Introduction To Directional Drilling And Telemetry

Historically oil and gas wells were vertically drilled. However, in the 20th century, the industry slowly moved from vertical wells to slanted wells and from slanted wells to directional well. Modern oil and gas wells are typically directional wells; they follow a predetermined well plan and are composed from three main section, vertical section, build section and horizontal section. The vertical section is as the name suggests vertical, the build section where the direction of the well changes from vertical to horizontal; and finally, the horizontal section is as the name suggests horizontal. In some cases, there is additional section called the tangent section; it is a part of the build section where the tool remains at a set inclination for a prolonged time before completing the build. The goal is to drill a well in such a way that the horizontal section is located within the reservoir; maximizing the overlap between the drilled section and the reservoir allows for to extract more resources from the ground.

To successfully follow a well plan, the operator needs to know the direction they are drilling at. This is why the bore hole assembly (BHA) is equipped with monitoring while drilling (MWD) tools and telemetry tools. The MWD tools collect data regarding the orientation of the bore hole, gamma, vibration, temperature, RPM and other and then use the telemetry tools to transmit it to the surface. Land rigs have two main telemetry modes, mud pulse (MP) and electromagnetic (EM).

MP utilizes the pressure pulses generated by modulating the flowing drilling mud column to transmit the data from downhole to the surface. On the surface pressure transducers are attached to the pipe, the transducers measure the pressure which includes signal and noise.

EM telemetry transmits data by generating electromagnetic waves. A downhole transmitter injects an electric current into the surrounding formation, creating an electromagnetic field. The electromagnetic waves travel through the earth's formations to the surface. This method is particularly effective in formations with low conductivity, such as sandstones and carbonates. At the surface, a receiver detects the electromagnetic signals.

When MP compared to EM it has several advantages:

- it is more mature technology when compared to EM
- it is reliable, tested, and proven. EM can be finicky; the signal strength and quality can be affected by formation resistivity and thickness.
- it has relatively low operational costs, EM usually requires more expensive equipment.
- it can be adapted by choosing the right tools and mud composition to overcome the difficulties of the environmental conditions. EM signal may also vary as a function of the sampling location, it may be improved by using more sensors for sampling at different locations, sometimes may require repeaters (some repeaters may have to be located downhole).

The main disadvantages of MP are:

- it is relatively slow; EM can be faster.
- as the well depth increases the pulse needs to travel further and amplitude of the pulse diminishes as a function of the distance. EM has similar problem, but it is a function of the formation rather total well depth.

- is prone to interference by rig pump noise and agitators or other conditions that disturb the mud flow. Also, is prone to interference from mud pulse echoes created by the original pulses. EM does not depend on the mud flow; this is one of the main advantages of EM.

Phoenix Technology Services (PHX) offers our clients tools that can transmit both EM and MP telemetry simultaneously. This document discusses some of the technology that Phoenix Technology Service employ to deliver its client top tier MP decoding.

Introduction To Mud Pulse Telemetry

PHX utilizes velocity data encoding to send the data via MP. This format is composed out of frames where a frame is composed out of three main components the synchronization sequence or the header, the frame ID and the data. The frame repeats itself to make for MP transmission as shown in Figure 1. The white between the frames indicates that there is a pause during the MP data transmission.

Figure 1 Velocity data structure. The data is composed out of frames, each frame is composed out of three main components the synchronization sequence or the header. The components are schematically shown here, not to scale. The white between the frames indicates that there is pause during the MP data transmission.

The velocity header is shown in Figure 2. It is a unique sequence of pulses that can be easily recognizable from the rest of the data. The times t_1 and t_2 are pulse width and data idle correspondingly, they can be configured, however mostly they are kept the same.

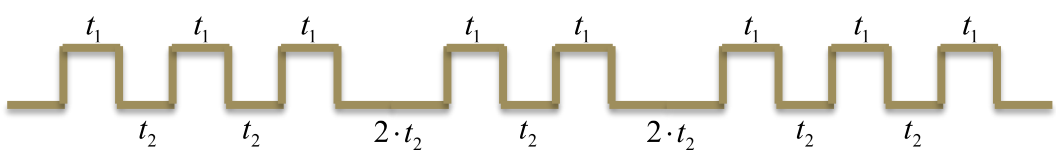


Figure 2 The header is a unique sequence of pulses that can be easily recognizable from the rest of the data. The times t_1 and t_2 are called pulse width and data idle correspondingly, they can be configured, however mostly they are kept the same.

