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On-ice vibroseis and snowstreamer systems for geoscientific research

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Abstract

We present implementations of vibroseis system configurations with a snowstreamer for over-ice long-distance seismic traverses (>100 km). The configurations have been evaluated in Antarctica on ice sheet and ice shelf areas in the period 2010–2014. We discuss results of two different vibroseis sources: Failing Y-1100 on skis with a peak force of 120 kN in the frequency range 10–110 Hz; IVI EnviroVibe with a nominal peak force of 66 kN in the nominal frequency range 10–300 Hz. All measurements used a well-established 60 channel 1.5 km snowstreamer for the recording. Employed forces during sweeps were limited to less than 80% of the peak force. Maximum sweep frequencies, with a typical duration of 10 s, were 100 and 250 Hz for the Failing and EnviroVibe, respectively. Three different concepts for source movement were employed: the Failing vibrator was mounted with wheels on skis and pulled by a Pistenbully snow tractor. The EnviroVibe was operated self-propelled on Mattracks on the Antarctic plateau. This lead to difficulties in soft snow. For later implementations the EnviroVibe with tracks was put on a polyethylene (PE) sled. The sled had a hole in the center to lower the vibrator baseplate directly onto the snow surface. With the latter setup, data production varied between 20 km/day for 6-fold and 40 km/day for single fold for 9 h/day of measurements. The combination of tracks with the PE-sled was especially advantageous on hard and rough surfaces because of the flexibility of each component and the relatively lose mounting. The systems presented here are suitable to obtain data of subglacial and sub-seabed sediment layers and englacial layering in comparable quality as obtained from marine geophysics and land-based explosive surveys. The large offset aperture of the streamer overcomes limitations of radar systems for imaging of steep along-track subglacial topography. With joint international scientific and logistic efforts, large-scale mapping of Antarctica's and Greenland's subglacial geology, ice-shelf cavity geometries and sea-bed strata, as well as englacial structures can be achieved.

Keywords: Vibroseis; Seismics; Antarctica; Subglacial properties; Ice sheet; Ice shelf

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1. Introduction

When the first active source reflection-seismic measurements were carried out on glaciers (Mothes, 1926, 1927) as preparation for the 'German Greenland Expedition Alfred Wegener' in the early 20th century, the interest was to deploy a new method for the determination of the ice thickness of the Greenland ice sheet (Brockamp, 1935). In addition, their interest was also to use the seismic method for the determination of englacial temperatures. From the analysis of reflection seismic data Brockamp (1935) draws the conclusion that the seismic method will gain importance in the future to answer general glaciological questions particularly to determine the temperature regime and the elastic constants in ice sheets. However, after recognizing the advantegous characteristics of the propagation of electromagnetic waves in ice, the emphasis in the glacio-geophysical community was put in the development and application of the radar method. Especially for the determination of ice thickness and bed topography, radar methods have been very advantageous, as they can cover large distances in short time on airborne platforms. Consequently, less effort was put in advancing the application of ground-based seismic methods.

Thus, 75 years after Brockamp's statement, the basic operation of reflection seismic surveys on ice regarding the utilized source was still the same: explosives. These are deployed in boreholes several tens of meters deep to overcome the attenuating and wave-guiding properties of the firn column. Because borehole drilling to depths of 10–60 m requires both time and energy, standard seismic profiles in Antarctica and Greenland have been usually restricted to short sections several kilometers to at maximum of several tens of kilometers length per season (e.g. Peters et al., 2006; Horgan et al., 2011). Moreover, data have been often only acquired in single fold coverage, as emphasis was put on covering longer stretches rather than better quality for short sections. This partly also inhibited the application of rigorous pre- and post-stack seismic data processing, which requires multi-fold coverage.

Consequently, a considerable gap developed between the amount of coverage and degree of interpretation of marine and land-based ice-seismic data in the vicinity of the polar ice sheets (see e.g. coverage documented in the Seismic Data Library System (SDLS) data base (Cooper, 1991)). Large areas surrounding Greenland and Antarctica are already covered with marine-seismic configurations with ships using airguns as sources and pulling marine streamers as receivers. In contrast, on-ice reflection-seismic data mostly covers small local areas, considered to be key regions for ice dynamics (e.g. Horgan et al., 2013).

Despite the shortage in coverage, on-ice seismic methods have been contributing considerably to understanding the properties of ice sheets, the paleoclimatic interpretation of physical proxies retrieved from ice masses and their underlying strata. The true advantage comes along by combining the two active geophysical methods, radar and active source seismology. Compared to methods which directly access interior parts of the ice sheet, geophysics has the ability to deduce information about the three-dimensional body from measurements at its surface boundaries. Only airborne radar can provide the ice-thickness distribution (Fretwell et al., 2013) and the integrity of internal layering over larger regional scales, being of utmost importance for reconstructing paleo-dynamics (Siegert et al., 2004); aerogravimetry and -magnetics mutually yield regional high-resolution information about subglacial geological settings and their influence on ice dynamics (Blankenship et al., 1993; Bell et al., 1998); and active explosive seismics has been used to investigate the englacial and basal properties of ice bodies as well as the geology of the underlying strata on the local scale (Peters et al., 2006). The postulation by Anandakrishnan et al. (2007) to determine subglacial stratigraphy from ground-based low-frequency radar surveys was questioned by Jacobel et al. (2014). Thus, the one and only method to spatially map subglacial strata and determine their properties is active source seismology (seismics for short). The major shortcoming of operational land seismic surveys on ice is the comparable low production speed (the amount of profile progress per time) caused by the necessity of shothole drilling, charging and firing (e.g. King and Jarvis, 1991). Either a considerable effort of personnel operating in multiple teams is necessary (Sen et al., 1998), or data coverage is compromised in order to approach production speeds comparable to industrial land seismic data acquisition. Thus, the achievement of long-distance overland seismic surveys in Antarctica and Greenland with quasi-continuous data acquisition have so far been beyond reach. However, such traverses are considered an important means to unravel the subglacial properties of the ice sheets, as, for instance, envisaged in the next Scientific Committee of Antarctic Research Scientific Research Program ''Past Ice-Sheet Dynamics'' (SCAR SRP PAIS, Escutia et al., 2012).

To overcome present limitations in production speed of on-ice active seismic surveys the young investigators group LIMPICS ("Linking micro-physical properties to macro features in ice sheets with geophysical techniques") at the Alfred Wegener Institute (AWI), Germany, introduced the vibroseismic technique to glaciology (Eisen et al., 2010). Together with a snowstreamer (Eiken et al., 1989), we used three different types of vibrators, covering three orders of magnitude in peak force. The lightest version, an electrodynamic vibrator (ELVIS) with about 500 N peak force, is suitable for shallow investigations and high-resolution studies. However, it is not applicable for long-distance traverses on ice sheets with penetration beyond 0.5–1 km depth. Therefore, we will not discuss it here but refer to other publications for scientific applications (Diez et al., 2013; Polom et al., 2014).

