Towed streamer EM comes of age

Folke Engelmark[1*], Johan Mattsson[1], Allan McKay[1] and Zhijun Du[1] reflect on ten years of the first commercial towed EM system.

This year marks the 10th anniversary since PGS decided to engineer a towed-EM acquisition system. There was no existing model to improve upon, since it was 'common knowledge' that it is impossible to bring the noise level of a towed system down to where it becomes possible to recover a useful signal. Neither were there any new concepts in mathematics or engineering that suddenly would make the engineering of a towed EM system possible. The decision was taken simply on the realization that a towed system would leapfrog the existing node-based controlled source EM (CSEM) methods and automatically become a market-leading service based on acquisition efficiency, ability to monitor the source signal and recorded data in real time, and facilitate simultaneous acquisition of seismic data.

The initial start-up team was created by convincing a small group of people to leave their employment with a Swedish defence contractor and join PGS. They had appropriate background experience based on their R&D on marine EM. A fit-for-purpose office was established in a technology focused suburb of Stockholm in 2004.

Part of the design brief, based on the handling requirements and theoretical arguments, was that the system will record only the inline electric field component, and that this would be sufficient. In the development phase it was eventually found that the optimal receiver system should be based on the dual-sensor seismic streamer hardware with electrodes instead of hydrophones and geo-sensors, hence the name 'towed-streamer EM' was adopted. The first commercial towed-streamer EM system as configured for simultaneous acquisition of EM and 2D seismic is shown in Figure 1.

The first generation of the system would also have to be a shallow tow system in order to keep the development costs down and facilitate a sailing speed that is typical for seismic acquisition. As a marine seismic company PGS has lots of experience in towing geophysical equipment and related hardware behind purpose-built vessels. The overwhelming problem to solve was how to keep the noise at an acceptably low level in a line of receiver electrode pairs that are towed at 4-5 knots. The movement of the receivers in the conductive seawater under the influence of the earth's magnetic field is bound to generate a noisy electric field. Following field tests on a small scale of various receiver electrode geometries, it was decided to try a design based on the dual-sensor seismic streamer. As it turned out, this proved to be a very promising way forward, and eventually we had a streamer-based design that was exhibiting low noise as it was being towed. This was very serendipitous since the handling of the EM streamer is really no different from the handling of the seismic streamers, something we know how to do.

The shallow tow also simplified the source design. The high current that is necessary to power the source dipole suffers very little loss of power in the short distance it has to travel from the generator onboard the ship to the dipole towed at a depth of 10 m. A deep tow, on the other hand, requires a transformer onboard the vessel that converts the high source-signal current to a high signal voltage that is transmitted down to a transformer mounted at the front electrode of the source dipole, where the voltage is subsequently converted to a high current

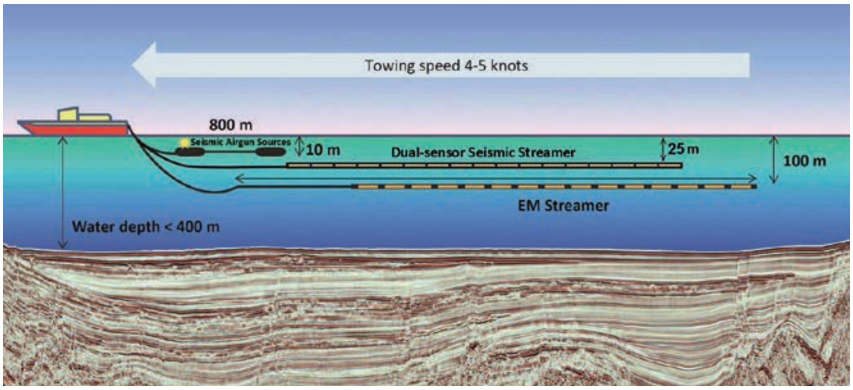

***Figure 1** The layout shows simultaneous acquisition, with the first commercial towed-streamer EM system in combination with the dual-sensor seismic streamer.*

[1] *PGS.*

* *Corresponding Author, E-mail: folke.engelmark@pgs.com*

again that is transmitted through the dipole. This involves very expensive engineering and the towing speed is reduced to 1-2 knots depending on towing depth. The shallow tow also makes it easier to use a long source dipole. The strength of the source, referred to as the dipole moment, is the product of source current and dipole length. The current source is based on 1500 A into an 800 m long dipole for a dipole moment of 1.2 MAm.