Velocity transmits data via symbols, each symbol carries three bits of data, the data is encoded in the timing of the bit relative to the header. The first two symbols are dedicated to transmitting the frame ID which determines the structure of the rest of the frame. Figure 3 shows how a position of the pulse inside of the symbol determines the binary value transmitted by the tool. The time t_3 is called an interval and usually $t_1 = t_2 = \frac{t_3}{2}$, and that is what the figure depicts. However, the length of pulses, the idles and the intervals and configurable and does not depend one on another. The length of a single symbol is always $t_1 + t_2 + 7 \cdot t_3$.

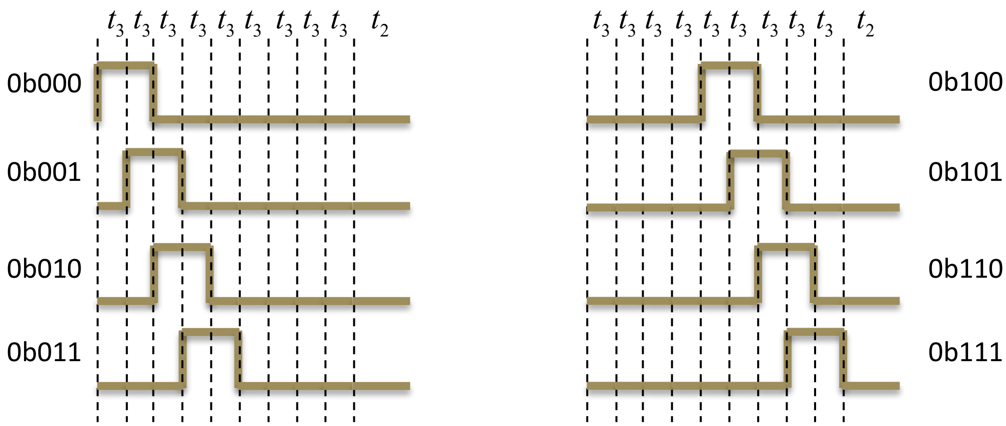


Figure 3 There are 8 pre-determined timing slots at which a pulse can appear within a symbol, each timing slot corresponds to a binary value. Decoding the pulse's location in the symbol, correlates to a value between 0b000 to 0b111.

As previously mentioned, velocity encoding uses two symbols to transmit the frame ID, there are total of four different frames that the tool may send, their frame IDs are shown in Figure 4. The frame IDs are survey, sliding rotating and status. Though it is possible to cramp all four frame IDs into a single symbol Velocity breaks into two rather distinguished symbols, though this slows the data transfer it makes it easier to decode the frame ID with confidence.

Survey frame is transmitted after flow on with survey data, sliding frame is used when the tool is sliding and rotating is used when the tool is rotating. Status frame is used by the tool after downlinking.

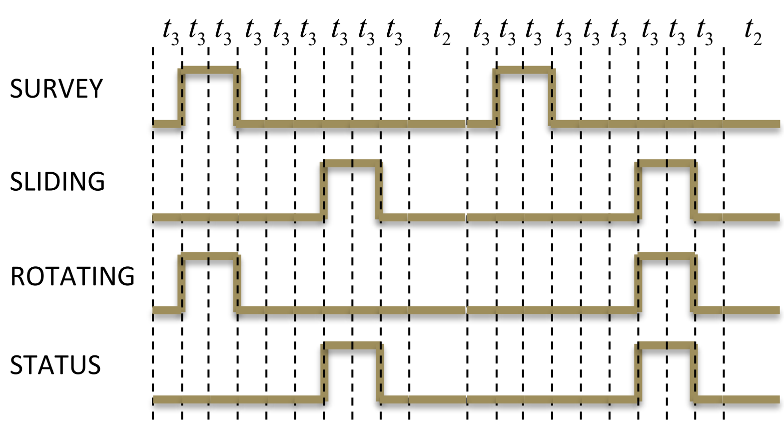


Figure 4 Velocity encoding uses two symbols to transmit the frame ID, there are total of four different frames that the tool may send, the frame IDs are survey, sliding, rotating and status.