This paper presents the final results and recommendations for two operational medium- (EnviroVibe) to heavy-weight (Failing Y-1100) vibroseis systems on firn and ice. It should provide a guideline for other institutions which either engage in vibroseis surveys with existing equipment or plan to implement new types of vibroseis systems. In the paper's main part we present the source systems, discuss their performance in conjuction with a snowstreamer at different field sites (Fig. 1) and demonstrate possible geoscientific applications of these systems. The appendix provides a detailed discussion on miscellaneous operational and logistic aspects, which are of interest for new or adapted implementations of vibroseis systems.

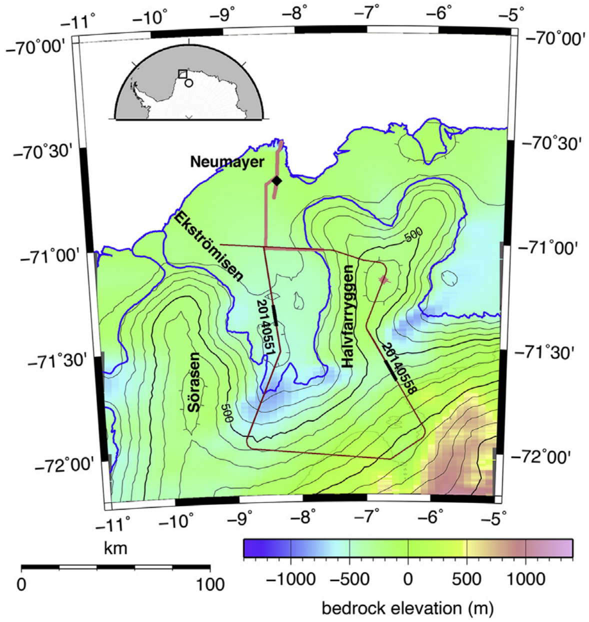

Fig. 1. Overview of the study region Ekströmisen and the Ekströmisen catchment, including ice sheet and ice shelf. Surface topography is given as black lines with 100 m interval. Interpolated bedrock topography is color coded, based on airborne radar (ice sheet) and gravimetry (ice shelf) data—not yet including seismic data; blue solid line: grounding line and ice-shelf front; thick red line: seismic traverse 2014; rose lines: seismic sections from 2010 to 2011 with different sources and frequencies. Sections displayed in Fig. 7 (20140551) and 8 (20140558) are labeled black lines. Inset shows study regions Ekströmisen (square) and Kohnen (circle) on Antarctic continent.

2. Vibroseis systems – general considerations

The vibroseismic method has been an established technique in industrial land seismic operations since the 1970s. However, it has never been applied on glaciers, ice sheets and ice shelves until 2010. Apart from the logistic support necessary to collect seismic data on ice masses, the major concerns in the community were: vibroseismic signals are too weak to reach far into the ice and underground because of diverging ray paths and high attenuation in the firn layer (Eisen et al., 2010); vibrator pads sink too far into the surface snow and firn, thus making vibroseismic operations useless. Whereas conventional explosive seismics creates a strong impulse of about a millisecond duration, a vibroseismic signal consists of a pre-defined sweep over a certain frequency range (e.g. 10–300 Hz) of typically 10 s duration and, thus, lower instantaneous forces and energy. Post-processing pulse compression by correlation with the original sweep creates a seismogram comparable to explosives. Previous resistance for employing vibroseismics on firn-covered ice stems from the experience that seismic waves are strongly attenuated in the firn column (e.g. King and Jarvis, 1991) (Firn on the Antarctic plateau is typically 50–150 m thick.). The conventional explosive seismic techniques therefore require to drill holes into the firn, typically 10–30 m deep, which is labor, time and energy consuming.

The main advantages of vibroseis systems are

- a source at the surface,
- known and repeatable source signal,
- increased safety.

The first issue implies that a vibroseis source does not generate a ghost signal, thus yielding higher data quality. Moreover, it avoids time-consuming drilling of shotholes. The second issue improves data processing, because the source signal's characteristics, especially bandwidth, are known. The source signals can be effectively stacked as often as necessary to improve signal-to-noise ratio (SNR). This is not possible in the same manner with explosives, because the borehole is altered considerably with every detonation, changing the characteristics of the source from one shot to the next in the same hole, especially for small charges (e.g. Sen et al., 1998; Smith, 2007). For most effective coupling and repeatability, it is in fact necessary to apply springing of boreholes (Sen et al., 1998).

The third issue, on the one hand, is important for the actual field personel operating with explosive materials. Despite construction- and handling-specific regulations, especially detonators always pose a risk of possible unwanted ignitions. On the other hand, as health-and-safety regulations are evolving over time and in general become more strict, the continued usage of explosives increases overhead time and expenses for administration and logistics. To ensure regulation-conform operations, the general purchasing and shipping of explosive material, especially to remote places like Antarctica, requires a fair amount of administrative work and licensed facilities for transport and storage on the way. For instance, operation in remote places with airborne deployment might require two separate flights in order not to have boosters and detonators on the same flight, thus increasing safety but also logistic expenses.

A further advantage is the directional excitation of ground motion by the vibroseis source. Usage of explosives in boreholes excite a spherical wave with almost equal radial particle motion over the sphere. In contrast, in a pressure-wave mode, elastic waves are excited at the surface by the vibrator baseplate in vertical direction, coming along with energy focusing. Although the vibrator does not excite a plane wave, this is energetically more efficient than explosives.

3. Field sites

The vibroseis systems have been tested at four different sites in Antarctica (Fig. 1) over the period 2010–2014 in very different glacial regimes:

Kohnen station. The German summer station (position at 75°0.1′S/0°4′E) at an elevation of 2900 m; it is characterized by typical Antarctic plateau climate. The ice is 2785 m thick. The survey took place in 2013.

Ekströmisen, near Neumayer III station (70°39′S/08°15′W). An ice shelf of some 100 m thickness and an underlying water column of several 100 m thickness. Surveys took place in 2010, 2011 and 2014.

Halvfarryggen (71°10′S/06°40′W). An ice dome about 120 km south of Neumayer III with a maximum surface elevation of about 700 m and an ice thickness around 900 m (Drews et al., 2013). Firn-layer thickness is about 80 m (Fernandoy et al., 2010). Surveys took place in 2011 and 2014.