All engineering involves trade-offs, but we found that the towed-streamer EM really did not have any significant weaknesses, except the shallow tow that also limits the water depth that we can operate in. The water column attenuates the injected source energy, and at depths exceeding 400 m, the signal loss will increasingly become a limiting factor for depth penetration below the seabed. The fact that there is always some water column between the towed system and the seafloor even in shallow water was initially seen as a limitation. However, we also came to realize that it is beneficial to have the receivers up in the water column, and we now consider towing 50 m above the seafloor as an ideal towing depth for future designs. The first inverted layer is then the water column with known homogenous and isotropic resistivity, and the seafloor forms the top of the second layer. Local resistivity variations at the seafloor are then either resolved or averaged depending on their size. With autonomous receiver pods stationed at the seafloor having short electrode pairs, the response will be dominated by the resistivity of the seafloor immediately underneath, which may turn out to be an abnormal resistivity due to a local gas hydrate or a small carbonate mound.

During the development phase it was also decided that the EM streamer should be based on configurable electrode pairs. The current streamer has 72 electrode pairs and it is typically configured with short electrode pairs (~200 m) for the near offset. They are then successively increasing in length with increasing offset, such that the most distant electrode pair is ~1,100 m long. This is an important aspect of maintaining high signal-to-noise (S/N) ratio throughout the offset range to counteract the natural signal decay.

Initial tests were done with the conventional EM source signal that consists of a monochromatic square-wave with its natural odd harmonics. However, we quickly found it to be beneficial to have denser spacing between the discrete frequency peaks, so we designed the Optimized Repeated Sequence (ORS) that typically has twice the density of harmonics compared to the monochromatic square-wave. Once again there is a tradeoff. If the available energy is distributed over a sparse range of discrete frequencies, the peak amplitude for all useful frequencies will also be larger, hence also penetrating deeper, so spreading the energy over too many peaks is also suboptimal. However, for very shallow targets we have found that an ORS with four times the density of harmonics compared to the standard square-wave is optimal.

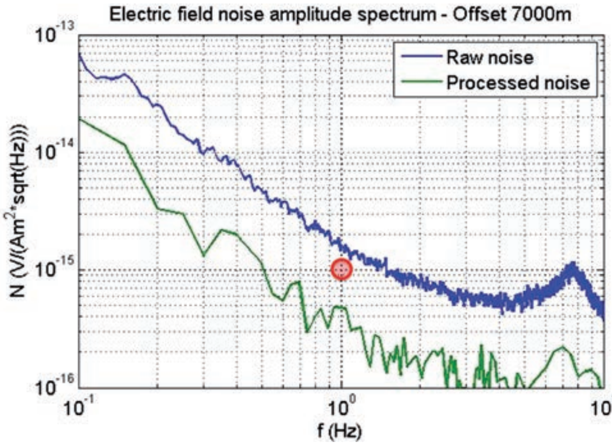

Figure 2 *A noise record scaled by the source strength from the North Sea recorded at an offset of 7000 m. The blue represents the raw noise record and the processed noise record is shown in green. The circle indicates a good point of reference. If the normalized noise is less than* 10^{-15} *at 1.0 Hz, the noise level is acceptably low.*