Header Recognition For Timing Synchronization

The velocity header as transmitted by the pulse is shown in Figure 2. However when each pulse traverses up the drill string its shape is affected by various physical properties of the mud, the movement of the drill string, the losses to the formation, the pump noise dampeners, the pressure transducer and finally the filtering. By the end of all of these transitions and filters the pulse is expected to have a Gaussian shape

when the data comes from the pressure transducer, after filtering the results may look slightly different than expected. Since it is possible to filter the data in many ways there is no truly best approach where one set of pre-selected filters will always work. The conditions in the field change rapidly and approach that worked a few hours ago may no longer produce viable results. Example of how different filter combinations may affect the same header is shown in Figure 5.

There are several things that can be done in the software to make sure not to miss the frame's header. The most obvious choice is to select the best possible filter combination so that header looks closest to the expected shape. This approach is viable and PHX implements it as a part of the technology package, this approach is discussed more in depth in the Multi Decoder – Filter Optimization section. However, there are also other tools that PHX uses to help to capture the header.

1. When the header shape is poor, PHX decoder may capture more than one potential header and temporarily maintain decoding from several time points (suspected headers) in the data, the decoder will report to the user data from the most likely header, however based on the decoding quality the decoder may decide that it was wrong and switch to another header.
2. Since the headers appear periodically the decoder knows to lock on to the timing of the headers, the decoder uses this lock to find even the most unrecognizable headers and ignore potential headers when the time is not right.
3. Finally, if the shape of the header is abnormal (see Figure 5 (c)), but it is repeatable; meaning each header looks similar to the previous, while being abnormal. The decoder can learn the shape of the header and recognize it better each time it appears.

The combination of the tools above allows PHX decoder to adapt to various header shapes even with poor signals, and select the correct headers while ignoring patterns that look like a header but are not.

