period seismic waves [1-3, 5] and based on array-processing techniques. These long-period slow events cause surface waves that cannot be described by the moment-tensor for crustal events [1]. The vertical-component data recorded at the seismic stations are filtered (35s-150s) and the phases are correctly adjusted for the propagation delay of surface (Rayleigh) waves from reference location to each station in the German Regional Seismic Network (GRSN) [2]. When the locations corresponding to an event are identified, all the detected signals are in phase. Then, the corrected surface wave arrivals for the observed events in Greenland are aligned and all the observed signals are in phase [1]. These surface waves were recognized to fit to a single source model [6].

The first application of the signal location algorithm to 3 years of data (1999–2001) from the Global Seismographic Network (GSN) led to the detection of 46 unreported events of $4.6 \leq M \leq 5.0$ in Greenland, Alaska, and Antarctica, with 42 of the events located in and along the eastern and western shores [1]. The source parameters for the fifty-nine events detected during 2006–2008 are listed in Table 1. For the Western Greenland region, 11 or more earthquakes were

Table 1. Source parameters for 59 glacial events in Greenlanda [1, 4] and high-quality (A/B) glacial events selected for this study contained in the red bold font.

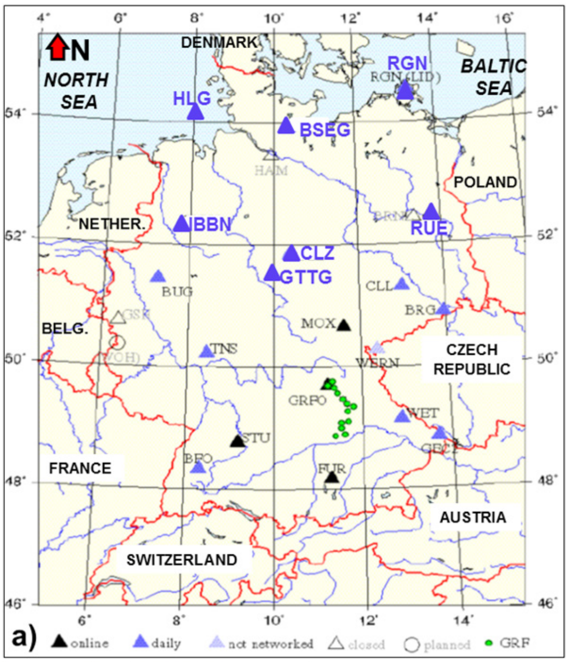
Date	*Time*	*Latitude*	*Longitude*	*M*	*Date*	*Time*	*Latitude*	*Longitude*	*M*
2006/02/13	*20:29:52*	*70.25*	*-30.75*	*4.8C*	*2007/08/03*	*19:25:12*	*72.25*	*-52.25*	*4.8C*
2006/02/28	*22:44:32*	*69.00*	*-33.00*	*4.8A*	*2007/08/13*	*20:37:52*	*66.25*	*-38.75*	*4.8B*
2006/03/04	*23:05:20*	*65.75*	*-41.25*	*4.7B*	*2007/08/25*	*09:19:04*	*75.25*	*-56.75*	*4.9A*
2006/04/29	*11:39:12*	*65.25*	*-41.25*	*4.8B*	*2007/09/11*	*22:42:00*	*70.25*	*-50.75*	*4.6C*
2006/05/01	*06:44:32*	*72.25*	*-52.75*	*4.9A*	*2007/10/13*	*05:55:12*	*74.75*	*-56.75*	*4.8A*
2006/06/24	*10:48:32*	*69.25*	*-49.75*	*4.7E*	*2007/11/21*	*18:04:56*	*66.25*	*-38.75*	*5.0A*
2006/07/10	*18:13:36*	*65.25*	*-40.75*	*4.8A*	*2007/11/24*	*00:08:56*	*68.50*	*-33.50*	*4.8A*
