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INVENTION DISCLOSURE

Invention: Means and method for mitigating shot interference during a seismic survey

Date: February 13, 2017

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Field of the Invention: Land and Marine Seismic Acquisition

Abstract

There is an economic need to boost productivity in seismic surveys. This has led to continuous data acquisition techniques in which there is insufficient listen time between shots to allow for all reflected energy to dissipate. This gives rise to the presence of residual adjacent shot energy contamination in a shot gather. Oftentimes simultaneous data acquisition is carried on at the same time that uses a second source deployed at a different shot point location. The disclosed invention provides means and method to mitigate both crosstalk due to residual shot energy from the same source and crosstalk due to other sources operating simultaneously by utilization of a collection of special sweeps that are all constrained to cover about the same frequency range. In a preferred embodiment the collection of sweeps is comprised of a family of frequency-perturbed swept sine waves and a family of band limited pseudorandom signals, from which each source selects a unique sweep to be used at its current shot location based upon a rule. In another embodiment, the second source or other sources may cover a different frequency range than the first source, but have some spectral overlap.

References

US patent application 2016/0131776 describes a method for creating a family of sweeps that each span about the same frequency range, but are phase and/or frequency-perturbed. The perturbation is selected to reduce crosstalk between simultaneously active sources in which each source uses a different sweep from that set of phase-perturbed sweeps.

US patents 7859945 and 8619497 contain descriptions of how pseudorandom sequences can be modified to match a target spectrum with some form of level compression to boost their energy. US 8619497 describes how the signal is modified so that equipment limits are not exceeded. Furthermore, US 7859945 describes how the pseudorandom sequences can be modified to suppress cross-correlation noise between sweeps in that family over a time interval of interest.

The publication "First production application of high-density vibroseis acquisition on Alaska's North Slope" by Olivier Winter, Peter Maxwell, Ron Schmid, and Howard Watt, May, 2014, The Leading Edge provides a simultaneous sweep land application of HPVA that uses identical swept sine wave sweeps transmitted by different sources in a slip sweep model in which data is recorded continuously. http://www.cgg.com/technicalDocuments/cggv_0000020842.pdf

Summary

There are several embodiments disclosed to mitigate noise associated with continuous shooting, simultaneous shooting by sources that cover the same frequency range and simultaneous shooting by sources that cover substantially different frequency ranges but may have some spectral overlap. These embodiments include:

1) Creating a family of frequency-perturbed sweeps each covering about the same frequency range that are selected for use by a source following a rule.
2) Using frequency-perturbed sweeps by different sources that cover different spectral ranges but may have some overlap to mitigate cross talk noise in the overlap region that are selected for use by a source(s) following a rule.
3) Creating families of pseudorandom sweeps that all cover about the same frequency range that are level compressed to increase their power and are adjusted to reduce notches in their power spectrum that are selected for use by a source following a rule.
4) Creating a collection of sweeps that are comprised of families of frequency-perturbed sweeps and pseudorandom sweeps that are selected for use by a source(s) following a rule.

Background

In the past, on land Vibroseis surveys, typically a group of vibrators would advance to a shot position, execute a sweep with all vibrators in the group synchronized and then the emission would be followed by a listen time to allow time for the energy from a sweep to propagate and reflect and in some cases to allow reverberant energy to die out before the next sweep was initiated. Typically too, the vibrators would advance to their next position during the listen time. In land surveys, while conducting a seismic survey, more and more Vibroseis survey crews have employed continuous recording methods in conjunction with simultaneous shooting to improve productivity. More than one vibrator or vibrator array may sweep at the same time or with some overlap in time with each vibratory group using some form sweep technique that can be separated later in processing to provide different shot records corresponding to the location of the separate vibratory sources. In addition, new methods for example sparse sampling are being used in some cases to further reduce acquisition costs. In some applications a land vibrator may execute repeated sweeps, or a cascaded or concatenated sweep in the same shot location where the sweeps or sweep segments may or may not include some dead time (listen time) between segment/sweep emissions. In land seismic surveys, signals are typically detected by geophones. Because imaging targets of interest can be quite deep, the two-way travel time to a target of interest may be in excess of 8s in some areas and long sweeps in excess of 30s may be required to deliver the source energy required.

In conventional marine acquisition, sources and streamers equipped with receivers, for example hydrophones, are towed behind vessels with airguns fired at regular intervals, for example every 6 to 10 s depending upon the survey requirements, so as to provide uniform spatial sampling. With the introduction of marine vibrators, in order to achieve adequate spatial sampling, we need to initiate a new sweep every 6 to 10s, but in doing so we don't have time to introduce a listen time or the listen time may be too short between sweeps if the sweep duration needs to be 6 to 10 s to transmit the total acoustic energy needed per shot. If the same sweep is repeated again and again with no listen time or insufficient listen time for the received signal to die out, then this creates what we will call a wraparound apparition. Wraparound signal is received during a current shot record interval (the shot record interval is typically longer than the sweep length) that is due to signal from a previous or subsequent sweep transmission. In conventional Vibroseis, typically the data recorded is correlated with the sweep signal to produce correlated data shot records that resemble data recorded using impulsive sources. The correlation operation compacts the received transmitted signals into compact wavelets corresponding to the propagation time from the source to the receiver for different arrivals corresponding to direct, refraction or reflection arrival events. After correlation, the residual reflected signal from an adjacent shot will manifest itself as wraparound apparition, additional events in the correlated record due to an earlier and/or later sweep signal transmission that can appear within the arrival time of interest. These wraparound apparitions can make it more difficult to identify target reflection events that correspond to subterranean event horizons of interest. Furthermore, if the same sweep is used repeatedly, this wraparound apparition will tend to constructively interfere rather than be attenuated when correlated data is stacked in processing. Furthermore, this wraparound apparition is also present in received data when means other than correlation are used to compress the signal, for example signature deconvolution where a measured or modeled source signal is used to compute the impulse response of the earth.

In WAZ marine surveys often more than one source is utilized. The second source or other sources can be towed by the same vessel or by a separate source vessel that is offset from the receiver streamer in the crossline direction. This further complicates matters. During simultaneous source acquisition, signal contributions from all sources are received and recorded at the same time. Figure 1 illustrates a marine example where we have three vibratory sources deployed in a seismic survey, where for example VibA and Vib C may be towed behind a vessel that also tows a hydrophone streamer. VibA may execute a low frequency sweep and be deployed at 20m while Vib C may emit a high frequency sweep at about the same time and deployed at a depth of 5 m. In a WAZ survey Vib B, may be towed by a separate source vessel and execute a low frequency sweep also deployed at depth of 20m, but be offset crossline from the hydrophone streamer.