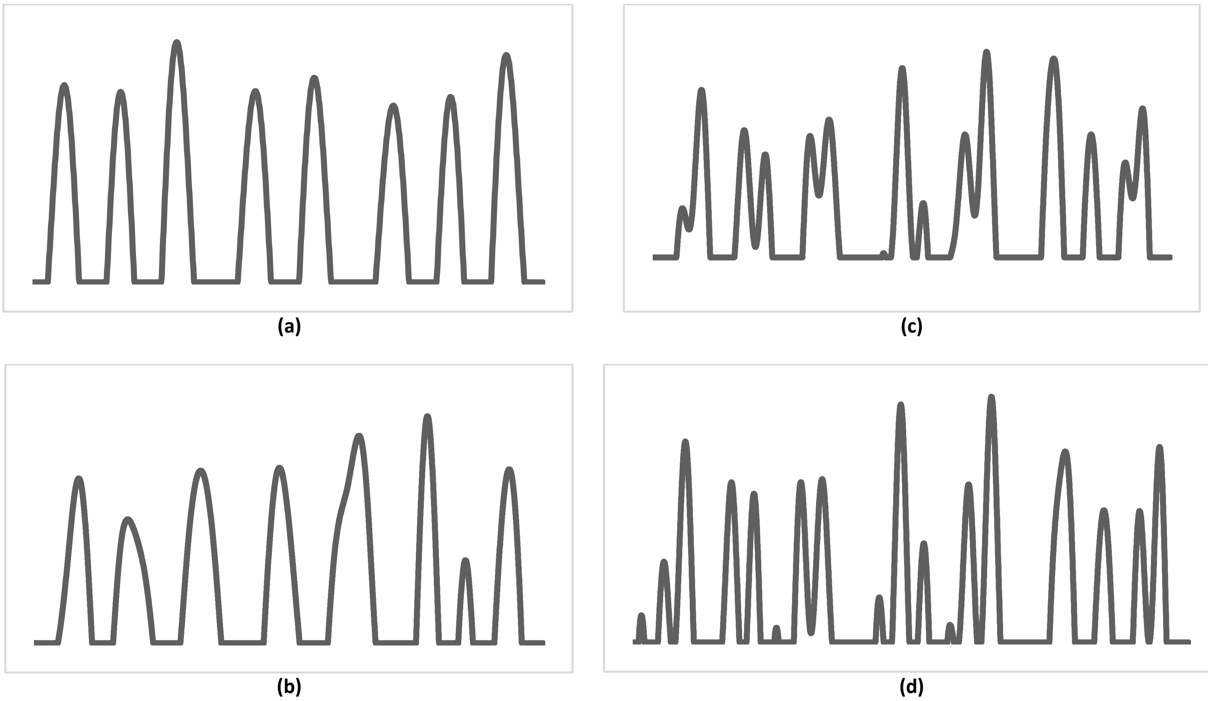


Figure 5 (a) sometimes the header will look as expected, (b) in some cases the pulses composing the header may have slightly different shapes and sizes, (c) in some cases the pulses may have vast differences between the expected pulses and themselves, (d) in extreme cases the header is unrecognizable.

Pulse Timing

As previously mentioned, Velocity transmits data via symbols, each symbol carries three bits. The value of the bits is encoded in the timing of the pulse, this means that it is not enough to recognize the pulse, to extract the correct bits it is necessary to extract the correct timing of the pulse relative to the synchronization sequence, i.e., the header. Figure 6 shows an example of real-life data snippet that includes a header (highlighted in red) with some pulses around it. The pulse shape is mostly repeatable however some variations occur. Despite these variations the decoder needs to determine the timing of the pulses to convert the timing to bits correctly.

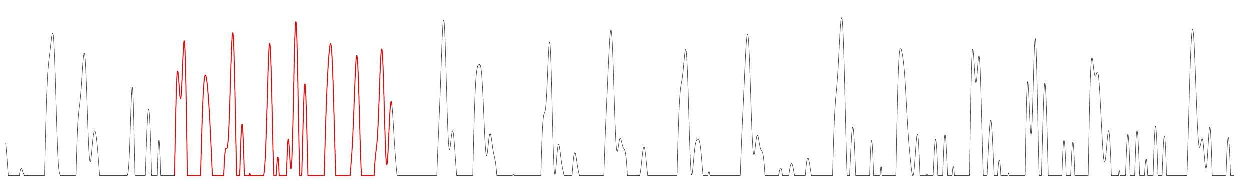


Figure 6 an example of real life data snippet that includes a header. Despite abnormal and irregular looking pulses this data can is decoded by PHX decoder with very high confidence (over 95%).

The first thing the read should notice is that the header does not end with an end of a pulse. The header has a specific shape and length and it does not need to include an integer number of pulses, depending on the shape of the pulse the found header in the data may include a fraction of a pulse at the start and the end. It is up to the decoder to decide best fit for the header and a function of that where the header starts and ends.

To get the correct timing the first thing the decoder does is break the data into symbols, for the readers convenience the leading pulses before the header were trimmed out, the header and 11 complete symbols were left and are shown in Figure 7.

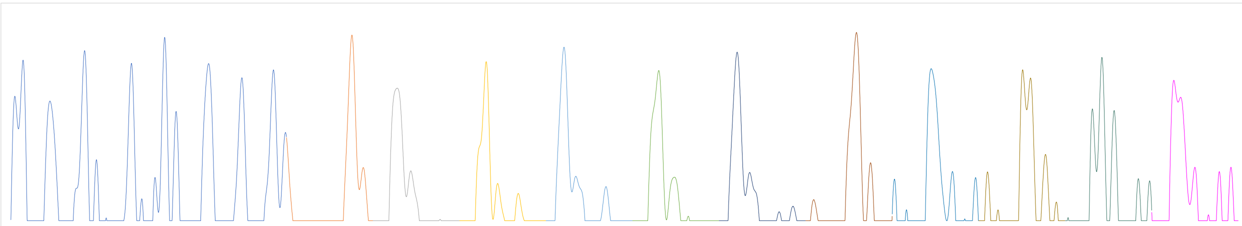
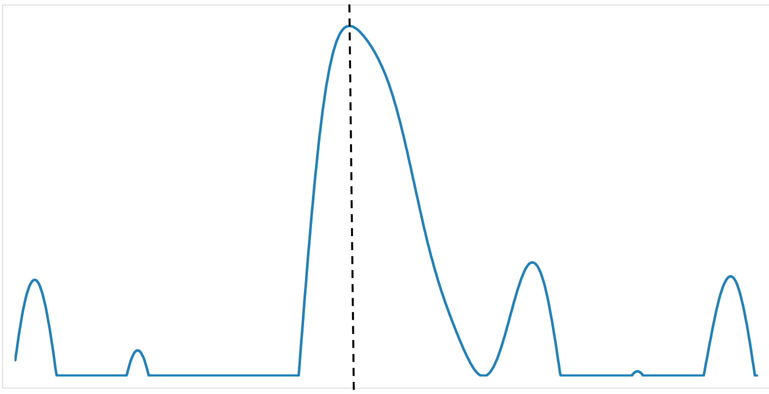