2006/07/16	*03:15:28*	*69.00*	*-31.00*	*4.6C*	*2007/11/24*	*12:54:32*	*66.50*	*-38.50*	*4.9A*
2006/07/16	*06:41:52*	*73.25*	*-53.25*	*4.7C*	*2007/11/24*	*13:29:52*	*67.25*	*-38.25*	*4.8A*
2006/07/25	*04:51:44*	*68.75*	*-49.75*	*4.7C*	*2007/12/14*	*06:39:36*	*75.25*	*-56.75*	*4.9A*
2006/08/10	*18:45:20*	*77.50*	*-65.50*	*4.8B*	*2007/12/31*	*14:40:56*	*66.25*	*-38.75*	*4.9A*
2006/08/23	*17:19:28*	*65.75*	*-37.75*	*4.7C*	*2008/02/14*	*05:12:24*	*72.75*	*-55.75*	*4.8B*
2006/08/28	*07:55:04*	*69.50*	*-25.50*	*4.6B*	*2008/04/05*	*21:06:08*	*75.50*	*-56.50*	*4.8A*
2006/09/10	*04:20:16*	*77.75*	*-57.25*	*4.9C*	*2008/04/07*	*13:58:00*	*74.25*	*-56.75*	*4.7C*
2006/10/09	*04:03:12*	*76.50*	*-60.50*	*4.8B*	*2008/05/04*	*12:52:40*	*65.50*	*-41.50*	*4.8B*
2006/10/14	*07:23:20*	*76.00*	*-58.00*	*4.8B*	*2008/05/28*	*21:06:40*	*70.75*	*-49.25*	*4.7B*
2006/11/05	*09:13:04*	*75.75*	*-58.25*	*4.7C*	*2008/06/12*	*17:20:08*	*69.00*	*-49.00*	*4.7E*
2006/11/28	*10:55:44*	*68.75*	*-32.75*	*4.9B*	*2008/06/13*	*15:40:40*	*75.75*	*-57.75*	*4.8C*
2006/12/19	*16:57:44*	*74.75*	*-57.75*	*4.8B*	*2008/06/19*	*15:20:00*	*74.75*	*-58.25*	*4.8B*
2007/04/22	*08:55:04*	*66.25*	*-38.25*	*4.7A*	*2008/07/13*	*04:59:44*	*69.50*	*-49.50*	*4.8C*
2007/04/23	*21:56:56*	*75.25*	*-58.25*	*4.8A*	*2008/08/01*	*14:43:20*	*66.50*	*-38.50*	*4.8A*
2007/05/30	*02:57:12*	*77.50*	*-63.50*	*4.7C*	*2008/08/01*	*23:00:40*	*66.75*	*-39.25*	*4.8A*
2007/06/09	*05:16:56*	*75.75*	*-60.75*	*4.8B*	*2008/08/14*	*20:58:24*	*77.75*	*-58.75*	*5.0A*
2007/07/04	*16:55:20*	*69.25*	*-49.75*	*4.9A*	*2008/08/19*	*21:05:28*	*66.25*	*-38.25*	*4.8B*
2007/07/09	*01:08:16*	*66.25*	*-37.25*	*4.8A*	*2008/11/03*	*16:44:48*	*68.75*	*-33.75*	*4.9B*
2007/07/09	*02:42:08*	*66.75*	*-38.25*	*4.7B*	*2008/11/07*	*13:44:24*	*77.50*	*-66.50*	*4.7E*
2007/07/09	*05:31:12*	*75.00*	*-57.00*	*4.6C*	*2008/11/21*	*20:31:52*	*76.00*	*-58.00*	*4.9A*
2007/07/20	*00:36:16*	*69.25*	*-33.25*	*4.7A*	*2008/11/25*	*04:10:40*	*68.50*	*-33.50*	*4.9A*
2007/07/24	*23:03:12*	*77.25*	*-60.75*	*4.9A*	*2008/12/13*	*14:47:52*	*68.00*	*-34.00*	*5.0A*
2007/07/26	*22:42:48*	*66.50*	*-38.50*	*4.7A*					