So a means to use vibratory sources without requiring a listen time, or a reduced listen time, and that addresses both wraparound noise and crosstalk from other sources without compromising data acquisition productivity is of value.

The disclosed invention describes how by using a collection of sweeps designed to cover about the same frequency band can be generated. That collection is comprised of two families the first using swept sine waves that are frequency-perturbed about the same parent sweep, and the second family are spectrally shaped level compressed pseudorandom signals.

Description

Please note the term “sweep” will be defined loosely as the desired signal to be transmitted by the vibrator. The sweep signal can be a swept sine wave, either linear of nonlinear, upsweep or downsweep or a concatenation of short sequences that are repeated with different phase offsets within the sweep time or an arbitrary waveform transmission, for example, a pseudorandom signal. Also note that the term continuous shooting will be defined as a repeated transmission of a seismic signal, for example a sweep, with no listen time between transmissions or with a small delay that is typically insufficient for energy transmitted during the current transmission interval to dissipate before a subsequent sweep begins.

The description begins with an example of the wraparound noise issue followed by various embodiments designed to mitigate problems associated with residual shot noise and crosstalk from other sources when simultaneous shooting is used. A section is also devoted to a means for generating a collection of sweeps comprised of sweeps from a family of frequency-perturbed sweeps and a family of pseudorandom signals.

Wraparound noise

The vibrator operates at shallow depth about 20m and the surface reflection will be ignored. Figure 3 shows the earth reflectivity series vs. the two-way travel time from the source to the receiver, and for simplicity we will assume the reflection times are spatially invariant. When sources are towed behind a seismic vessel in a conventional arrangement, typically the vibrator and the streamers will advance about 25m over a 10s interval. If the source and receivers depths are well controlled and there are no steeply dipping reflectors, the reflectivity sequence will change very little during the 10s interval, and of course the deeper the reflector is the less its arrival time will change as the sources and receivers move. In this example assume that Figure 3 shows the earth reflectivity sequence. Note that the reflectivity sequence has late arrivals at about 10.6s and at 11.7s. In this example we are interested in imaging reflection events with less than a 10s two-way travel time.

For simplicity we assume that only Vib A (shown in Fig 1) is in use and repeats sweep S0 every 10s. This repeated sequence of shots is shown in Fig 4 that shows the source advancing from shot point 1 (SP1) to SP2 and so on. In this case S0 is a linear upsweep frequency range of 4 Hz to 30 Hz using a 10s sweep length, it has a 0 degree phase offset. In this document, much reference is made to sweeps repeated as a function of time; however, instead of repeating a signal based on a time interval, a signal may also be repeated as a function of space. For example, we may begin the emission of a new signal every time the source reaches a pre-defined position in space, for example a pre-plot map of desired source positions. The pre-plot may relate to a regular sampling in space, or may, at least in part, relate to source excitations from a previous acquisition which we want to repeat (e.g. time-lapse survey). Due to variations in vessel speed (for example due to ocean currents), the shooting interval in time may vary. Considering a nominal speed of 2.5 m/s and a spatial sampling of 25 m, we would expect to begin a new sweep every 10 seconds. However, to allow for the case that vessel speed may increase to 3 m/s, we may reduce the sweep length to 25/3=8.33s. A longer sweep would mean that the desired spatial sampling would not be achieved. In reality the vessel speed will depend on a number of factors and may not be predicted in advance. As such, the sweep length may be adjusted during acquisition of the survey, calculated dynamically as a function of the vessel speed. In this idealized example, the sweep signal is assumed to be a scaled version of the actual pressure signal transmitted by vibratory source with no harmonic distortion present.

As VIB A sweeps and advances through the water, typically the data received by the sensor is continuously recorded to form a mother record, and that mother record is parsed to form daughter records or records corresponding to the various shot point locations. If the data is parsed into for example 20s segments, (10s for the emission and 10s for the energy to propagate with a 2-way travel time of 10s), and then correlated with pilot signal S0, then we get a correlated traces displayed in Figure 5. Figure 5a-d are the resulting correlated traces for SP 2, 3, 4, and 5 respectively. Note that 5a-d do not exactly match reflectivity sequence in Figure 3, there are wraparound apparitions 501 and 502 due to the late arrivals at about 10.6s and at 11.7s. These wraparound artifacts affect image quality and can complicate image interpretation. (Note surface ghost effects have been ignored for simplicity.) The potential for wraparound apparition (depends on geology and strong reflections at depth) will occur whenever the same emission signal is utilized for an adjacent shot, by changing some characteristic (frequency content, sweep rate, type of sweep, phase offset and so on) of the emitted signal on the adjacent shots the wraparound signal will not constructively interfere during the stacking process when shot records are combined. Not evident are wraparound apparitions due to the subsequent sweep, and associated with reflection arrivals with less than a 10s two-way travel time—in this case since we have assumed the geology has no dip these apparitions get mapped on top of the shallow reflection events for example at 1s. (If there was dip in this example, the wraparound apparitions due to the subsequent sweep would be evident.)

Wraparound mitigation using frequency-perturbed sweeps

Instead of repeatedly using the same sweep signal S0, we can use frequency and/or phase perturbed sweep signals that are derived from S0. A method of generating these is covered in US Patent Application 2016/0131776. Figure 2 is a flowchart depicting a procedure for generating a family of phase or frequency-perturbed sweep signals. The term Ns refers to the number of sweeps to be generated. This is the same flowchart that is explained in US Patent Application 2016/0131776. For now let us assume in an embodiment that we have created four different frequency-perturbed sweep signals from S0, called S1…S4 (we can generate just 3 or more than 4 as well). Figure 7 shows a repeating sequence (other sequences are possible) in which data is acquired such that for SP1-SP4, S1-S4 are emitted respectively; then the sequence repeats and for SP5, S1 is emitted and so on. The sweeps can follow a pre-determined sequence or by randomly selected, so long as this selection rule is observed. The selection rule being that the sweep to be utilized cannot have been in use in a time interval T1 prior. T1 is the expected two-way travel time for the deepest recoverable reflection event. (Comment, there may be some advantage to varying the sequence order. Also the method could be combined with phase offset changes such that the same frequency perturbations are used as before but the initial phase of each sweep is changed from time to time.) For the previous example, reflection sequence of Figure 3, with late arrivals at 11.7 s, T1 would be about 12 s.