Ekströmisen catchment area. The ice sheet upstream of the Ekströmisen grounding line, approaching the subglacial foothills of the Giæverryggen (71°45′S/04°45′W). The survey took place in January/February 2014 at an elevation range of 50–1050 m.

4. Vibroseis source types and characteristics

We used two conventional hydraulic vibrators, developed for and mainly used in industrial applications. The measurement sweeps of both systems were chosen to have 10 s duration with a 0.5 s long ramp at the beginning and the end of the sweep. Longer sweep length were employed, too, but with only marginal differences.

4.1. Heavy-weight source

The Failing Y-1100 is a heavy vibroseis source with a total vehicle weight of about 17 metric tons. In the standard configuration it is mounted on a 10 m long truck (Fig. 2). Sweeps can be adjusted in the frequency range from 10 to 110 Hz with a maximum peak force of 120 kN (27,000 lbs). The baseplate has a rectangular shape of 1 m × 2.5 m, i.e. an area of 2.5 m^2. It has been employed on the Ekströmisen (Kristoffersen et al., 2014) and on Halfvarryggen (Hofstede et al., 2013) with a 10 s long sweep 10–100 Hz at a maximum of about 70% (84 kN) of the peak force. This equals a maximum ground pressure underneath the baseplate of about 34 kPa.

4.2. Medium-weight source

The EnviroVibe (Industrial Vehicles Inc., IVI, US, Figs. 3 and 4) is a 8.5 metric ton vehicle in standard configuration, operated as a buggy. Theoretical maximum peak force is 66 kN (15,000 lbs). The circular baseplate has a diameter of 122 cm, equal to an area of 1.17 m^2. Nominally the EnviroVibe is capable to excite vertical pressure-wave sweeps in the range of 10–300 Hz. At Kohnen station, we limited the sweep to 10–220 Hz because this yielded best resolution. Sweep force was set to 60% of the peak force, i.e. around 40 kN or a maximum baseplate pressure of ~34 kPa. This was necessary to avoid sudden drops of the baseplate during sweeping, which could eventually cause severe damage to the vibrator itself. With the soft

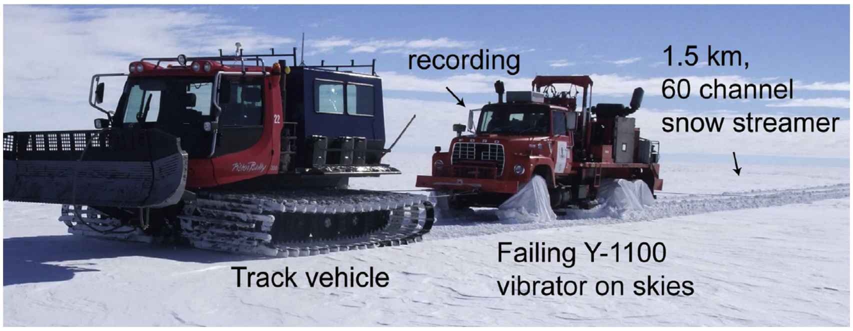

Fig. 2. Failing vibrator mounted on skis and pulled by a Pistenbully as used in 2010 and 2011 on Ekströmisen and Halvfarryggen. In 2011 the streamer was mounted to and pulled by the Failing truck. For wide-angle surveys, the streamer is pulled by a different vehicle, independently of the source.

snow conditions encountered at Kohnen station, the first sweep could lower the surface underneath the baseplate by as much as 25 cm. Therefore, not more than 3 sweeps were carried out at the same location.

On Ekströmisen and in the Ekströmisen catchment we employed sweeps in the range from 10 to 250 Hz at a maximum force of 80% (53 kN). This equals a maximum ground pressure underneath the baseplate of 45 kPa. Note that this is about 25% higher than the baseplate pressure for the Failing in the same region. We recommend these upper limits for frequency and force to avoid excessive wear of the servo valve. With the surface conditions encountered during the traverse in 2014, the first sweep compressed the surface in the range of 1–10 cm. Subsequent sweeps caused no further surface lowering.

Fig. 3. EnviroVibe with tracks mounted on a PE-sled. Note the hole in the middle to lower the baseplate onto the surface. The white cable at the rear is the streamer lead-in and runs on the opposite side of the vehicle to the cabin. The black rope pulls the streamer. The two eyes on the front and rear bumper (red arrows) are used to lead a second pulling rope when operating the streamer winch in front of the vibrator to change streamer offset (see Fig. 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3. Penetration depth

We estimate an upper bound for penetration depth of on-ice vibroseis-induced seismic waves based on overall travel path length observed in multiple reflections and maximum depth of coherent reflection events. As the penetration depth depends very much on the properties of the penetrated strata, mainly quality factor and impedance contrasts, the figures provided below should be considered orders of magnitude estimates.

Failing. Data examples are presented and discussed by Eisen et al. (2010) Hofstede et al. (2013) and Kristoffersen et al. (2014). Penetration depth of the Failing is estimated from the fourth multiple reflection from the ice–bed interface at Halvfarryggen at a two-

Fig. 4. Seismic train used in 2014 for the long-distance traverse on Ekströmisen and in its catchment. From left to right: Pistenbully Polar 300 pulling vehicle, living quarter, extended high-cube container set-up as EnviroVibe garage and workshop, freight sled with streamer winch, EnviroVibe on PE-sled. The streamer lead-in cable (white, far right) is guided to the front of the EnviroVibe and connected to the data acquisition units inside the operator's cabin.

way traveltime of 2.75 s for a 6-fold survey set-up. Deeper events were not recorded because the listening time was set to 3 s. With an average velocity of 3800 m/s in ice this corresponds to a total path length of about 10.5 km or 5.25 km distance in ice. Taking into account higher velocities in the basement of more than 5500 m/s (Diez, 2014), this corresponds to a penetration depth of more than 7 km. Achieving this upper bound for operation purposes is, of course, only possible if a sufficiently large reflection coefficient exists at that depth and wave attenuation is reasonably small. The latter is, for instance, the case in crystalline rock.

Estimation of penetration depth on the Ekström ice shelf is more difficult, because the record contains numerous multiple reflections from the ice–water and water-seabed interface. After data processing, clear events are visible at least down to 2 s (Kristoffersen et al., 2014). This corresponds to an approximate depth of 4 km for a typical average velocity of 4000 m/s.

EnviroVibe. At Kohnen station the first multiple from the ice-bed interface for a single sweep recording was observable at around 2.9 s (Fig. 5). This corresponds to a total propagation path of 4×2785 m = 11.1 km. In fact, the first multiple could also be observed during a wide-angle experiment with a source–receiver offset of 9 km, corresponding to a total path length of more than 14 km. For the polar plateau we estimate that penetration depths of up to 5 km into the geologic sub-ice strata are feasible, given high quality factors.