detected in every five years from 1993 to 2003 (an average of 4.5 events per year during the same period). These long-period (T>30s) events with magnitudes of M~5 require the use of long-period surface waves to explain this new category of seismicity model. In this study, the glacial event-detections for Greenland updated through 2008 and the understanding of the high quality events that resulted from some investigations of rapidly moving outlet glaciers in Greenland were reviewed [1]. The four high quality events in Greenland with their source mechanisms through 2008 (Table 1) were selected to analyze these slow events in the context of the array processing technique and array parameters using the software Seismic Handler Motif (SHM) [7]. The surface wave characteristics of these four glacial events with the magnitudes of M = 4.9, 2007-07-04; M = 4.8, 2007-07-09; M = 4.7, 2007-07-09; and M = 4.7, 2007-07-20 (Table 1) were also provided to update the detection results. The main purpose of the array processing technique for the observations available for this study was to calculate the beam-slowness (the apparent velocity) and beam-azimuth for particular time intervals to analyze the observed glacial events. The style of processing used is similar to that undertaken in some styles of signal-processing analysis and time-series applications [1]. Finally, we present the array parameters of the four selected events regarding the nature of the glacial earthquakes with the German Regional Seismic Network (GRSN; GERMAN-GR and GEOFON-GE).

MATERIAL AND METHODS

Throughout our study, we processed data obtained from GRSN consisting of the large regional GERMAN (GR) and GEOFON (GE) arrays (http://geofon.gfz-potsdam.de/waveform/archive/index.php). Fig. 1a shows the configuration of the GRSN array and the layout of the seismometer sites for the regional arrays. GRSN (Fig. 1a) [8] comprises 16 STS2 digital broadband stations with a flat, velocity-proportional response characteristic in the frequency range of 8.33 mHz to 40 Hz [9]. GRSN is designed to monitor and collect high-quality data from regional and global seismic events as well as recording and locating all events with Ml > 2 in German territory. All stations are continuously recorded and, with one exception, are connected via the Internet with each other and with the network center at the Gräfenberg Observatory (GRFO) in Erlangen [9] (Fig. 1a). GRSN is a combination of a physical and a virtual network (for more details, see http://www.szgrf.bgr.de/).

In this study, the GRSN array was defined by a set of stations; RUE, GTTG, CLZ, RGN, IBBN, BSEG, and HLG with two stations, CLZ and GTTG, being assigned the role of reference sites (Fig. 1a). The relative distances from these reference points to all other array sites are used later in all array specific analysis algorithms. The four glacial events (Table 1) were observed in seven stations; RUE, GTTG, CLZ, RGN, IBBN, BSEG, and HLG (Fig. 1b). The recorded events from Germany were processed with SHM improved by K. Stammler [7], which is used for waveform retrieval and data analysis [9] (available via http://www.szgrf.bgr.de/sh-doc/index.html). Seismic arrays generally differ from local seismic networks mainly by the methods used for signal analysis being superior to three-component stations in terms of improving the quality of seismic stations and detecting and characterizing signals from earthquakes [10]. Array processing techniques require high signal coherency across the array, and this places important constraints on the array geometry, spatial extent, and data quality. The appropriate analysis of the array data is dependent on a stable, high-precision relative timing of all the array elements. Small temporal differences in the arrival of seismic signals between the different sensors play an important role in all array-processing techniques [10]. Hence, the signal detection capabilities of arrays are obtained by applying the beamforming technique, which suppresses noise while preserving the signal, thus enhancing the signal-to-noise ratio (SNR). In addition, array parameters, the station-to-event azimuth (backazimuth)



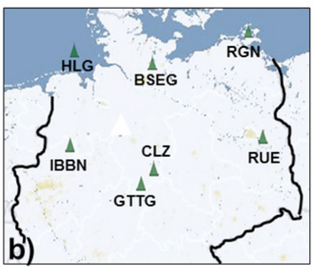


Figure 1. a. Map of the station sites of GRSN (site details are given in the legend) shows the locations of the stations (large blue fonts and triangles; HLG, BSEG, RGN, IBBN, CLZ, GTTG, RUE) used in our analyses. **b.** The inset map shows the simple array geometry of these seven stations used in this study with the reference stations assigned; GTTG and CLZ (see text for details).

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and the apparent velocity (slowness) of various styles of event signals, are also estimated from arrays. These parameters are essential for both event relocation and the classification of signals [10].

In this study, the general seismic array processing beamforming technique was applied using SHM to analyze the event signals. SHM used in this study is an interactive analysis program preferably used with continuous waveform data [7]. It was developed at the Seismological Observatory Gräfenberg and in this study was used in the routine analysis of the four detected glacial events [9] (Table 1 and Fig. 1). SHM is well suited to the analysis of glacial seismic data since it has advanced features for trace manipulations and automatic or semiautomatic phase picks [7]. The basic tools and features of SHM are built around reading traces of the detected events from continuous data streams in Steim-compressed MiniSEED files associated with a set of standard filters (simulation filters and Butterworth filters) on broadband input traces of the events (see also [7]). Teleseismic beam traces using array-beamforming are computed using SHM. The slowness and back-azimuth of an incoming wavefront for array processing are also determined. The detected events are located using the LOCSAT program. Moreover, in this paper, the applied procedures for estimating the slowness parameter, the angles of approach (azimuth-backazimuth) of detected event signals and processing algorithms for event detection are briefly described. This study also documents array-processing technique with concluding remarks from the SHM for detecting and associates event signals from regional seismic events using the array installation data from the regional GERMAN (GR) and GEOFON (GE).

The automatic processing steps in SHM are divided into three separate cases: a) Event array processing to associate phase arrivals to define events, b) event signal detection using beamforming, filtering, and location-relocation, and c) signal attribute to estimate the array parameters; slowness, azimuth and/or back-azimuth.

RESULTS AND DISCUSSION

The source parameters of the four glacial events in Greenland are given in Table 1 and were recorded in GRSN stations; HLG, BSEG, IBBN, RGN, CLZ, GTTG, and RUE (Fig. 1b). The recorded glacial events from the GRSN network were processed and seismic array beamforming and alignment of the events were performed by SHM. The waveform resemblances (vertical component) of the recorded four events from the seven stations are shown in Figs. 2-5.