Following the same procedure as before, the mother record is parsed into shot records and correlated with a selected pilot signal S1-S4 that corresponding to the signal emitted by the source at that shot point. Figure 7 a-d shows the correlated traces corresponding to SP2-SP5. Note that the apparition artifacts are missing, but there is some low level noise (cross-correlation noise) near those positions. Note too that the noise is different for each shot point. So by stacking the shot point records we can get some additional attenuation of this cross-correlation noise. Refer to Figure 8, trace 8a is the same as trace 7b (SP3 correlated record), trace 9b is a vertical stack (simple average) of correlated traces corresponding to SP1-5 and trace 8c is a median stack of correlated traces corresponding to trace SP1-5. Other means for combining traces are possible, for example trimmed mean. When the traces are combined the residual shot noise is reduced. Now in reality, the geology is not flat and the reflectors may have some dip, but still combining traces in subsequent processing steps will tend to attenuate these artifacts. Other processing means can be used to suppress them further since the cross-spectral properties of the S1-S4 are known and can be computed beforehand.

All the preceding examples have assumed that the reflection events are invariant as the source and/or receiver move from shot location to shot location. Furthermore, in most cases shot records are not simply vertically stacked in processing, generally some form of move-out correction is applied or other correction before shot gathers are combined. In practice the trace alignment and summation/averaging process may take the form of a migration or imaging process. Such algorithms may include Kirchhoff migration, beam migration, one-way wave equation migration, reverse time migration, or another type of migration. Migration algorithms may output data in the time domain or the depth domain by multi-channel process. The multi-channel process will combine traces from several shots to form an image of the subsurface. The multi-channel process will operate on the main signal energy, which is usually spatially consistent. However, as the wraparound energy will vary it will be attenuated during the migration process. So application in processing of some form of trace alignment may correct for variation in reflection event timing as source and receiver move. The main advantage of the invention is that wraparound apparitions do not constructively interfere and propagate through the image processing sequence. In the final display, thousands of shots may contribute to a single trace in the final display image.

In the common receiver domain, the wraparound noise will sit at the spatial Nyquist. As such, the wraparound noise may be, at least partially, be attenuated with a spatial Nyquist filter. Data in the receiver domain may be spatially aliased, which may cause complications. An alternative approach is some other kind of spatial (i.e. structural) filtering. This may include coherency filtering, fx prediction filtering, SVD, rank reduction, projection filtering, or another type of filter. Some spatial filters (e.g. fx filtering) will naturally attempt to predict the 2:1 pattern of the wraparound noise. For this reason, a filter may be derived at a first frequency and applied to a second frequency. For example, we may derive a filter at frequency f with spacing 2x, and apply the filter to frequency 2f with spacing x. The derivation of filters at a first frequency and application at a second frequency is the same principle as used in fx interpolation (Spitz, S., 1991, Seismic trace interpolation in the fx domain, Geophysics). Domains other than the receiver domain may be used, for example the common channel domain, cmp domain, common offset domain, etc. The spatial filtering approach may be combined with other multi-channel processes, for example data regularization or interpolation.

Figure 9 shows the amplitude spectrum for sweeps S1-S4 in the preceding example. Figure 10 shows the frequency perturbation profiles that were applied to linear sweep S0's frequency profile to form S1-S4. Figure 11 shows the frequency vs. time profile for S1-S4, which is the result of combining the frequency profile for S0 and the frequency perturbation profiles shown in Figure 10.

1. In another embodiment, we have two different sources operating simultaneously but covering substantially different frequency ranges with each source utilizing frequency-perturbed sweeps that cover substantially different frequency ranges. Refer to figure 1 where for example Vib A is a low frequency source covering the frequency range of 4-30 Hz and Vib B is a high frequency source covering the range of 25 to 100 Hz. Note there is some spectral overlap in the 25-30 Hz band. Vib A may be towed at a depth of 15-25 m and Vib B towed at a depth of 3-6 m. For this case, as before we can create a separate family of HF frequency-perturbed sweeps that cover the range of 25-100 Hz. Now the sweeps for LF and

HF need not be of the same sweep length, in some situations it may be desirable for the HF sweep to be of shorter duration to obtain finer spatial sampling in towed marine source. Also the start times for each LF and HF sweep could be different, for example a fixed time delay between the starts of each sweep. It can be appreciated that by sequencing through the family of HF sweeps, wraparound noise can be mitigated in the stack as we saw in the first embodiment if you use the same rule in sweep selection for the HF family of sweeps. The rule being that a sweep cannot be repeated until time interval T2 has passed. T2 is similarly defined as T1, but because HF energy tends to dissipate more quickly, T2 may not be the same length but actually a shorter interval of time. Since signals emitted by LF and HF sources for frequencies that are not common to both sources are orthogonal, the correlation process will tend to suppress any crosstalk. Crosstalk noise will however be present due to emissions in the spectral overlap region of about 25-30 Hz. Now because different members of LF sweeps and HF sweeps are selected at each shot point, cross-talk interference will tend to be smeared and randomized, so in processing this will be mitigated. If the source signal is known and/or measured, for example through the use of sensors mounted on or near the source, these signals can be used to compute a source separation matrix that is based upon cross-spectral density estimates. The source separation matrix can then be applied as part of a source signature deconvolution to improve the separation of the LF and HF contributions.

<u>Wraparound mitigation using pseudorandom and swept sine waves</u>

Instead of using frequency-perturbed sweeps, different pseudorandom signals can be used instead. If the prior and subsequent pseudorandom sweeps are not strongly correlated with the current sweep, as we sequence through a family of pseudorandom sweeps, the wraparound noise will be mitigated in later processing when the correlated records are stacked. One issue with pseudorandom signals is that they generally have less energy than swept sine waves, so in an embodiment different pseudorandom sweeps can be interleaved between frequency-perturbed sweeps to increase the energy. By using both PR and swept sine waves allows us to get around a limitation on the number of unique frequency-perturbed sweeps that can be created so as not to exceed a predetermined cross correlation level. Because frequencies are spread randomly throughout a pseudorandom sweep, when a PR sweep is correlated with a swept sine wave there is no distinct wavelet, but instead we just get some scattered smeared noise. If the pseudorandom sweeps are changing and/or the frequency-perturbed sweeps are changing then this will tend to randomize any wraparound noise due to cross-correlation between a swept sine wave shot point and adjacent shots in which pseudorandom sweeps were used; therefore, noise associated with residual shot energy that can result in wraparound apparitions will tend to be suppressed when stacked.

The pseudorandom signals used are designed to follow a target spectrum, for example a spectrum that is flat over a desired frequency range, or it could have some other shape. As has been mentioned before, band limited pseudorandom signals typically do not have the same power as a swept sine wave covering the same frequency band. Level compression can be used to boost the RMS level in the signal while keeping the peak below a prescribed level. Level compression in general will add harmonic energy outside the range of interest, so an iterative process needs to used to achieve level compression without compromising the target spectrum matching. Furthermore it is desirable that the source spectrum is fairly smooth to avoid artifacts in the correlation wavelet. Furthermore it is desirable that the members of the pseudorandom sweep family be weakly correlated with respect to one another, making it easier to separate their contributions. Another requirement is that the pseudorandom signals need to be designed subject to equipment constraints, for example actuator stroke and other limits like current, flow, voltage, velocity, acceleration, force and so on that depend upon the type of actuator used. Figure 13, shows a representative amplitude spectrum of a pseudorandom sweep from a family of LF pseudorandom sweeps.