On Ekströmisen, the listening time was limited to 3 s for the sake of efficiency of data recording time. The raw shot records on the ice shelf usually showed coherent events down to a maximum two-way traveltime of 2 s. For operational applications we therefore estimate the usable maximum penetration depth of the EnviroVibe to be around 4 km for an average velocity of 4000 m/s. However, full advantage of the higher bandwidth of the EnviroVibe in contrast to the Failing pays off for imaging subglacial geomorphology and sedimentary strata in higher resolution (Figs. 6 and 7). Under those conditions the practical penetration depth for interpretation is limited to around 1000 m below the subglacial bed or seabed. At larger depths, the advantageous higher frequencies are lost and the reflected signature will differ considerably from the full-bandwidth source signals because of wavelet dispersion. Thus, the records become increasingly decorrelated at larger depths.

Comparison. The main difference between the two systems, Failing and EnviroVibe, is the sweep bandwidth and the peak force. Consequently, the recorded englacial and subglacial characteristics differ in terms of penetration depth, resolution and resolvable features. Which system to employ on long-distance traverses depends on the envisaged target. For imaging englacial seismic layering and subglacial (possibly sedimentary) stratigraphy on ice less than 2–3 km thick, the EnviroVibe would be the obvious choice (Fig. 7). For a comparision we refer to Hofstede et al. (2013) for englacial examples of the Failing system and Diez et al. (2014), Diez (2014) and Fig. 8 for the EnviroVibe. For imaging deeper targets, such as tectonic features (Kristoffersen et al., 2014), and on very thick inland ice a vibroseis source with the Failing characteristics is advantageous because of the higher energy input by the larger baseplate area with higher force.

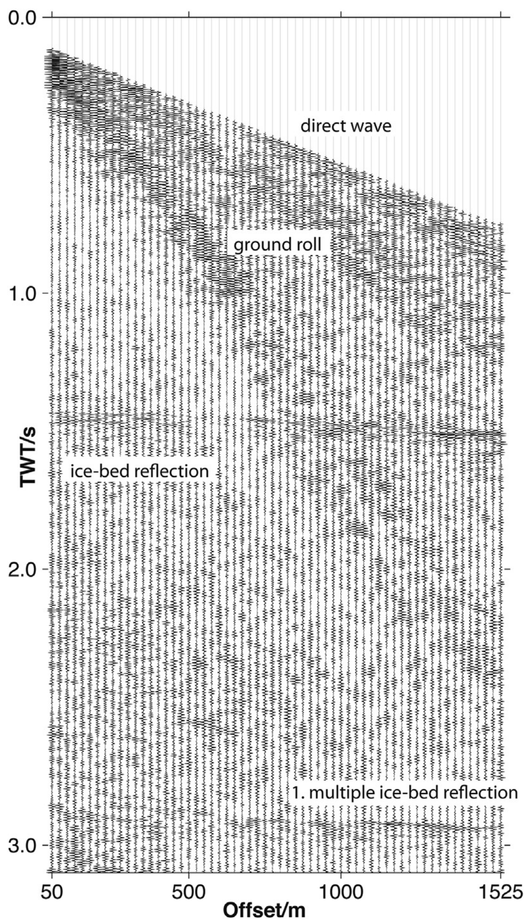

Fig. 5. Unprocessed single-sweep vibroseis recording 20130571 near Kohnen station as wiggle display. Ordinate is source–geophone offset along profile, abscissa is two-way traveltime (TWT). Source: EnviroVibe, 10 s sweep 10–220 Hz, 0.5 s taper, 60% peak force ~40 kN. Recording: 60 channel snowstreamer.

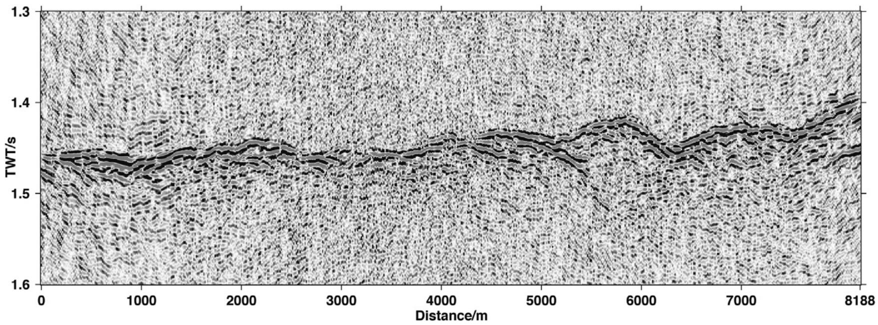

Fig. 6. Processed section of vibroseis profile 20130551 near Kohnen station focusing on the ice–bed interface at around 2800 m depth. Ordinate is distance along profile, abscissa is two-way traveltime. Source: EnviroVibe, 10 s sweep 10–220 Hz, 0.5 s taper, 60% peak force ~40 kN. Recording: 60 channel snowstreamer with a recording geometry of 15-fold coverage outside and 7-fold coverage within the Kohnen camp.

Industry and scientific applications have been demonstrating for decades that the combination of several vibroseismic sources, repeated stacking and high fold have the capability to allow imaging of even larger depths, such as the Moho (e.g. Steer et al., 1996). Repeated stacking and higher fold will, however, decrease the production speed of vibroseis surveys to the speed obtained with a low-fold but large charge explosive surveys, as for instance carried out by Sen et al. (1998). Nevertheless, the benefit of high-stack and high-fold vibroseis surveys for deep geologic features is favorable because of improved incoherent noise cancellation and imaging of structural dips. In addition, employment of vibroseis sources with low environmental impact might always be favorable at environmentally sensitive sites or where transport of dangerous goods is not feasible.