The waveforms presented in Figs. 2-5 show the surface wave peaks of the detected glacial events observed at the GRSN network and the aligned traces of all single observations. All the signal traces were adjusted and relocated to

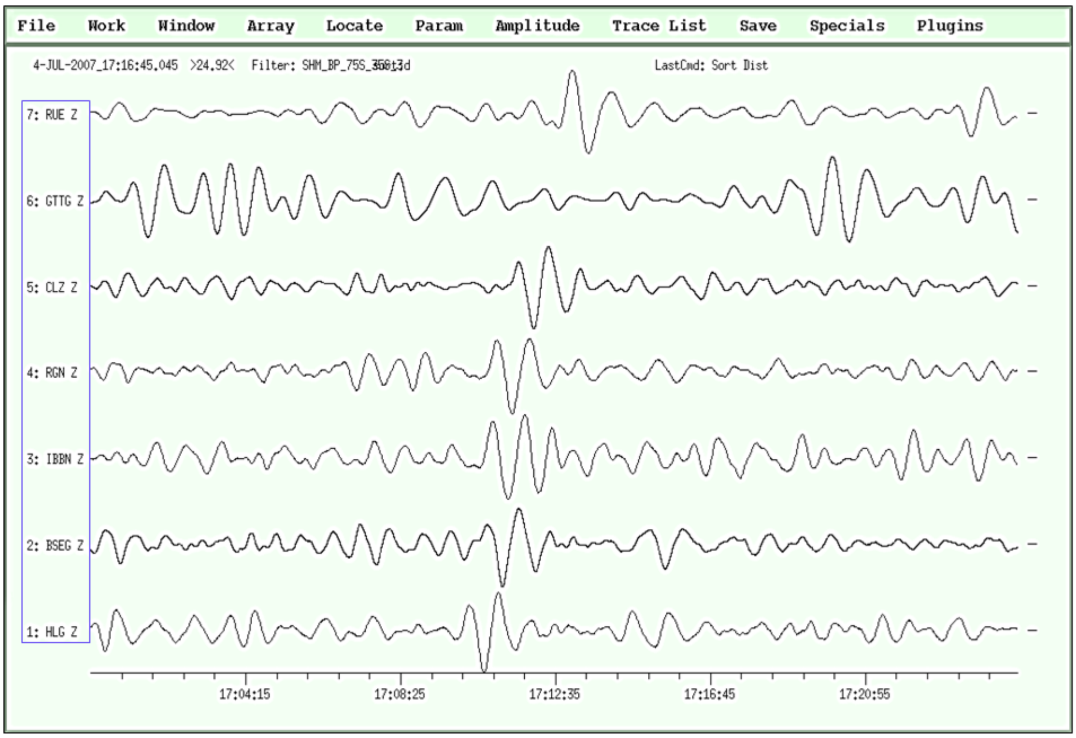

Figure 2. Mean root square residual: 0.51, distance: 32.5, beam-slowness: 29.0 ± 0.4 (x), beam-azimuth: 322.4 ± 0.5 (x), reference: CLZ, origin time: 4-JUL-2007_16:55:20.000, epicenter: 69.25 lat. -49.75 lon. and FE region: Western Greenland (Kalaallit Nunaat).

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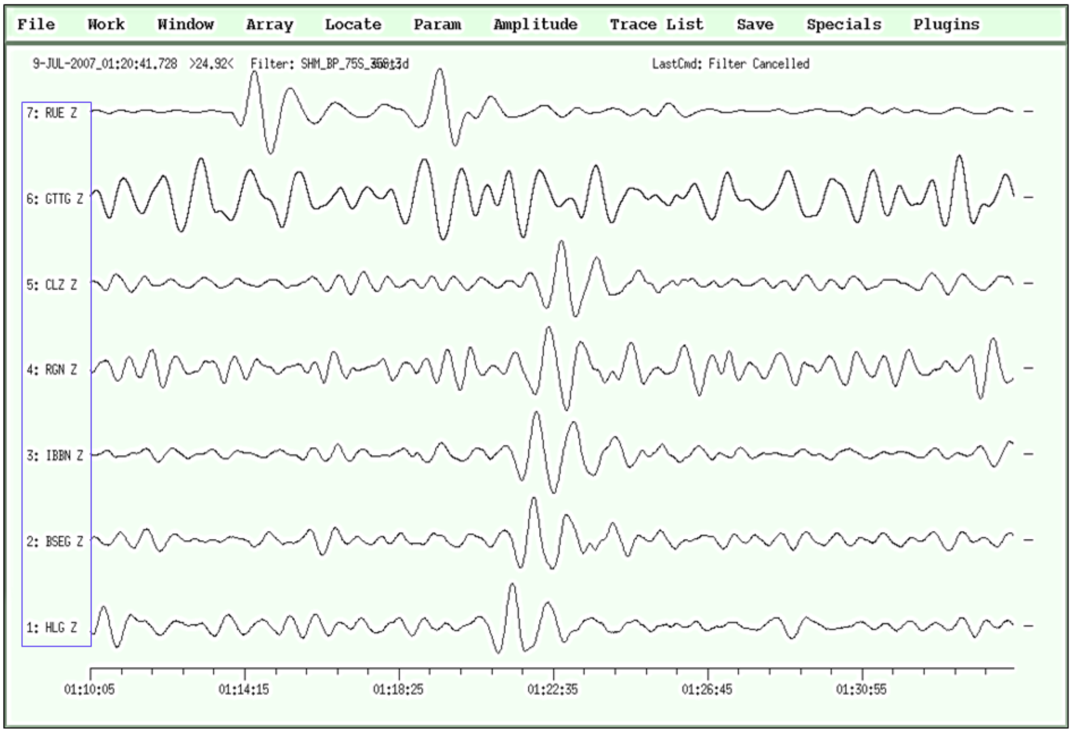