Figure 7 trimmed data from Figure 6, a header followed by 11 complete symbols, the first two of which (orange and gray) are the frame ID and the next nine are data.

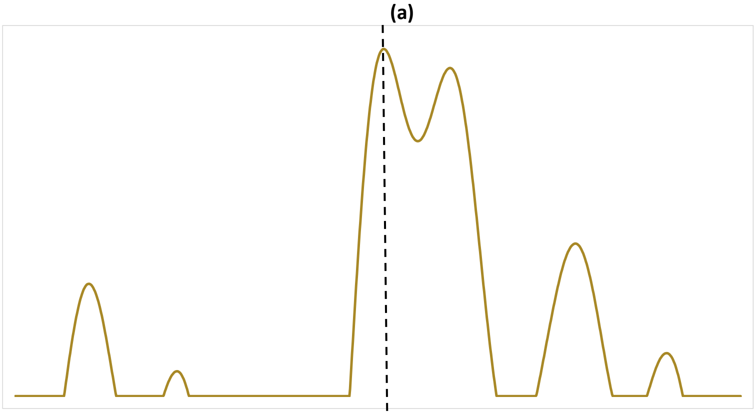
Initially the reader may be drawn towards peaking the time in the symbol based on the peak in the pulse, however this approach rarely yields good results because the peak may be arbitrary in some instances. For example, we can review three consecutive symbols more closely, symbol number eight (light blue), nine (yellowy brown) and ten (faded green). The results of following the peak are shown in Figure 8, from there we can see that the location of the peak inside the pulse is almost arbitrary and it can substantially move the timing.

PHX decoder has several methods to determine the timing of the pulse, the most common setting is to consider the pulse as a whole rather than just the peak. To do that the decoder developed by PHX uses artificial intelligence (AI) and machine learning (ML), it studies the data and generates a reference pulse that for best results. The decoder than uses this pulse as a correlation kernel across the symbol and finds the location in the symbol where it correlates best. The reference pulse that the decoder has used to decode this data set and the optimal location it has chosen for it are shown in Figure 9. The pulse shape may look like an odd choice for the human operator; however, it usually works substantially better than a pulse a human could have picked. In the example from Figure 9 the decoder is using the peak of the reference pulse to determine the timing shown in dashed pink line. Also, for reference the peak of the data in symbol is shown in dashed black line. The reader may find it surprising that the timing is aligned best for symbol #10 see Figure 9 (c), while it symbol #9 and #8 have a relatively large difference between the peak of the data and the location used by the decoder for timing. Though the distance between peak data to the decoded timing may not seem to be far, for those symbols (#8 and #9) it is important to remind the reader that the maximum allowed deviation is a quarter of the pulse-width, a deviation bigger than that will change the timing slot of the pulse and will hinder the decoding.