5. Vibroseis source movement

Commercially available vibroseis sources are either mounted as payload on an automobile vehicle or

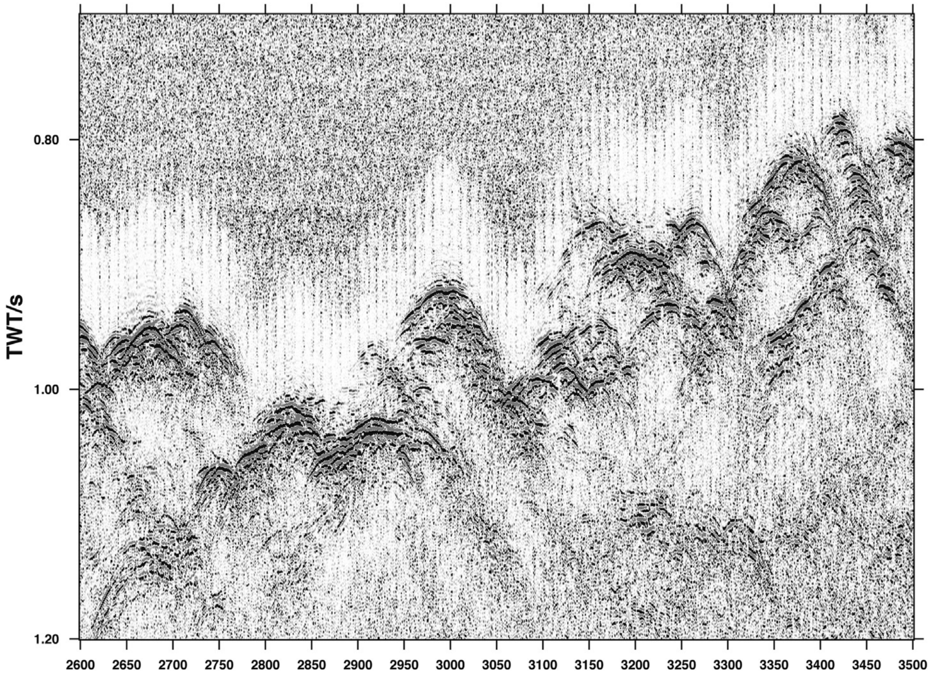

Fig. 7. Zoom of ocean floor seismic events of processed, unmigrated section of profile 20140551 recorded during the EKSEIS campaign on the Ekström ice shelf (see Fig. 1 for location). Ordinate is CDP number, abscissa is two-way traveltime (TWT). Source: EnviroVibe, 10 s sweep 10–250 Hz, 0.5 s taper, 80% peak force ~53 kN. Recording: 60 channel snowstreamer, 6-fold recording geometry, display of a single sweep per shot.

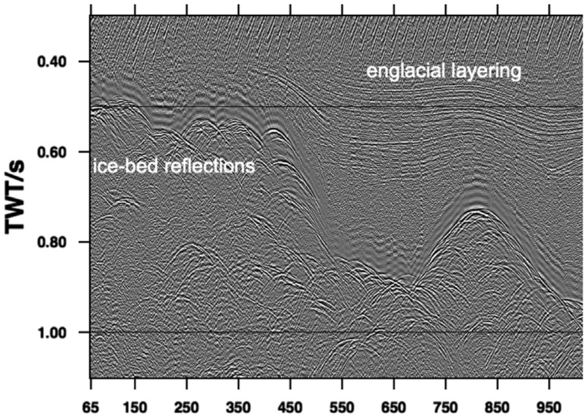

Fig. 8. Processed unmigrated section of profile 20140558 recorded during the EKSEIS campaign on the ice sheet south of Halvfarryggen over a deep trough (see Fig. 1). Note the numerous strong and continuous englacial reflections. Ordinate is CDP, abscissa is two-way traveltime (TWT). Source: EnviroVibe, 10 s sweep 10–250 Hz, 0.5 s taper, 80% peak force ~53 kN. Recording: 60 channel snowstreamer, 3-fold recording geometry, display of a single sweep per shot. The ringing visible above the bed event is an artefact of the sweep correlation required for vibroseis processing.

configured as trailers. For land-seismic applications, sources are moved independently of the recording truck, which hosts the data acquisition/recording equipment and remotely operates the sources.

5.1. Self-propelling

To implement an automobile vibroseis source for polar environment, the standard configuration of the EnviroVibe with off-road tires was changed to a tracked vehicle by replacing the wheels by Mattracks 7070 series tracks. This set-up was used at Kohnen station. However, the operation was problematic as the vehicle burried itself into the snow. This could be overcome for test measurements by preparing a groomed track for the EnviroVibe as is routinely done on Antarctic air fields. After settling for one to two days the EnviroVibe could propel itself on the hardened surface and carry out measurements. However, the vehicle was not able to pull the snowstreamer itself, first, because of the spinning of tracks, second, because of too low power provided by the engine. Therefore, we hosted the data acquisition system in a different vehicle, which also towed the streamer. A radio telemetry system (Universal Decoder and ForceTwo encoder from Seismic Source Inc.) performed the synchronous triggering of source sweep and data recording. Details are presented in the appendix.

5.2. Trailer configurations

Different types of vehicles have been used for pulling large loads for operation in polar environments. The advantage of trailers and sleds is that an established and well-proven vehicle can be used for pulling rather than introducing another vehicle type, a self-propelled vibroseis, with not well-known performance and possible risks. We tried several set-ups: the Failing mounted on skis and pulled by another vehicle; the self-propelled EnviroVibe with tracks; and the EnviroVibe mounted on a polyethylene PE sled. Details on the implementation can be found in the appendix.

Using skis and tracks resulted in severe problems because of sinking into soft snow. Most successful operation and least problems occurred with using a vibroseis mounted on a PE sled. We therefore recommend such or a comparable sled-based set-up for future operations.

6. Snowstreamer set-ups and operation

Application of a vibroseis system is especially advantageous when a snowstreamer is used for data recording, which can be pulled across the surface. It does not require any special treatment before a measurement. In contrast, spiked geophones or georods (Voigt et al., 2014) have to be deployed by hand, which is much more time consuming and labor intensive. We therefore only consider streamer configurations in the following section.

6.1. Geophone groups vs. single geophones

Our proof-of-concept studies in four Antarctic field seasons employed a 60-channel snowstreamer with a channel interval of 25 m (compare Eiken et al., 1989). Each channel consists of a group (or array) of eight SM-4, 14 Hz geophones mounted in a gimballed configuration in a casing type SG-1 (Sensor NL). In general, several geophones per channel, connected in series, increase the sensitivity of the system because of larger output voltage and higher signal-to-noise ratio. Moreover, their purpose is to reduce the effect of ground roll by destructive interference. However, for shallow targets at less than about half of the maximum offset (1.5 km), the angle of incidence for far offsets channels amounts to several tens of degrees. Consequently, the geophone group acts as a low-pass filter, not only eliminating ground roll, but also higher frequencies at oblique angles of incidence. Hofstede et al.

(2013) found this effect to be significant especially for englacial reflections. In contrast, single-geophone set-ups have a lower sensitivity than multiple-geophone groups, but are lighter and easier to handle.

6.2. Group spacing

To decrease group spacing we operated the streamer at various offsets from the same shot point or vice-versa. In the first two seasons it was also towed in a loop to effectively half the group spacing. Further details on technical implementation, streamer and maintenance operations, maneuvers, and accomodatable pulling velocities for the streamer can be found in the appendix.