Figure 3. Mean root square residual: 0.70, distance: 27.6, beam-slowness: 28.9 ± 0.7 (x), beam-azimuth: 314.5 ± 1.2 (x), reference: GTTG, origin time: 9-JUL-2007_01:08:16.000, epicenter: 66.25 lat. -37.25 lon. and FE region: Eastern Greenland (Kalaallit Nunaat).

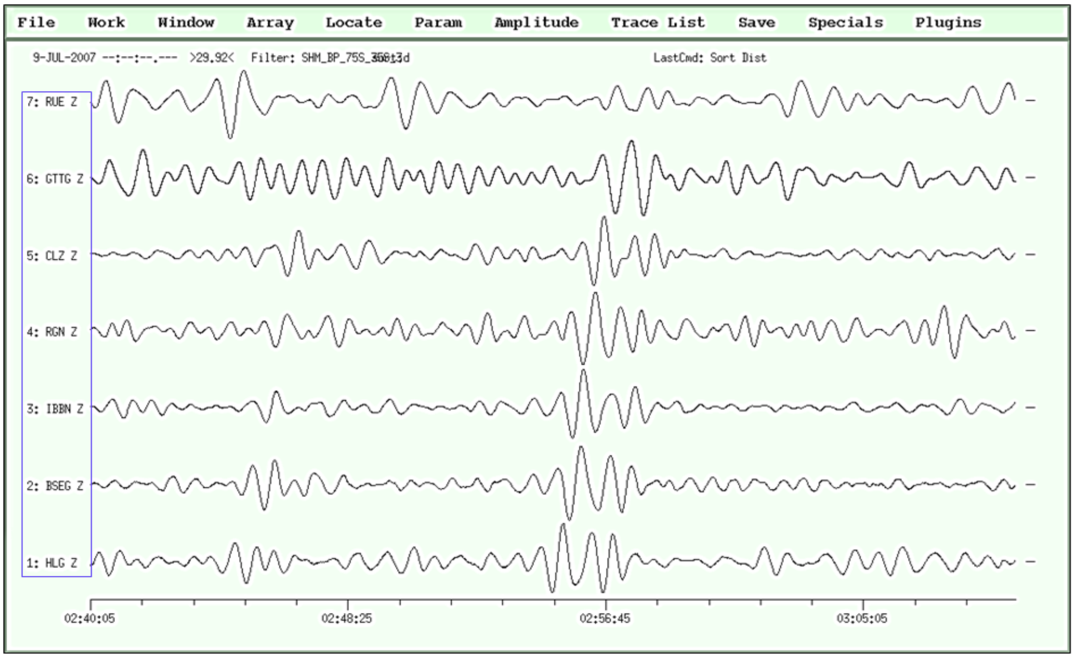

Figure 4. Mean root square residual: 0.83, distance: 28.1, beam-slowness: 29.6 ± 0.9 (x), beam-azimuth: 312.4 ± 1.4 (x), reference: CLZ, origin time: 9-JUL-2007_02:42:08.000, epicenter: 66.75 lat. -38.25 lon. and FE region: Eastern Greenland (Kalaallit Nunaat).

provide the alignment of the event pulses. The SNR of an observed signal calculated by summing the coherent event signals from the array sites was improved with an array. All the seismic data were filtered with Butterworth band-pass filter between 35s and 70s and are displayed with a common amplification. All the signal traces were aligned and summed without any delay-time application. The important process during the beamforming was to identify the delay times, with which the single signal traces were shifted before summation ('delay and sum') to obtain the highest ampli-

