Adaptive attenuation of surface-wave noise

A new method developed to deal with the issue of surface waves is described by David Le Meur,* Nigel Benjamin, Luke Twigger, Katia Garceran, Laurie Delmas and Guillaume Poulain of CGGVeritas. Although originally conceived for land seismic data in the Middle East and North Africa, the authors suggest that the method may have much wider application.

Surface waves, such as ground roll or guided waves, are a major source of coherent noise in land seismic data, especially in the Middle East and North Africa. Such noise typically hinders imaging and restricts the maximum usable angle. Variability in near surface conditions translates into variability in the noise character, reducing the effectiveness of conventional noise attenuation methods which tend to use fixed parameterization.

This issue has been addressed with the development of a more robust and flexible approach for adaptive ground roll attenuation (AGORA). This data-driven approach attenuates surface waves and adapts to changing noise characteristics. Designed primarily for the removal of ground roll from land seismic data using vibroseis or dynamite sources and a variety of acquisition designs, many other types of noise can also be attenuated using this technique, such as ocean bottom mudroll, guided waves or ice-cracks in Arctic permafrost, unwanted shear waves from multicomponent VSP data, and ground roll from point receiver data prior to digital array forming. Successes have been achieved in removing mud roll and highly aliased guided waves on marine data from conventional or undershot acquisition. Effective noise attenuation enables the use of wider angles, leading to more accurate velocity analysis, more focused stacks, and improved AVO analysis amongst other benefits.

Background
To be able to deliver clear images of the subsurface, we must overcome the problem of noise. Land seismic data, particularly from the Middle East, are plagued by coherent noise from surface waves such as ground roll and guided waves, as shown in Figure 1a. As a result, image quality in time or depth has historically been low, characterized by poor signal-to-noise ratio, limited offsets, and poor quality prestack data.

Ground roll arrives directly from the source to the receivers. For near offsets, it appears linear on inline cables but hyperbolic on broadside cables. Ground roll is characterized by low velocity, low frequency, and high amplitude (see red arrow in Figure 1a). It can be strongly dispersive, aliased, and have higher modes, i.e., for each frequency there are different apparent velocities. This can make it difficult to remove with dip- or velocity-based methods.

Guided waves are visible on records as repeated linear arrivals on the far offsets due to multiple refractions and/or converted refractions (see blue arrows in Figure 1a). They are generated by specific subsurface geological conditions, such as high-low-high acoustic impedance layers. Guided waves are characterized by high velocity and high amplitude.

Figure 1 Example shot record, with ground roll and guided waves identified.

Figure 2 Example shots taken from a variety of locations in the same survey area, showing the variation in character and properties of the surface wave noise.

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They are generally of higher frequency than ground roll but less dispersive. After NMO correction, guided waves appear more dispersive due to the NMO stretch and mask the weaker primary underneath at far offsets, as shown in Figure 1b. Without any attenuation of the guided waves at far offsets, the incidence angle of the stack response is dramatically reduced to small values (20–30°).

Analyzing several gathers (shot or receiver) from the same survey shows that the characteristics of ground roll and guided waves can change vastly from one shot/receiver to the next, due to a rapid change of the velocity at the near surface reaching up to a factor of four over short distances, as is shown in Figure 2a. Observations and measurements on records indicate a real change in the ground roll characteristics (frequency content, phase velocity, amplitude, and degree of aliasing – Figure 2b-e). This is the reason why spatial variation of the characteristics of the ground roll should be taken into account during the filtering step as: frequency content, group and phase velocity, amplitude, and degree of aliasing.

Over the past 30 years, many approaches have been developed to attenuate surface waves on 2D and 3D data. These include FK methods, Radon methods, wavelet transforms, and modelling. All of these methods are used currently, sometimes individually and sometimes in a cascaded fashion. However, they tend to have fixed parameterization and hence a poor response to the changing characteristics of the near surface that affect any generated coherent noise. This often results in leaving coherent artefacts and gives poor preservation of primary amplitudes caused by over/under aggressive or inadequate filtering.

By contrast AGORA is a data-driven method developed to perform adaptive filtering of aliased and dispersive surface waves at their true spatial coordinates for both 2D and 3D narrow/wide azimuth data. It handles rapid variations in near surface character and adaptively subtracts coherent noise while preserving primary amplitudes. In short, it can handle the noise attenuation needs of a large number of processing scenarios in different domains, such as cross-spread or common receiver/shot point domain.

**How it works**

The basis of the method is to extract characteristics contained in each gather to model ‘signal’ and ‘noise’ in the FX domain. The signal is modelled as hyperbolic events, whose trajectories are described by stacking velocities. The ground roll and guided waves are modelled as a series of dispersive linear events, each distinguished by group and phase velocities. This modelling uses the true distance between source and receiver, i.e., the spatial sampling can be irregular.

A least-squares iterative approach is then used to adapt this model to the input data before subtraction of the noise (ground roll, guided waves). Note that this scheme is efficient if the current frequency is reasonably close to a defined central frequency. However, in most cases, the noise may have a bandwidth range of more than 30 Hz. This dilemma is resolved by splitting the data into several frequency sub-bands to allow the use of several different central frequencies in order to optimize the modelling within each frequency sub-band. The principle of the modelling is described in...
Data Processing

Cascaded application

To address the more complex case of handling both ground roll and guided waves, the method can be applied in a cascaded fashion. The first pass is used to remove ground roll, followed by a second pass to remove guided waves. CMP gathers, from a narrow-azimuth land survey, are shown in Figure 5. The raw CMP shows slow ground roll (blue arrow) and a curtain of faster guided waves (red arrows). After the first pass, the ground roll has been attenuated, revealing weaker primary reflections on the near offsets. However, the far offset hidden primaries are always masked by a curtain of dispersive guided waves. The second pass removes the guided waves, and then weaker primaries can be seen across the whole offset range (black arrows).