The method can be extended to multiple sources acting simultaneously, with sources that emit acoustic energy over the same frequency range while others operate over a substantially different frequency range. The 3 vibrators shown in Figure 1 emit sweep signals selected from collections of sweeps following the sequence shown in Figure 13. Vib A and Vib C are assumed to be low frequency vibrators and can select from a LF collection of candidate sweeps. Vib B which is a high frequency vibrator uses sweeps selected from a HF collection of candidate sweeps. The LF collection contains a family of frequency-perturbed swept sine waves and a family of pseudorandom sweeps that are designed to cover a frequency range of about 3-30 Hz. The HF collection contains a family of frequency-perturbed swept sine waves and a family of pseudorandom sweeps that are designed to cover a frequency range of about 25-125 Hz. Other frequency ranges are possible. The rule becomes an LF source cannot repeat any LF sweep that any source emitted over the previous T1 interval. The same holds true for the HF source that it cannot repeat any HF sweep that any source emitted over the past T2 interval. The sweep sequences shown in Figure 13 show a pattern of sweep utilization that follows this rule. In this case the sweeps are all shown to be of the same duration and all sources begin and end their sweeps at the same time; however, the invention is not limited to this mode of operation. Source start and end times can be asynchronous with respect to one another. Also for the sweep utilization sequences shown, there is an alternating pattern between swept sine wave sweeps and pseudorandom sweeps; this is an option, but not a requirement. There may be some benefit to alternating between swept sine wave and pseudorandom sweeps to help randomize the residual shot energy and by including the swept sine wave sweeps in the mix boost the signal energy. The LF frequency -perturbed sweeps are labeled S and the LF pseudorandom sweeps are labeled PR, while the HF frequency-perturbed sweeps are labeled U and the HF pseudorandom sweeps are labeled QR.

Process:

1. Decide on the number of sources to be used and the frequency ranges for each source type
2. Determine the maximum two-way travel time for an arrival to determine T1 and/or T2 and so on
3. Generate a collection of sweeps suitable for each source type where the collection is comprised of a family of frequency-perturbed sweeps and/or a family of pseudorandom sweeps
4. Download the appropriate collection of sweeps in the memory of the source controllers where the sweeps are stored so that a sweep can be accessed upon command. For example the sweeps could be arranged in a table that is indexed.
5. When the source management system is notified that a source is in position, a sweep is selected for that source based upon a rule.
6. The source management system sends the sweep index number to the source
7. The source emits its sweep.
8. Process repeats until the survey is complete

GPS times could also be used to determine the sweep schedule.

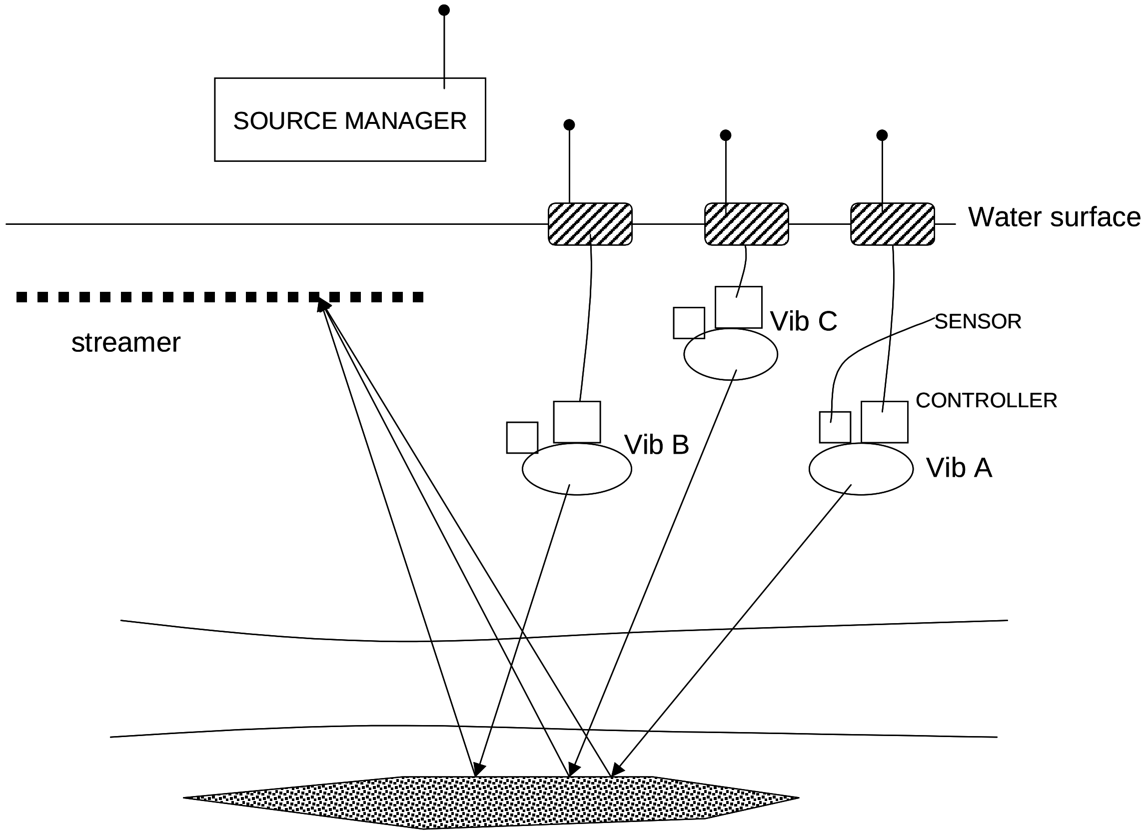
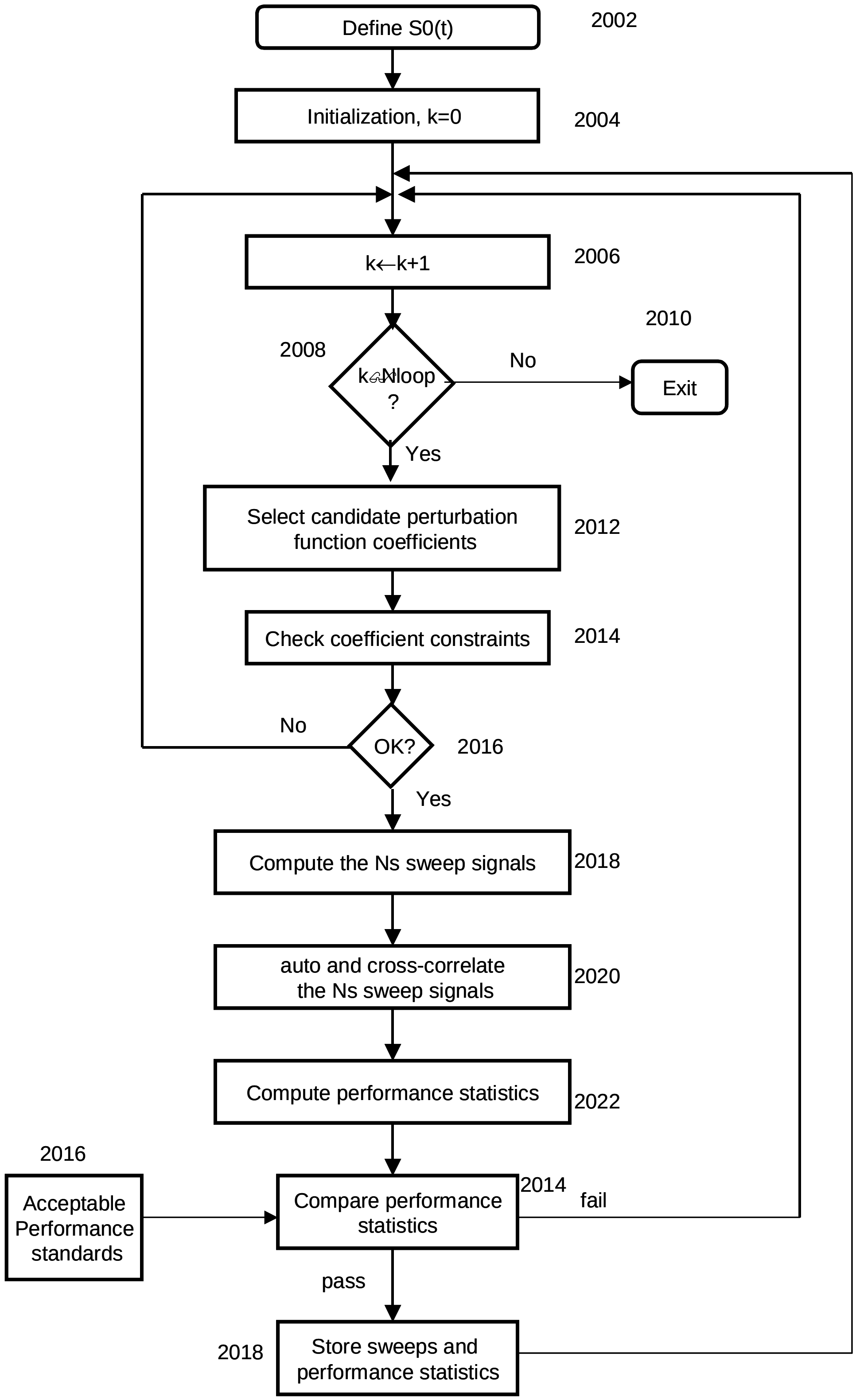