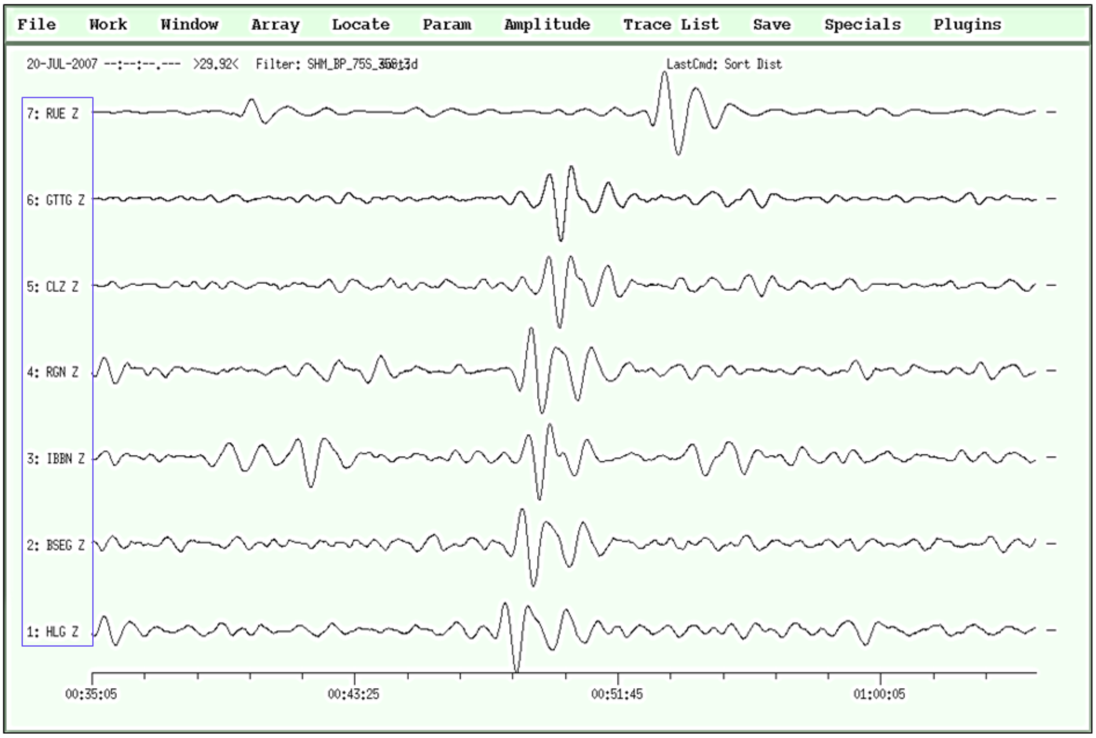

Figure 5. Mean root square residual: 1.38, distance: 26.8, beam-slowness: 30.0 ± 0.8 (x), beam-azimuth: 323.3 ± 1.2 (x), reference: CLZ, origin time: 20-JUL-2007_00:36:16.000, epicenter: 69.25 lat. -33.25 lon. and FE region: Eastern Greenland (Kalaallit Nunaat).

tude due to the coherent interference of the observed event signals. The onset times of the event signal on each trace were simply picked and the traces were shifted with respect to the onset time at the reference site of the array.

Computing event signals

The seismic data from the GRSN network are installed and read in the appropriate data window of SHM for monitoring and analyzing the event signals. The Butterworth bandpass filter is chosen to provide a good SNR. The slowness and azimuth of incoming waves are determined using visible minimum / maximum peaks of automatically picked up signals; then, the Plane Wave option of SHM is called. The resulting slowness and azimuth were checked using the Beam option of SHM to correct some of the essential phase readings and then, Location is called and the event is located. The following subsections present the stages of how the installed seismic data is read, monitored and analyzed using SHM software.

Reading the MiniSEED data format

The MiniSEED data format used in this study is a subformat of the commonly used SEED data format. It is suited to continuous data or for storing long time spans of data [7]. SHM accesses the MiniSEED format by start time and read length and reads only part of the file rather than reading a filename completely. SEED and MiniSEED data formats are quiet flexible and allow a large variety of subformat types. For reading the MiniSEED data with the read option, the dialog box of SHM should be correctly configured.

MiniSEED files are prepared as the GRSN stations are inserted (Fig. 1a). When all the stations have been configured, the menu entry Read is selected. This opens a dialog box. The appropriate buttons for stations, data channel (e.g., BH, LH, and HH) and component(s) (east-west, north-south, and z-vertical component) are selected. Date and time are chosen using the arrow buttons above and below the time field. The data are entered by specifying the station list, channel code, start time, read length, and components as shown in Figs. 2-5. In order to find the data file(s) to be read, SHM needs to have a directory file which contains the information about the location, filename and content of MiniSEED files called sfdfile.sfd (sfd refers to seed file directory) and resides in the data directory. SHM reads data that are given in such a file. Before processing the data in the MiniSEED format, sfdfile requires to be updated. The SHM package also contains a program to create sfdfile.sfd. After sfdfile.sfd has been generated, SHM reads the data files given. The SHM command for reading the MiniSEED data needs to have the location of the sfdfile.sfd.