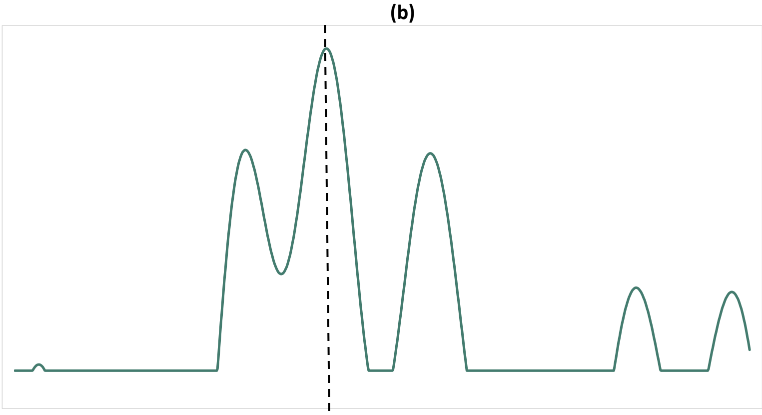
There are other methods to determine the timing of the pulse, for example the decoder can look at the leading edge of the pulse, by looking at Figure 9 we can see that the leading edge of the pulse in the symbol corresponds very well with the leading edge of the reference pulse; with small deviation in Figure 9 (c). PHX decoder may utilize the leading edge instead of correlation value for decoding, moreover it may also use the leading edge for the header (symbol synchronization) timing.



(a)

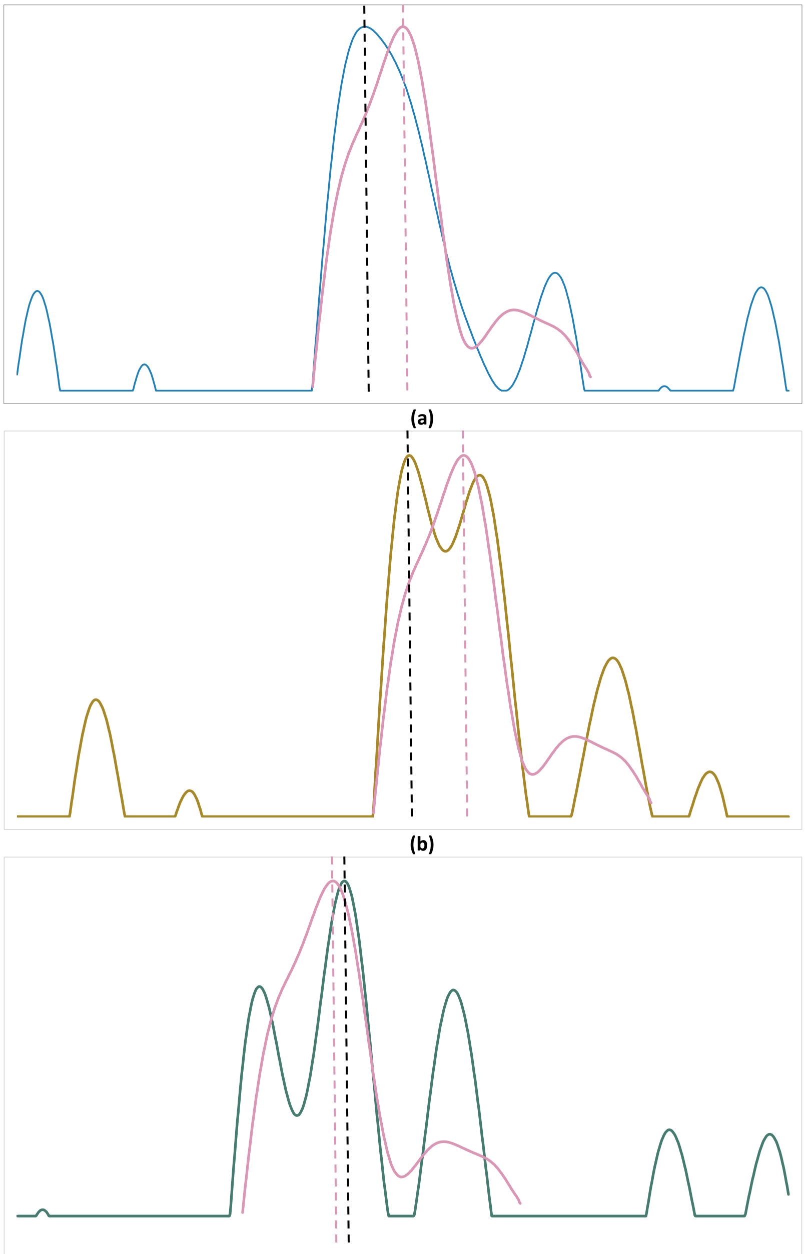


(b)



(c)

Figure 8 (a) the eight pulse has a common single peak shape where the pulse itself is not symmetrical, which is very common. (b) the ninth pulse has a double pulse shape where the first peak is higher than the second. (c) the 10th pulse has a double pulse shape followed by 3rd pulse, where the 2nd peak from the first pulse is the highest peak in the symbol.