SOURCE MANAGER
Water surface
streamer
Vib C
SENSOR
CONTROLLER
Vib B
Vib A

Figure 1



Define S0(t)
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Initialization, k=0
2004
k←k+1
2006
2010
2008
k≤Nloop
?
No
Exit
Yes
Select candidate perturbation function coefficients
2012
Check coefficient constraints
2014
No
OK?
2016
Yes
Compute the Ns sweep signals
2018
auto and cross-correlate the Ns sweep signals
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Compute performance statistics
2022
2016
Acceptable Performance standards
Compare performance statistics
2014
fail
pass
2018
Store sweeps and performance statistics

Figure 2

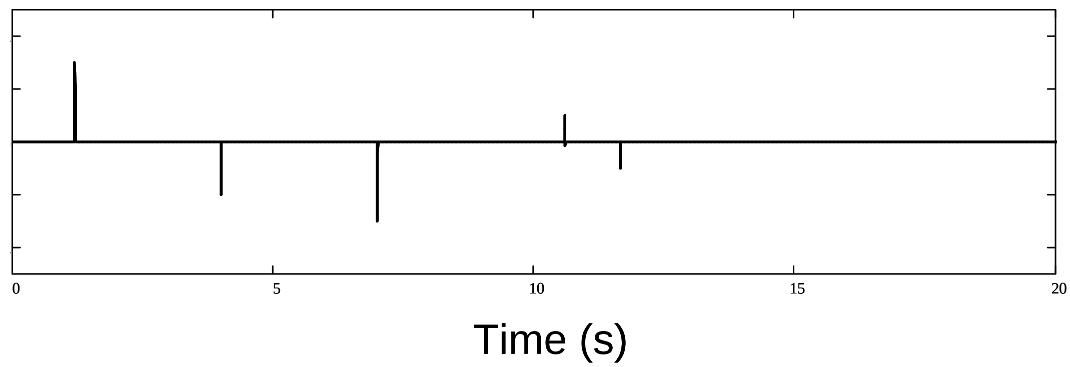


Figure 3

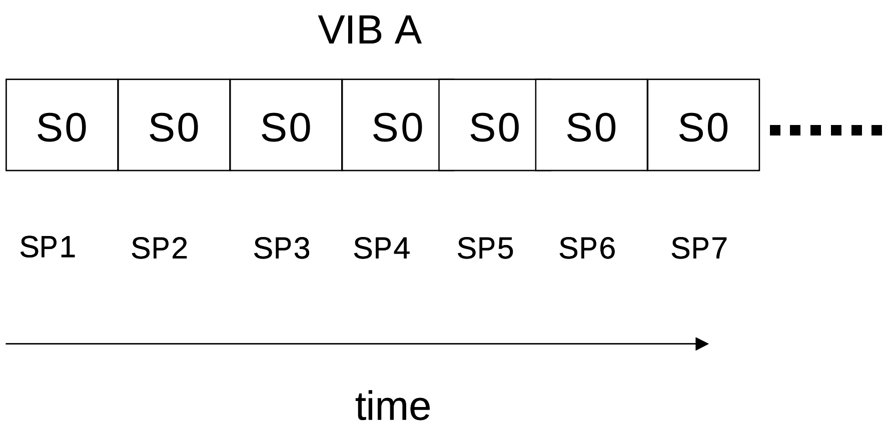