Reading and filtering data

The requested data streams and time window are selec-

Table 2. Summary of the array parameters of the detected events (see Table 1 for the source mechanisms of the selected events and Fig. 1 for reference stations).

Glacial events	*RMS*	*Dist.*	*beam-slowness*	*beam-azimuth*	*epi-slowness epi-azimuth*	*Depth*	*Ref.*	*Origin Time*	*Epi.*	*FE region*
Event 1	*0.70*	*27.6*	*28.9± 0.7(x)*	*314.5± 1.2 (x)*	*not specified*	*0.0*	*GTTG*	*9-JUL-2007_ 01:08: 16.000*	*66.25 Lat. -37.25 Lon.*	*Eastern Kalaallit Nunaat*
Event 2	*0.83*	*28.1*	*29.6± 0.9(x)*	*312.4± 1.4 (x)*	*not specified*	*0.0*	*CLZ*	*9-JUL-2007_ 02:42: 08.000*	*66.75 Lat. -38.25 Lon.*	*Eastern Kalaallit Nunaat*
Event 3	*1.38*	*26.8*	*30.0± 0.8(x)*	*323.3± 1.2 (x)*	*not specified*	*0.0*	*CLZ*	*20-JUL-2007_ 00:36: 16.000*	*69.25 Lat. -33.25 Lon.*	*Eastern Kalaallit Nunaat*
Event 4	*0.51*	*32.5*	*29.0± 0.4(x)*	*322.4± 0.5 (x)*	*not specified*	*0.0*	*CLZ*	*4-JUL-2007_ 16:55: 20.000*	*69.25 Lat. -49.75 Lon.*	*Western Kalaallit Nunaat*

ted by opening a dialog box of the menu entry Read (the interface to the MiniSEED formatted data). The essential parameters; station list, channel, component, start time, length of time window and location of the directory file (sfdfile.sfd.) are chosen. Then, the Filter menu entry is selected and the desired Bandpass filter (35s-70s) is chosen in broadband waveform data. The filter is applied to the traces on the display and the read-in traces are filtered automatically. Then, the filtering is carried out on all the traces of the display if no trace has been previously selected. The resulting traces are displayed on the screen.

Plane wave

The epicentral distances of the recorded glacial events are larger than the aperture of the recording array of GRSN (Fig. 1). The major frequencies of the picked signals are in a range in which signal coherency is possible, indicating waveform similarity on the recording array (Figs. 2-5). Hence, the plane wave algorithm of SHM is applicable. Considering that the wavefront of the phase is a plane wave, the menu entry Plane Wave of SHM computes the array parameters, the slowness and backazimuth from coherent phases and uses all the phases of the name provided in the phase dialog box (Figs. 2-5). This algorithm detects the best fitting of the wave plane and parameterizes it by back-azimuth and slowness. The concluding values are given in the analysis parameter box and checked with the command Beam. The entry Beam needs to have the location entries (Lat. and Lon.) of the recording stations in the station information file.

Locating and sorting distances

After the locations (Lat. and Lon.) of the events have been manually written in the analysis parameter box and the appropriate settings of the reference stations have been checked, the epicentral distances to the chosen reference stations and the corresponding slowness are computed using the correction for ellipticity of the earth and the results entered into the analysis parameter box are shown. As a result, the epicenter locations are determined and all the traces are sorted according to the epicentral distance.

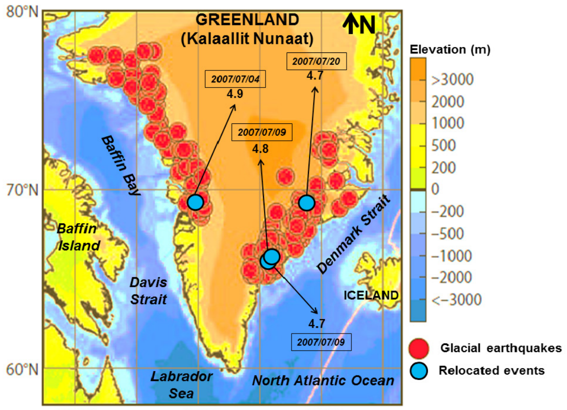

Figure 6. Glacial seismicity map showing 252 glacial earthquakes in Greenland for the period 1993–2008, detected and located using the surface-wave detection algorithm (data from [1]) and analyzed in detail by [4] (map modified and adapted from [1]) and also the locations of the four glacial events (magnitude and time) selected and analyzed in this study (see Tables 1 and 2 for related parameters). The tight clustering of the relocated epicenters is obvious near major outlet glaciers [1].

Array parameters

The GRSN array geometry (Fig. 1b) is defined by seismometers with two seismometers being assigned the roles of the two reference sites (CLZ, GTTG) during the data processing. The relative distances from the reference points to all other array sites are used in all array specific analysis algorithms.