7. Production rates

In contrast to marine seismic reflection profiling, where the data are recorded while cruising and cruising speed equals production rate, land-based seismics with a streamer requires the whole set-up to stop. The effective production rate consists of three components:

- residence time per shotpoint: ‘set-up’ and ‘production’ sweeps,
- shotpoint approaching deceleration and departing acceleration,
- transit speed between shotpoints.

The total time spent in residence at and in approach to/departure from shotpoints depends on the number of shotpoints and number of repeated shots at the same shotpoint location. In contrast, the transit speed is a fixed value, depending on the system. It depends on how long a distance can actually be covered at transit speeds. We discuss each point separately based on the experiences of the long-distance traverse in 2014 in the appendix. A video of a typical occupation of a shotpoint is available at: https://www.youtube.com/watch?v=iLQEuUy-_mQ.

In summary, as the distance between shotpoints depends on the data fold, this in turn determines the possible production rate in a non-linear way. During the 2014 traverse we performed measurements with single, 2-, 3- and 6-fold geometries. The average production rates for these folds is shown in Table 1. Because these are based on empirical data and take into account some other factors for delay, e.g. replacing geophone groups, they do not exactly match the numbers provided for an optimal survey. Nevertheless, they are the best guess to plan vibroseis surveys with the available set-up. While six people participated in the traverse, only three were necessary for vibroseismic operations and one person for occasional repair.

Table 1
Production rates depending on acquisition geometry for the 1.5 km long, 60 channel streamer with one set-up sweep and two 10-s production sweeps with a listening time of 3 s. Daily production is based on a 9-h day of measurements and a transit speed of 6 km/h. Decreasing the channel spacing to 12.5 m by two streamer positions (see text) adds another 2 min per shotpoint.

Fold	Shot interval	Time per shotpoint	Production rate	
	m	min	km/h	km/d
1	750	10	4.4	40
2	375	6	3.7	33
3	250	4.5	3.3	30
6	125	3.5	2.2	20

8. Summary

Two different vibroseis systems have been successfully deployed in Antarctica. Most efficient is the usage of a system mounted on a dedicated sled and pulled by an independent tracked vehicle. Production speeds were limited by the snowstreamer, which showed an increasing damage rate of geophone groups for towing velocities above 6 km/h. The sled-mounted source configuration itself could easily accommodate transfer velocities of 15 km/h. A streamer winch mounted in front of the vibroseis source on a separate sled was used to pull the streamer forward by integer fractions (two or four) of the 25 m spacing interval while the EnviroVibe was stationary. We were thus able to combine several sweeps at the same source location with various streamer positions to increase spatial resolution of the recordings. Data analysis demonstrates that sea floor geomorphology and stratigraphy underneath ice shelves can be imaged in a comparable quality as with open ocean marine reflection seismics. Considering single shots, ice sheet subglacial sediment layering and englacial layering can be imaged with a quality comparable to conventional explosive charges, in the respective resolution of the source's bandwidth. In comparison to airborne and ground-based radar surveys, the vibroseis–streamer system combination is able to quickly image very steep in-line sidewalls of subglacial trenches because of the large offset aperture where radar systems cannot provide any reflections. Due to the more efficient surveying with vibroseis, it enables the recording of a much higher fold than explosive charges within the same period. Hence, the possibilities for data pre- and post-stack processing are greatly extended, improving overall quality of processed data. Our operational systems presented here will help to considerably improve the future characterization of subglacial and englacial environments in Antarctica and Greenland.

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Appendix A. Details on vibroseis movement

Self-propelling

Exchanging tires with Mattracks 7070 units on the EnviroVibe increased the total weight to about 9.500 kg. With a track widths of 460 mm and ground contact length of 1090 mm for hard and 1575 mm for soft surfaces, respectively, the total contact area of four tracks (each about 350 kg own weight) is in the range of 2–2.9 m^2 for the whole vehicle for hard and soft surfaces, respectively. The effective ground pressure under the tracks for a total net weight of 9500 kg plus 500 kg operational load (two operators, fuel, data recording equipment, etc.) is therefore at least 34 kN/m^2.

The dry snow on the polar plateau near ice divides, as in the case of Kohnen station, is relatively soft and loosely packed, apart from some thin surface crusts formed mainly by wind. The EnviroVibe dug itself in with the rear tracks, which carry 10% more load than the front tracks. Apart from the weak snow conditions, digging in was also enabled by a missing synchronizing hydrostatic transmission lock between front and rear tracks and a comparatively weak engine, suffering power drop for the ambient air pressure of around 685 hPa. Once the rear wheels started spinning the vehicle was not able to move itself out. External salvage was necessary. Seismic operation was only possible on groomed and refrozen tracks, where the snow surface was harder.

Trailer configurations

Skis. In both field seasons the Failing vibrator was mounted on specially designed skis, which were modified for the second field season (Fig. 2). The wheels of the truck were chained to the skis. The vehicle was pulled by a fixed A-frame towing bar at the front bumpers, directly connected to a Pistenbully. Towing the Failing worked, in principle. However, for soft snow conditions, e.g. warm days with cloud coverage near the ice edge of Ekströmisen or unconsolidated snow on Halvfarryggen, the skis sank partly up to half a meter into the snow. At times, two Pistenbullies were necessary to pull the Failing. Although this configuration enabled data acquisition along more than 150 km in two seasons without serious damage on the truck, we recommend this configuration for pilot studies only. Clearly, the ground pressure underneath the skis was too high. Over time, the shear stress on the vehicle axles, especially in rough terrain, will likely be larger than for designated land-based off-road operations. Some sort of failure could therefore be expected.

PE sled. The experiences with the self-propelled EnviroVibe at Kohnen station and the ski-mounted Failing led to the conclusion, that operational deployment is only feasible with a dedicated trailer or sled. For the field season in January 2014 the EnviroVibe was therefore put on a double layer of high-molecular weight polyethylene (PE) sheet (Mentor Dynamics, MD, USA). Its molecular surface characteristics provide very low friction on snow. In contrast to metal, ice does not stick or freeze onto the PE surface, i.e. the sled can always easily be moved.