(a)

(b)

(c)

Figure 9 The decoder uses correlation to look for an optimal location of a reference pulse, where the shape of the reference pulse is previously determined by the decoder as the optimal pulse shape for decoding. Location of symbol peak is shown with dashed black line, while location of peak reference pulse is sown in dashed pink line. (a) the eight pulse (light blue) overlaid with reference pulse (pink), the timing is shown at the location of the peak of the reference pulse. (b) the ninth (yellowy brown) overlaid with reference pulse pink, the timing is shown at the location of the peak of the reference pulse. (c) the tenth pulse (faded green) overlaid with reference pulse pink, the timing is shown at the location of the peak of the reference pulse.

Multi Decoder

We have previously discussed how different filtering methods affect the data and as a result improve or hinder the decoding quality. We have also discussed how there are different methods to determine the timing of a pulse within a symbol. Since different combinations of filters and decoder techniques work for different situations, PHX has developed a multi-decoder (MD) system for mud pulse decoding (and for EM decoding, though the EM decoding system is different and is outside the scope of this publication).
The MD allows for sampling data from multiple locations on the rig, i.e. several different transducers (where the transducers may be of different type) may be placed in different locations on the rig for sampling the MP signal and connected to a receiver, the receiver sends the digitized signal to the MD as shown in Figure 10.

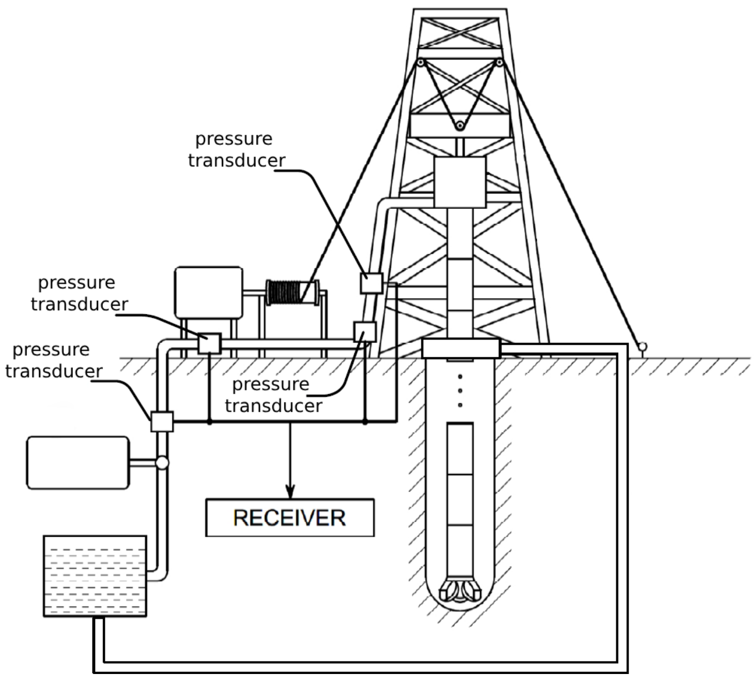


Figure 10 a schematic of a rig, multiple transducers attached to the return pipe in different locations, the data from the transducers is digitalized via the receiver and is transmitted to a computer (the computer is not shown).

The MD checks for flow, and if flow exists it sends the data into different decoding chain sets, where each decoding chain set is assigned for a single transducer and is comprised of a multiple filter-decoder chains. Different filter-decoder combinations decode the data and assign each output confidence, the output from all the different filter-decoder chains is consolidated into a single output via the confidence of the output. Additionally, there exists an AI system in the MD that monitors the output from the various filter-decoder chains and from time to time may remove existing filter-decoder chains to introduce new more-efficient filter decoder chains. It is important to note that when introducing new filter-decoder chains the goal is not to introduce filter-decoder chain that can decode the most of data, but rather introduce such combinations of filter-decoder that would allow to decode the marginal cases of data that other filter-decoder chains would not be able to decode. The schematic of the multi-decoder software is shown in Figure 11.