A seismic wave approaches a given array with a plane wave front for much larger distances from the source (more than 10 wavelengths) [7, 10]. The propagation directions of the plane wave front projected onto the horizontal plane are basically identified by the two main angles; ϕ and θ [10]. ϕ is the backazimuth, also called beam-azimuth, which is an angle-of-wavefront approach, measured clockwise between the north and the direction towards the epicenter in [°]. θ refers to the direction in which the wavefront propagates is also measured in [°] from the north with $\theta = \phi \pm 180^{\circ}$. The angle observed between the direction of approach and the vertical plane is called the angle of incidence i with $i \leq 90^{\circ}$. The seismic velocity below the array site and the angle of incidence define the apparent propagation speed of the wavefront crossing the array site.

The crustal velocity with the incidence angle determines the propagation speed of the wavefront at the instruments and is called an apparent velocity v_{app} (not the physical propagation speed). v_{app} is absolute value of the apparent velocity vector in [km/s] of a plane wave crossing an array and a constant for a specific seismic ray traveling through a layered Earth model. Apparent velocity vector vapp is given by $v_{app} = 1 / s$. vapp = (v_{app}, x, v_{app}, y, v_{app}, z), where (v_{app}, x, v_{app}, y, v_{app}, z) are the apparent velocity components in [km/s] of the wavefront crossing an array site. The inverse of the apparent velocity is called slowness s (a constant for a specific ray), which we call beam-slowness here. The slowness unit is [s/km] for local or regional studies and [s /°] for global applications (the slowness is also known as the ray parameter). s slowness vector is given by $s=1/ v_{app}$. $s=(s_x, s_y, s_z)$, where (s_x, s_y, s_z) are the inverse apparent velocity (= slowness) components in [s/km].

The computed array parameters of the events are given in Table 2 and their locations are shown in Fig. 6.

Beamforming

The event signals in the glacial data collected from the GRSN network are detected during the data processing by SHM in this study. The signals of plane waves recorded at different sites of the GRSN array are more coherent than random noise. These signals are found to be very distinct from the background noise due to their amplitudes, magnitudes, different shapes, and/or frequency contents (Figs. 2-5 and Table 2). The delay times for each detected event at each station are automatically defined to calculate an array beam as shown in Figs. 2-5 by a specific beam-azimuth and beam-slowness combination. The calculated delay times and array beams depend on the position of the single sites with respect to the reference points (CLZ and GTTG) of the GRSN array (Fig. 1b) and to the backazimuth of the signal. The noises and amplitude differences in the signals influence the beam quality and hence, the improvement of the SNR due to the beamforming is essential. The event signals shown in Figs. 2-5 indicate forming signals with beam-slowness and comparing the amplitudes of the beams and reveal the best slowness-backazimuth combination that provides the maximum energy on the beam. The filtering-beamforming and beamforming-filtering processes are performed to test the traces and beams. Theoretically, both procedures give the same result and the superposition theorem of algebra for both beamforming and filtering is true [10].

CONCLUSION

In this study, we detected four long-period glacial events; M 4.9, 2007-07-04; M 4.8, 2007-07-09; M 4.7, 2007-07-09; and M 4.7, 2007-07-20 recorded at the stations of the GRSN array (GR and GE) and monitored the waveform patterns of these events for Greenland updated through 2008. The array geometry (GRSN) was defined by a set of seven stations; RUE, GTTG, CLZ, RGN, IBBN, BSEG, and HLG. The stations, CLZ and GTTG, were assigned the role of reference sites. We used the long-period surface waves (Rayleigh) to detect and analyze this new class of earthquake model in the context of array processing technique and array parameters using SHM.

The GRSN array geometry was processed to associate phase arrivals to identify glacial events. The surface wave characteristics of the detected events with magnitudes; M 4.9; M 4.8; M 4.7; and M 4.7, were provided to update the detection results. The glacial event signals were detected for use in the beamforming, filtering, and location-relocation steps. All the seismic data were filtered with Butterworth band-pass filter between 35s and 70s and were displayed with a common amplification. The beam traces using array-beamforming were computed using SHM. The beam-slowness (the apparent velocity) and beam-azimuth of the incoming wavefronts for particular time intervals were calculated to analyze the observed glacial events. Then, the detected event signals were relocated and attributed to estimate the array parameters; slowness, azimuth, and back-azimuth.

Finally, this paper summarized the processing steps of the array processing technique used with array parameters computed from the SHM for detecting the events and associated seismic signals of the detected events from regional seismic events using array installation data from the GRSN array. Considering the detected glacial events in this study, the array parameters using the array processing technique can be used to constrain the glacio-mechanical processes active in Greenland. Additional event observations from different regional array geometries for various earth-science purposes (e.g., in Turkey [11-13]) are needed to improve the understanding of glacial and/or non-glacial earthquakes.

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