Cargo straps were put through several long slots at the sides of the sheet to tie down the EnviroVibe's tracks (Fig. 3). Wooden blocks at the rear avoided sliding back of the tracks. The front and rear of the sled were bolted together with supporting metal plates on top and underneath the PE sheet. A hole in the center of the sled allowed lowering of the vibrator baseplate directly on the ground. At the rear side of the hole the double sheet was also bolted together. The towing bar was an A-frame connected to the sled's front plate by two shackles. The towing bar was connected to the rear hook of a freight sled (Fig. 4). A 30 cm long piece of 5 cm angle steel on the rear of either side of the PE Sled served as stabilizing fins to avoid sideways movement. The rear plate accommodated an eye to pull the snowstreamer. This configuration had the advantage, that the streamer served as a rear anchor stabilizing the sled, especially downhill on hard and rough terrain, where the fins had little or no penetration into the surface. At the same time the force for pulling the streamer does not need to be accommodated by the vibrator and the mounting construction onto the sled, but directly by the sled.

With this configuration we performed a more than 500 km long traverse in January/February 2014 within three weeks. A distance of 407 km was covered with seismic reflection measurements. During the survey we found that it is of utmost importance that all components are loosely connected to each other and have some clearance to reduce the amount of instantaneous stress and allow for some small movement. This is certainly a necessity for the towing bar and the track-sled mounting. Moving the cargo straps from the metal pieces of the Mattracks onto the rubber tracks decreased the amount of wear considerably, because the rubber tracks themselves were also flexible enough to move slightly back and forth. Especially on rough terrain, the lose mounting of the tracks onto the PE sled helped to avoid damage, because the sled could smoothly adapt to small-scale surface undulations on the orders of several decimeters. Each track could separately adjust to the changed shape of the sled. The vehicle as a whole was only subject to minor tilt, but much reduced shocks.

Appendix B. Details on snowstreamer operation

Streamer maintenance

A major difference of single-geophone channels vs. geophone groups comes along with the movement of the streamer across the surface. A snowstreamer has the tendency to rotate around its own axis. Thus the geophone groups, each covering about 21 m, spiral themselves around the main cable. In the worst case, this causes the group cable to rip from the geophones if some sort of resistance occurs in pulling direction. Therefore, it is necessary to unwind the group cables on a regular basis from the main streamer cable. Single-geophone groups have shorter connection cables. They can thus be unwound much easier.

As the streamer cable is always under tension, individual geophones are at times hanging in the air over undulating ground. In the case of a geophone group, usually several geophones of a group are nevertheless in contact with the ground. With a geophone group, data acquisition is still possible in this case. In the case of single-geophone streamer set-ups, as used in Greenland in September 2013 in a different study, it sometimes happened that the geophone was not in contact with the ground anymore, basically leading to a dead channel for a particular shot.

The gimballed geophones consist of a cylindrical metal housing with conical terminations for lower resistance. As the streamer digs its own groove during operation, especially in soft snow up to 15 cm deep, the geophones are often within that groove. Depending on weather conditions, geophones are regularly solidly frozen into the groove over night. They therefore have to be manually removed before starting the daily operation. Otherwise, there is a high risk that the cable between the geophones are ripped out of the geophones when starting to move. Or that the connection is pre-damaged such that the group fails later, if resistance during movement is too large. For hard surfaces, the streamer groove is usually not that deep, if present at all. Nevertheless, the geophones can freeze to the ground over night.

To minimize damage we employed a standard procedure: after terminating daily data acquisition the streamer and the geophones were lifted out of the groove onto the surface. With 3–4 people and a snowmachine this took about 30 min. The next morning, all geophones were checked whether they are frozen to the ground. If so, they were freed by sideways movement. This took another 15 min for 3–4 people.

Channel health was monitored by observing the noise record window of all channels while the whole system was moving. Replacing a broken channel on the streamer using a snowmachine to drive to the respective location took about 15 min.

Increasing spatial resolution

The streamer geometry with a channel spacing of 25 m is too coarse for some applications, especially shallow events. First, a geophone group acts as a low-pass filter. Second, coarse spacing leads to spatial aliasing, thus limiting the usable frequency content of the data. This can be overcome by combining shots with different offsets between source and streamer. Preferably, the offset difference should be an integer fraction of the channel spacing (e.g. 12.5 or 6.25 m in our case). This can be realized by either leaving the streamer in position and moving the source or vice versa. Moving the source for fixed streamer positions was realized with the decoupled set-up of Failing vibrator and streamer. For the combined set-up as used in 2014, i.e. the streamer towed by the PE sled behind the EnviroVibe, the streamer was moved independently of the vibrator. A shortened-offset geometry was implemented by mounting the streamer winch on a freight sled in front of the EnviroVibe (Fig. 4). The winch was connected to the streamer tow-point by a second rope (which was guided through eyes on the side of the EnviroVibe).

This allowed us to use two geometries: the ordinary geometry and a shortened-offset geometry. The ordinary geometry corresponds to the offset between vibrator and streamer being equal to the full extension of the lead-in connection between streamer and the PE sled, about 50 m. After recording the sweeps in the ordinary set-up, the streamer winch pulled the streamer forward by 12.5 m. Then two more sweeps were recorded. When the seismic train moved to the next point, the streamer winch released the rope back to the ordinary geometry. Merging the recordings of the ordinary and shortened geometry results in a combined virtual shot record with 120 channels at 12.5 m channel spacing.

Usage of the hydraulic streamer winch has several advantages: it is strong enough to pull the streamer; a large diameter together with the hydraulic engine ensures high pulling speeds and thus short times for pull and release. Regarding the production speed, this operation with two additional measurement sweeps adds about two minutes per shotpoint.

Other implementations considered the usage of typical electric winches for off-road vehicles. Although these can pull the streamer, the pulling speed of several meters per minute is orders of magnitude lower compared to the streamer winch. Therefore, these implementations were discarded.

Streamer maneuvers

Seismic profiles should in general be as straight as possible. This is typically only possible on the polar plateau, away from ice streams. In regions with subglacial topography, near the grounding line or on ice shelves in general, the profiles must be laid out such that crevasses are avoided to ensure a maximum of safety for the operating crew. A detailed reconnaissance and track layout should be carried out before entering that region with a streamer in operational mode. Making sharp turns with a 1.5 km snowstreamer, however, is not possible without causing damage. The main cable and the groups are dragged sideways, spiraling up even more than during normal operation, and again causing the ripping off of geophone connections. As winding and unwinding the streamer takes about 2–3 h with a team of four people, we investigated two other ways to carry out maneuvers with an unspooled streamer.

U-turn. It is possible to turn a streamer by 180° in a short amount of time. The pulling vehicle (without sleds) drives along the remaining part of the streamer offset laterally by a distance of a couple of meters. The distance over which the geophones are dragged sideways (i.e. not in their intended direction of pull) is thus minimal, avoiding damage. We recommend that a person is following this operation at the actual bend.