Shallow water

Similar dispersive noise can be found in other environments, so it is not only land data which can benefit from this method. The following example comes from 3D shallow marine data recorded off Australia. In shallow water, ‘mud roll’ can affect the data on broadside cables especially when the source vessel is far from the receiver cables. Mud roll is an interface wave, the equivalent of ground roll along the sea bed.
Figure 7 Shot gathers with FK spectra showing raw data, with AGORA and the difference of the two. Note the hyperbolic mud roll noise on the near offsets.

Figure 8 Shot gathers with FK spectra showing raw data, with AGORA and the difference of the two. Note the guided waves on the far offsets.
A shot gather containing low frequency mud roll masking the near offsets is shown in Figure 7. The hyperbolic nature of the noise (broadside cable) causes difficulties for standard approaches such as FK or HR Radon with a cable per cable processing. After AGORA, the mud roll has been removed revealing near offset reflections. The difference display and the FK spectrum show that there is no signal leakage, i.e., primary amplitudes have been preserved at near offsets over the whole frequency range.

Guided waves can also be a problem for shallow water data. Figure 8 shows a shot gather with strong guided wave energy on the mid-far offsets that mask reflection series and diffractions. The aliased guided waves can be clearly identified in the FK spectrum, with an average velocity of 1500m/s associated with its wraparound. After AGORA, the guided waves have been properly removed on mid-far offsets maintaining adequate near offset protection. Hyperbolae and diffractions are now visible on the whole offset range. Again the difference displays and the associated FK spectrum show no signal leakage.

**Other applications**

The method was developed to address the complex problem of aliased and dispersive coherent noise attenuation, primarily on conventional land data recorded in the Middle East. Subsequently, it has proved useful in many other scenarios, on other types of survey, and in different environments.

The Arctic, in many ways, is very far from the Middle East. However, Arctic data share many of the same problems, albeit from different physical origins. For example, there is sometimes high amplitude linear noise due to ice cracks recorded during the acquisition. The permafrost also gives highly variable near surface conditions that generate large magnitude statics distorting the surface and the body waves. A raw shot gather shows the impact of large magnitude statics on the shape of the reflection series (see red arrows in Figure 9a). Moreover, patched permafrost generates surface waves only on one side of the shot and ice cracks appear at specific zero time (see blue arrows in Figure 9a). In this case the estimation and application of a set of statics before AGORA is required to be sure that body waves will appear as hyperbolae and surface waves as linear events (Figure 9b). Then AGORA assumptions are respected and the statics could be de-applied after the attenuation (Figure 9c). The difference shows that the surface waves and the ice-cracks have been removed without harm to the body waves (Figure 9d). The method is therefore equally as effective at improving data from the Arctic as from the desert.

Recent advances in processing and acquisition technology, particularly the ability to record many more channels, have allowed us to record using point sources and point receivers. This provides much denser spatial sampling than ever before, allowing us to record unaliased coherent noise, amongst other benefits. Finer sampling makes the data more responsive to spatial variation in the near surface. The lack of aliasing and the extra spatial information allows much better modelling, and hence subsequent removal, of the noise prior to any digital array forming (DAF).

A recent development has allowed multi-component VSP data to also benefit from the method. In this mode it can be used to remove unwanted shear waves and associated down-going multiples, while preserving up-going P waves. In fact it can be used on all multi-component data, either land or ocean bottom.
**Further improvements**
Additional benefits beyond the obvious reduction in coherent noise may also be possible. Removal of such noise from the data allows the use of greater angle ranges for velocity picking, stack mutes, AVO analysis, and internal multiple attenuation (more offsets to stack). This gives flatter gathers, more focused stacks, and more accurate AVO results with implications for areas such as reservoir modelling, fracture characterization, and azimuthal analysis.

Stack results from a NAZ Middle East survey are shown in Figure 10. The vintage data were processed using 3D FK noise attenuation targeting ground roll only. This restricted the use of far offset data such that only 2nd order moveout correction could be used and the stack mute was limited to 30°. The reprocessed data benefited from a cascaded AGORA flow to attenuate ground roll and guided waves. This permitted the stack mute to be opened out to 45° and the picking and application of 4th order moveout corrections, thus utilizing mid-far offset data which would otherwise have been muted out. Hence the much improved final stack results.

**Conclusions**
Noise issues have historically held back seismic imaging in the Middle East, causing difficulties for interpretation, exploration, and development. Recent advances in WAZ acquisition and noise attenuation are combining to deliver a step-change in image quality. The common problem of coherent surface wave noise and its spatial variability can be solved by a data-driven approach which offers advantages over conventional methods. The method constitutes a technical breakthrough for noise removal, not only for the conventional land surveys for which it was originally designed, but for various applications like shallow water, ocean bottom cables, point receivers, and VSP amongst others. Benefits go beyond the obvious reduction in coherent noise, as it enables other improvements such as wider stacking angles.

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References