Noise attenuation is the most important aspect, and it became the dominant sub-project discussed in detail in Mattsson et al., (2012). The first step in the signal enhancement is deconvolution. The fact that the transmitted source signal is recorded in a closed circuit means the source signal is exactly known. The synchronized measurement of the source output current and the electric potential differences in all the receiver electrode pairs implies accurate deterministic deconvolution, and hence also accurate estimates of the earth's frequency responses. Stochastic noise is reduced by means of two methods: First the very dense sampling facilitates stacking that boosts the S/N ratio as the square root of the number of averaged signals. The second method involves the low rank approximation based on singular value decomposition. Correlated noise caused by sudden tugs in the streamer can be attenuated by measuring the local velocity changes with motion sensors distributed along the length of the streamer. The temporarily increased noise level is then attenuated in a custom process of 'reference filtering' that is based on the Wiener filtering technique for correlated signals. An example of the raw noise record scaled by the source strength acquired at 7000 m offset is shown in Figure 2 together with the processed noise in green. The residual noise or uncertainty in the processed data is normally within 2-3% for most of the offsets, and typically within 5% even for the longest offsets and lowest frequencies.

A good reference point is the noise level at 1 Hz. If the normalized noise is below 10^{-15} at 1.0 Hz, it is considered very low for data acquired with a shallow tow. The general noise trend displays the characteristic inverse of frequency trend typical for ambient electromagnetic noise.

The hardware description and performance limitations for the towed-streamer acquisition system can be summarized as follows:

- An 800-m long bi-pole source with a 1500A switched DC-current is towed at a depth of 10 m.

- The source signal is an ORS of 120 sec length. There is no signal transmission for the last 20 sec. This time-window is used for noise evaluation followed by noise attenuation processing.
- The receiver streamer is 8000 m long and configurable with 72 receiver electrode pairs. The near offset has a receiver pair separation of 200 m, and the separation between the far offset receiver pair is 1100 m. The streamer is towed at a nominal depth of 100 m, or shallower if the water depth so dictates. The dense subsurface sampling improves resolution and facilitates stacking to improve the S/N ratio.
- Nominal depth penetration below the seafloor is 2500 m.
- The water column absorbs some of the radiated source energy, so to limit the losses the nominal maximum water depth is 400 m. Larger water depths are acceptable if the target is very shallow below mud-line, very large in lateral extent or has a very high transverse resistance.
- The seismic streamer is laterally separated from the EM source by 100 m. This ensures that there will not be any cross-talk from the powerful EM source current to the weak signals that are transmitted through the seismic streamer.
- The seismic streamer is a dual-sensor streamer that facilitates de-ghosting. It is towed at a depth of 25 m.
- The seismic source consists of a conventional air-gun array.

The EM and navigation data are recorded and processed using the same software as we use for the seismic data. This simplifies the data management as well as the learning curve for onboard processing staff.

With the development of data acquisition and processing successfully brought to a point of maturity, all future developments will be evolutionary in a similar fashion as it is in the world of seismic. The final icing on the EM cake was to introduce powerful 2.5D and 3D inversion algorithms. Following a period of modification of the code to include anisotropic inversion as well as optimize the algorithms to take full advantage of the dense spatial sampling provided by our technology, the inversions were then successfully applied to the projects we acquired in 2012 and 2013.

A large-scale multi-client project

An extensive multi-client acquisition programme was undertaken in September 2013 in the Fastnet Basin in the Irish sector of the Celtic Sea as seen in Figure 3. The programme involved simultaneous acquisition of towed-streamer EM and 2D seismic, as well as 2D seismic only in areas where the water depth exceeds the nominal maximum of 400 m. In total 2800 line km of EM and seismic data was simultaneously acquired in 35 days for an average of 80 line km per day. Average daily acquisition for 2D seismic is assumed to be ~75 line km; obviously this will also depend on the number of line changes necessary to complete the programme.

An anisotropic inversion example

Bentley and Bressay are heavy oil fields in the North Sea that were originally discovered in 1977 and 1976, respectively. The fields have not been exploited so far due to a combination of low quality oil, low recovery factor and reservoirs that are rich in injectite sands forming dykes and sills located immediately above the main reservoir. The fact that the oil is heavy means there is no direct hydrocarbon indication in the seismic data, and the geometries of the thin sills and steep dykes of the injectites are difficult to image. In Figure 4 the Bentley Field is the larger area to the SSE, and Bressay is the smaller area to the NNW.