Figure 4

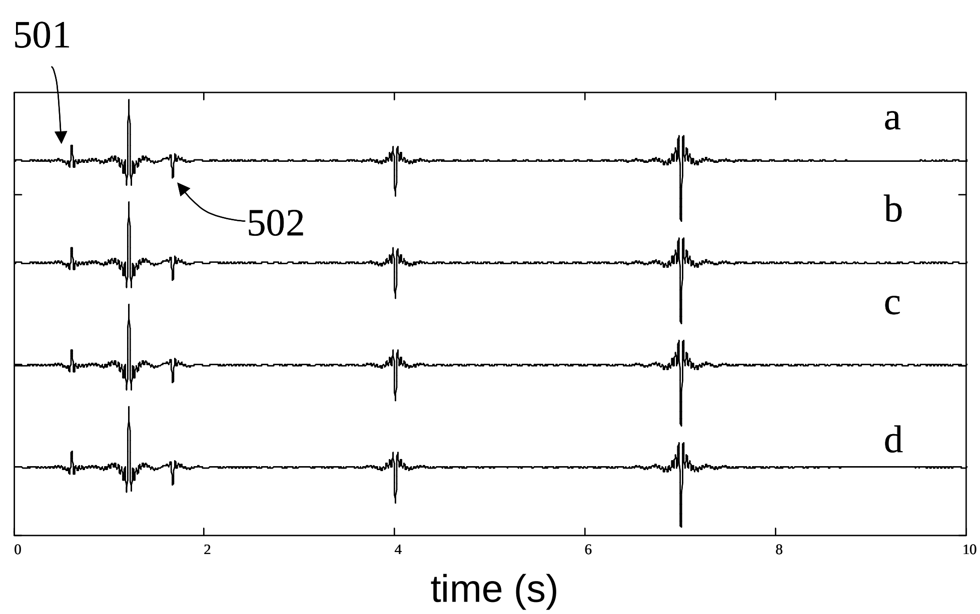


Figure 5

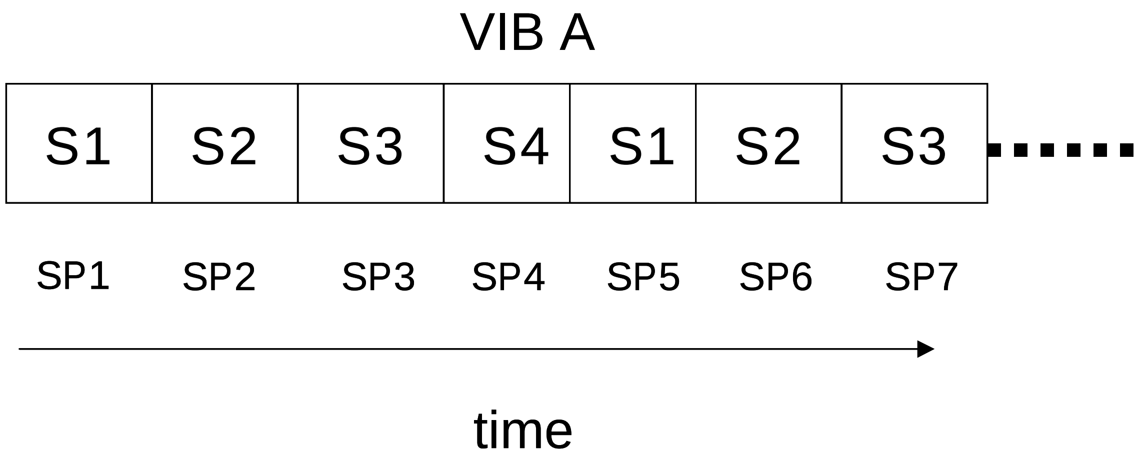


Figure 4

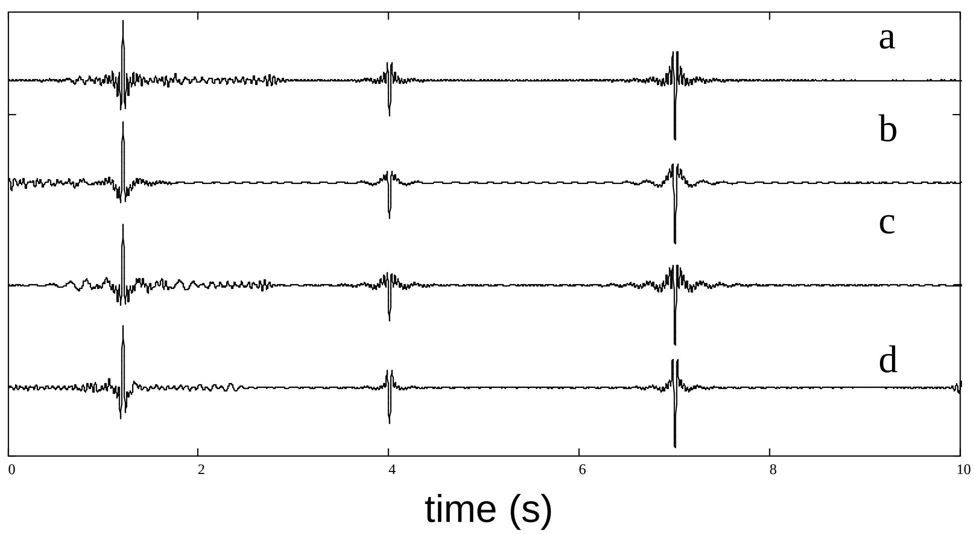


Figure 7

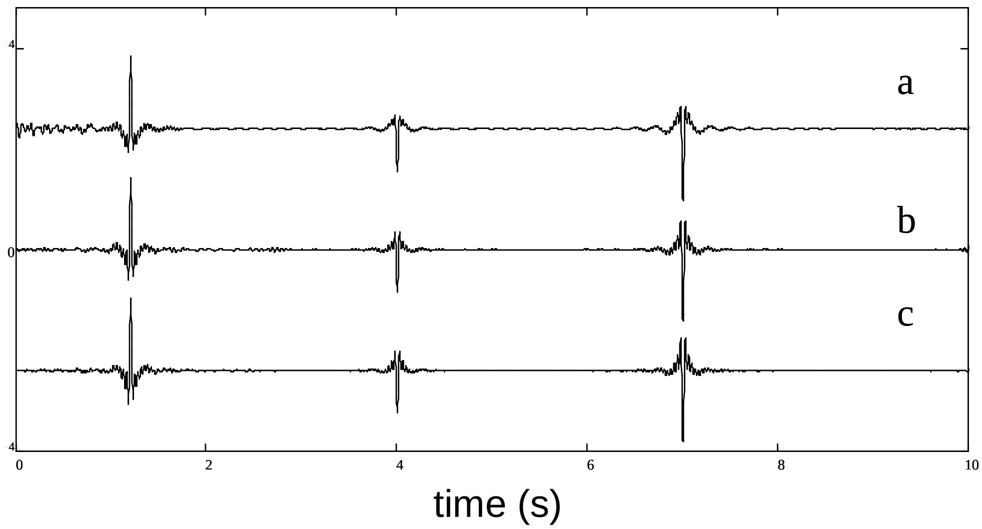


Figure 8

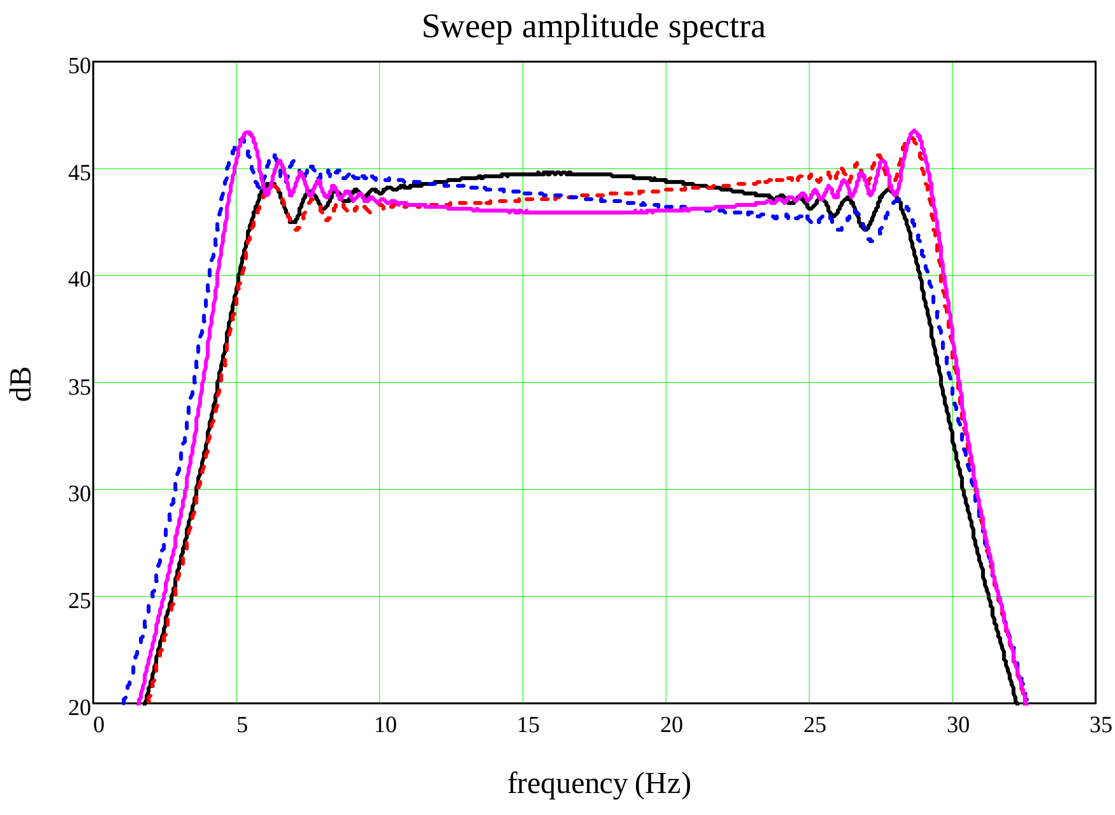


Figure 9

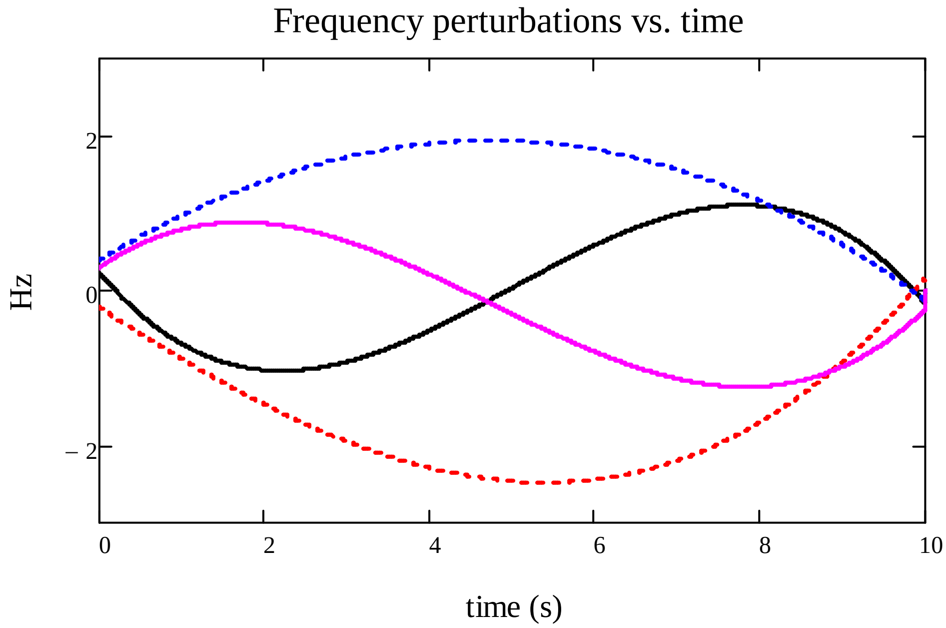


Figure 10