Gradual curves. For other maneuvering we used gradual turns of 10° per 750 m, which corresponds to a turning radius of about 4 km. In fact, we continued measurements along the curve in single fold. We experienced no problems with the streamer during these operations. The streamer basically stayed either in its own groove or at least within the vehicle tracks.

Appendix C. Details on production speed

Residence time

In standard operation a single ‘set-up’ sweep and two ‘production’ sweeps are carried out at each shotpoint. The lowering of the baseplate and performing the set-up sweep takes about 15 s. To a production sweep of 10 s the listening time of 3 s has to be added. Moreover, data transfer to the acquisition computer has to be taken into account. We used three Geometrics Geodes with 24 channels each. The data transfer after recording took about 20 s for 60 channels for a recording window of 13 s. Thus, the first production sweep takes about 33 s in total. The second production sweep only requires 20 s, because the baseplate can be lifted right after the 13 s recording has been accomplished, while data are still transferred to the acquisition computer. Likewise, the “go”-command to the driver in the pulling vehicle can be issued while the baseplate is still being lifted. Based on several thousand shotpoints occupied in this manner, an average residence time of 70 s per shotpoint is reasonable.

Shotpoint approach and departure

Navigating to the shotpoint requires a reduction of the transit speed of the seismic train a certain distance before the shotpoint. The distance spent while decelerating depends on GPS quality and other navigation aids, but amounts to some tens of meters. Likewise, after shotpoint occupation the train has to accelerate again. We estimate that about 2 min are spent at speeds less than the transit speed between shotpoints while in approach or departure from the shotpoint, covering about 125 m. This of course depends on the environmental conditions and the skills of the driver, but proved to be a lower limit for accurate occupation of shotpoints. Taken together, the residence time of each shotpoint and approach/departure times amount to about 3 min. For shotpoint distances of more than 125 m (i.e. less than 6-fold coverage for our streamer), the remaining time and distance was spend at transit speed of 6 km/h. This also implies that for 6-fold or higher the transit speed is never reached. Hence, it does not matter which is the maximum possible transit speed for average production rates.

Transit speed

For single fold-coverage with 750 m shotpoint interval, transit speeds of 10, 8 and 6 km/h were tested for several hours to be able to judge the performance of the whole system. We found that the damage done to the streamer groups increases considerably with speed. For example, on one day with a relatively hard surface, a transit speed of 10 km/h led to the failure of 10 geophone groups within several hours. As mentioned above, the replacement of a single group takes about 15 min. Thus, in total about 2.5 h were spent on that day for replacing geophone groups. The higher transit speed was consumed by the increasing streamer failure. The situation improved for a transit speed of 8 km/h, but group failure was still unacceptably high. For a speed of 6 km/h, daily failure rate came down to about none to one or two groups. We considered this an acceptable rate and thus performed the majority of the survey at this transit speed.

Appendix D. Miscellaneous

Baseplate operation

Common vibroseis controllers allow the usage of so-called half-up switch. It allows the baseplate to be lifted only half way up, ultimately to save time. We do not recommend the use of these switches for on-ice surveys. Instead, we recommend to even lock the baseplate lift system during shotpoint transit. Experience shows that the baseplate can actually lower itself during transit from one shotpoint to the next under rough conditions. If the baseplate hits the ground while moving, irreversible damage could be done to the vibroseis actuator.

Wideangle surveys

Two wideangle surveys with offsets up to 9 km with the EnviroVibe as a source were carried out at Kohnen station. This is only reasonable if the vibroseis source and the streamer with data acquisition are already hosted in different trains, as decoupling the streamer from the vibroseis source and removing the data acquisition system is time intensive. A more efficient way is the combination of the vibroseis source for profiling with explosive sources for wideangle surveys. This has been carried out repeatedly during the 2014 survey. A second train with drilling equipment and explosives starts preparing the shotholes several kilometers ahead of the vibroseis train. The vibroseis train then passes the shotholes. The explosive-survey geometries are chosen such that they match the streamer positions of vibroseis shotpoints, i.e. the streamer is used in the same position for fixed-offset vibroseis recordings and wideangle explosive recordings. Once the streamer is in the desired distance to the shothole, the occupied streamer location is first used for a profiling vibroseis shot. Afterwards, the explosive shot is recorded at the same position. The vibroseis/streamer train then moves on to the next shotpoints, while the shooting crew moves backward to the second explosive shotpoint. With this configuration, the vibroseis/streamer configuration can remain intact and the streamer has not to be turned. Triggering is achieved by using compatible telemetry encoders and decoders for vibroseis operation and explosive shooting. In our case, we used a BoomBox (an explosive decoder from Seismic Source Inc.), which is compatible with the Universal Encoder used for vibroseis triggering.

Shipping

To allow convenient shipping and overland transport without measurements, a vibroseis vehicle should be easily mountable on container platforms. In the case of the EnviroVibe, a high-cube 20′ container, extended by 0.6 m in the front and 0.5 m on each side, serves as shipping container, garage for shelter in bad weather as well as workshop. For the outlook of mounting a vibroseis system onto a sled, having the complete system consisting of vibroseis actuator, hydraulic aggregate and operator's cabin mounted on a container platform, preferably with removable side walls, is of advantage.

Outlook on using freight sleds

An obvious choice for a trailer set-up would be to mount the three basic units vibroseis actuator, hydraulic aggregate and operator's cabin on an established freight sled on skis. This has been considered over the years, but has not been implemented yet. As an example for evaluating such a vibroseis-sled combination we consider the freight sleds developed by the Alfred Wegener Institute. They have been proven as reliable and endurable for several decades now. Of particular difficulty is the clearance of the freight sleds. From the bottom of the skis to the top of the sled's platform the distance amounts to 93 cm. This height is the minimum distance to allow sled reliable usage in all types of Antarctic terrain, including very soft snow and 2 m high sastrugis. It is approximately equal to the lift system's stroke of the EnviroVibe (96 cm). It would thus not be possible to lower the baseplate much lower than a couple of centimeters into the snow surface.

This distance is considerably more than the lift cylinder stroke of the Failing (~70 cm). As these strokes are typical for available vibroseis actuators, any mounting endavour of a commercially available vibroseis unit onto a freight sled would therefore require an adjustment of baseplate clearance by some means. This is either possible by extending the lift system stroke, or by lowering the vibroseis system low enough above the surface. Using sleds with a lower platform would be possible, too, but complicate transport in regions with very soft snow or rough surfaces. For all types of encountered snow, we recommend that the baseplate's lower position can be at least 30 cm below the snow surface, allowing several sweeps at a single location. Otherwise, operation in soft snow might be hampered, even if the sled itself sinks in several decimeters.

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