The colour indicates the reservoir thickness as interpreted from 3D seismic. The warm colours indicate increasing thickness. The three dotted lines represent the towed-streamer EM lines that traverse both fields in a NNW to SSE direction. The colours of the dotted lines reflect the magnitude of the transverse resistance estimated over the depth interval that represents the reservoir, with orange and red colours indicating higher values. These survey lines were subjected to our new 2.5D finite element inversion.

Towed-streamer EM data facilitates anisotropic inversion in spite of the fact that only the inline electric field component is measured. The reason this is possible originates in the shallow tow of the EM source and receiver that allows a significant amount of energy, known as the airwave, to travel through the atmosphere. The airwave then couples with the horizontal conductivity in the anisotropic subsurface as described by Constable (2010). Anisotropic inversion algorithms are mandatory, since the overburden tends to be at least mildly anisotropic and the hydrocarbon-charged

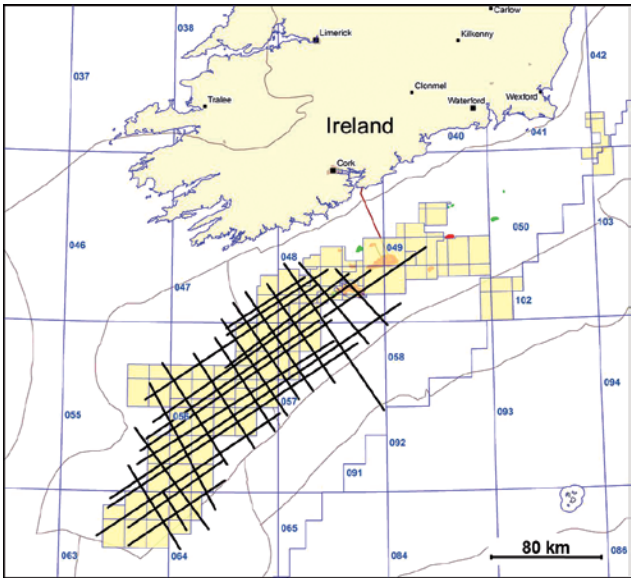

Figure 3 *The acquisition grid in the Fastnet Basin located in the Irish sector of the Celtic Sea. A total of 2800 line km of multi-client towed-streamer EM data was acquired over a period of 35 days, for an average of 80 km per day. Most of the programme involved simultaneous acquisition of EM and seismic data.*

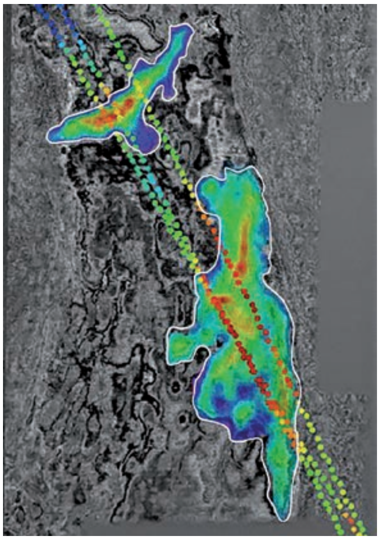

Figure 4 *The survey lines shown on top of a 3D seismic time-slice with Bentley (lower right) and Bressay (upper left). The reservoir thickness in the fields as interpreted from seismic is shown in colour with yellow and red indicating maximum thickness and blue minimum thickness. The dotted survey lines show high transverse resistance in red where the reservoirs are thick.*