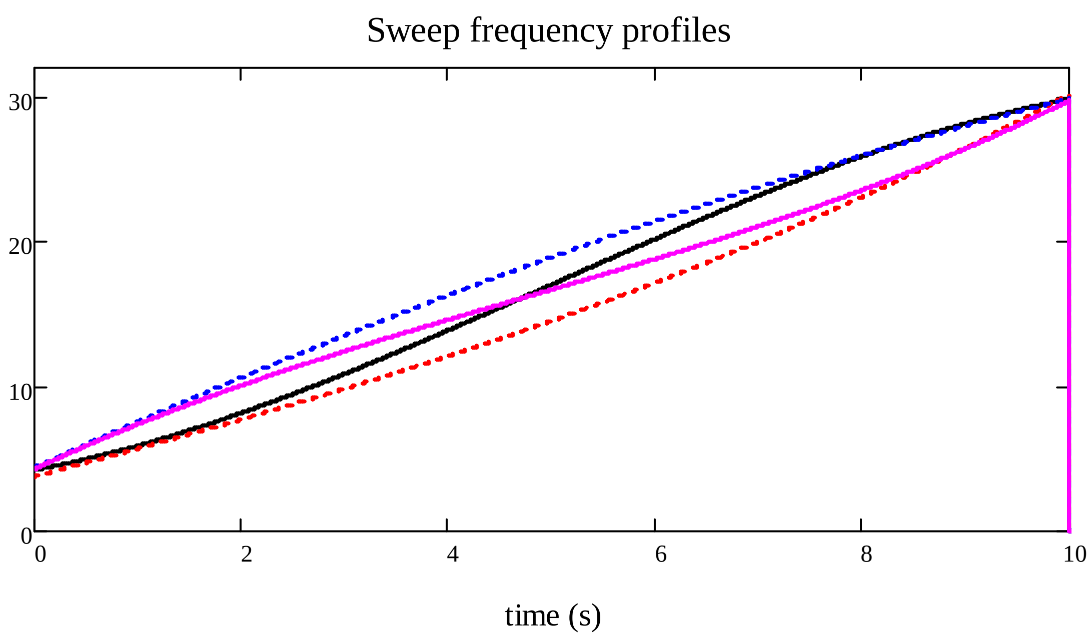


Figure 11

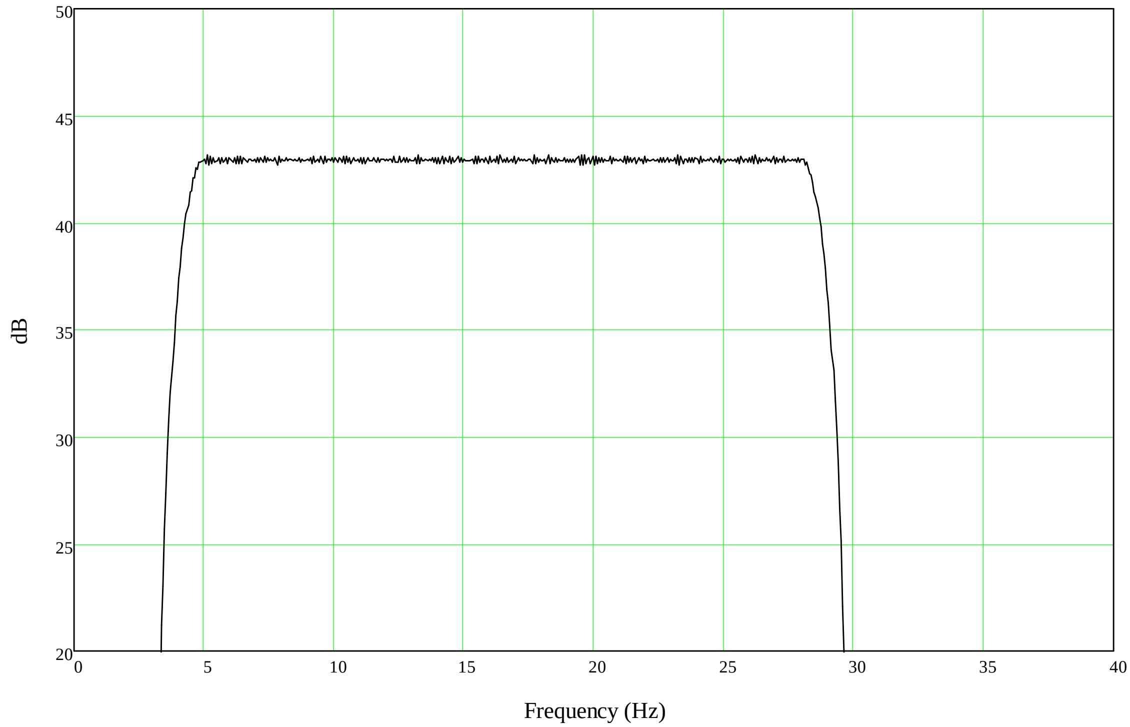
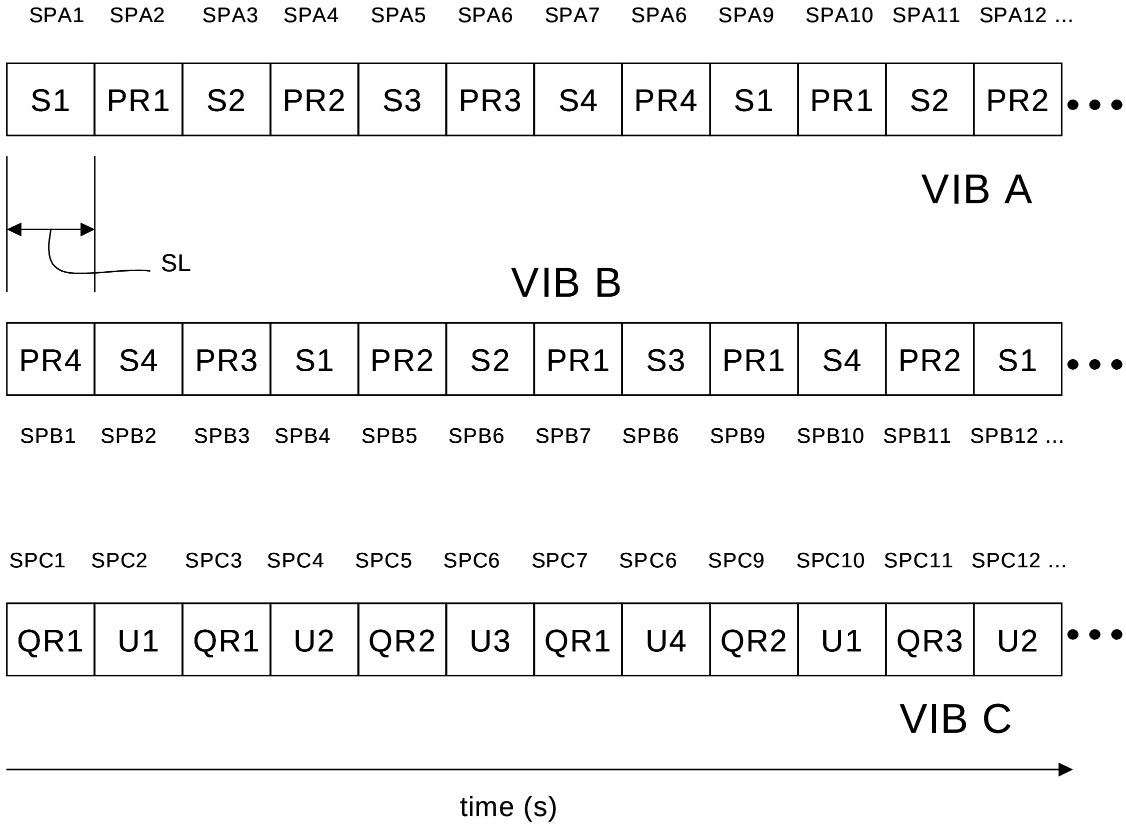


Figure 12.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VIB A
SL
VIB B
PR4 S4 PR3 S1 PR2 S2 PR1 S3 PR1 S4 PR2 S1
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QR1 U1 QR1 U2 QR2 U3 QR1 U4 QR2 U1 QR3 U2
VIB C
time (s)

Figure 13