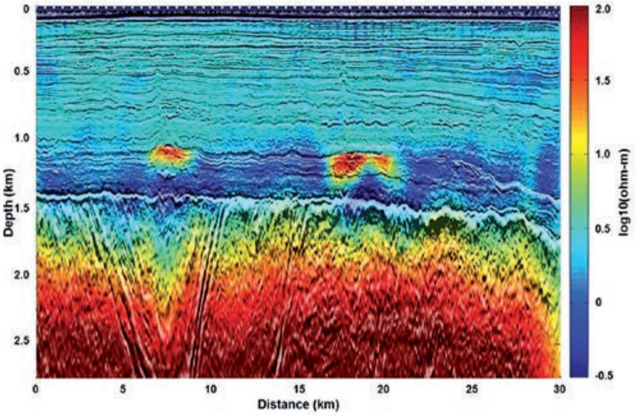

Figure 5 *A 2.5D finite element inversion shown in colour as an overlay on a seismic cross-section. The survey line runs from the NNW on the left to the SSE on the right. The top of basement is at 1.4 km to the left and dipping gently to the right. The two fields are seen in yellow and red at a depth of 1.2 km with Bressay on the left and Bentley on the right.*

reservoirs can be strongly anisotropic, especially when the high-resistivity sands are inter-bedded with layers of low resistivity shale. If an isotropic inversion is applied, the algorithms will typically create an artificial striping consisting of alternating resistive and conductive layers that achieve an effective anisotropy when they are not individually resolved. There is also a tendency to place the anomalously high resistivity at the wrong depth if isotropic inversion is performed. Figure 5 shows the result of the 2.5D finite element inversion of the line that is located to the far left up top and in the middle at the bottom of figure 4. The inversion has been guided by a series of sparse depth-converted 3D seismic horizons in the way the finite element inversion grid has been built. The basement is seen at 1.4 km to the left (NNW) dipping gently to the right (SSE). Bressay is the smaller anomaly in yellow and red to the left, and Bentley is the larger anomaly to the right at 1.2 km below the seafloor.

Conclusion

In the tenth anniversary since the inception of the towed EM system development, the product has finally come of age and reached the stage where it is now a mature commercial service all the way from feasibility studies through acquisition and processing to an inversion product that is a powerful deliverable to the client. Looking back at what we have achieved, it is interesting to see that throughout the development, we found aspects of the towed EM system that appeared as positive surprises, considering they were never anticipated. Some of these bonus points are listed here:

Towing the source and receivers up in the water column improves the inversion of the data. The first inverted layer is the homogenous and isotropic seawater. The seafloor then forms the top of the second layer, and all local high resistivity anomalies are either averaged or resolved depending on their size, but they will never come to dominate the response as they can when receiver nodes are placed directly on the seafloor.

The dense sampling in space and in discrete signal frequencies has offered multiple benefits that were not immediately obvious such as: 1. Noise attenuation by means of stacking and in-line averaging. 2. Improved spatial resolution. 3. A more accurate image of the overburden that will also facilitate an improved image of the deeper structures, locate them at the correct depth and render them with the correct shape. 4. Shifting the inversion from being model-based to mainly data driven. The dense sampling resolves the inversion profile top to bottom with only a sparse horizon model as constraint.

The ability to estimate both vertical and horizontal resistivity facilitates an estimate of the anisotropy ratio. As it turns out, hydrocarbon-charged reservoirs are typically anisotropic, whereas the basement is typically isotropic. Hence, displaying the resistivity ratio quickly reveals resistivity anomalies that are likely to be oil or gas charged reservoirs. It will also allow us to identify charged reservoirs in immediate proximity to the top of basement, which would be impossible if only the vertical resistivity was recovered in the inversion.

The anisotropy ratio also facilitates an evaluation of the net-to-gross (N/G) and also makes it possible to estimate the resistivity of the reservoir sands. The combination then makes it possible to estimate the total hydrocarbon volume in place.

The lesson after ten years of successful development of towed-streamer EM is that just because people say something is impossible to achieve, you should not necessarily believe them.

References

Mattsson, J., Lindqvist, P., Juhasz, R., Björnemo, E. [2012] Noise reduction and error analysis for a towed EM system. *82nd SEG Conference and Exhibition*, Extended Abstracts.

Constable, S. [2010] Ten years of marine CSEM for hydrocarbon exploration. *Geophysics*, **75** (5), 75A67-75A81.