The MD has an extensive graphic user interface that allows the user to dig deep into the system; for example, the operator may view output from each filter-decoder separately in addition to seeing the output selected by the consolidation process. The operator may select a specific filter-decoder combination to serve as the output from the MD overriding the consolidation process. The operator may exclude filter-decoder combinations from the consolidation process. The operator can view and adjust the filter and the decoder settings for each filter-chain, the user can also remove and add new filter-decoder chains. The operator can see detailed plots of how the data looks like for the different filter chains, as well as the selected pulse shape previously discussed in Figure 9. These are just some of the tools available for the operator to do their job.

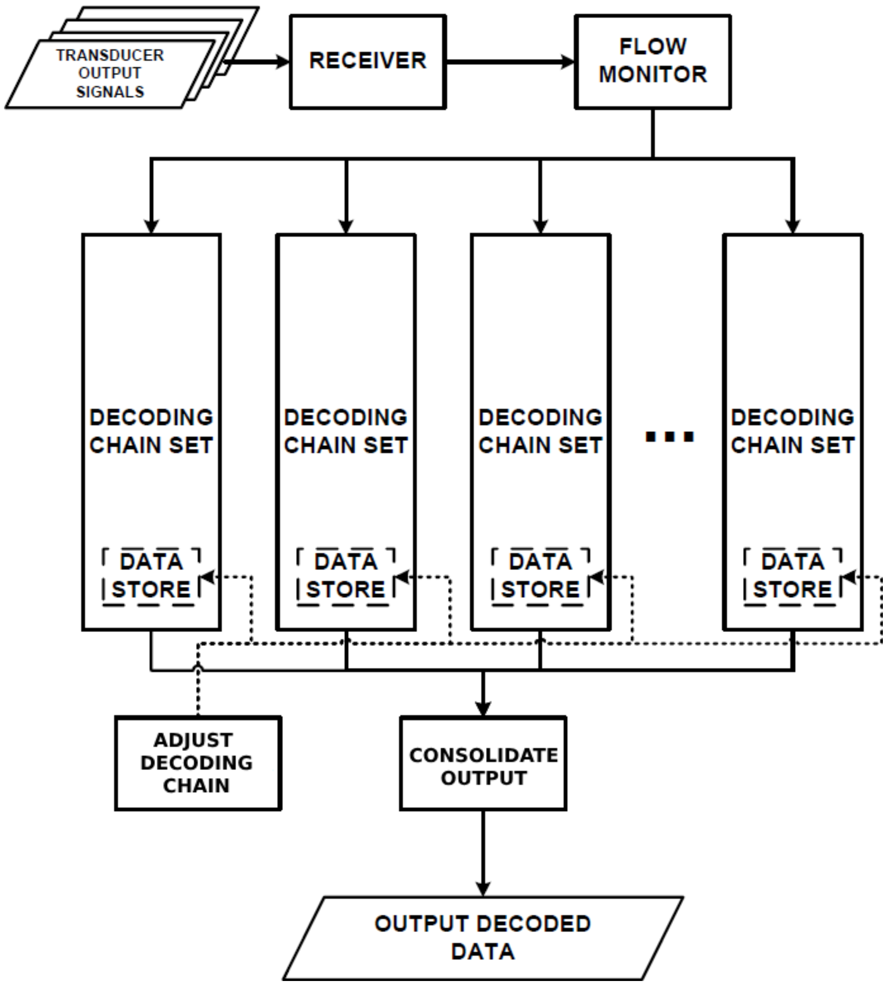


Figure 11 schematic presentation of the multi-decoder, the data travels from transducers into receiver, and from there into the multi-decoder. The multi-decoder checks for flow, and if flow exists sends the data into different decoding chain sets, where each decoding chain set is assigned for a single transducer and is comprised of a multiple filter-decoder chains. Different filter-decoder combinations decode the data and assign each output confidence, the output from all the different filter-decoder chains is consolidated into a single output via the confidence of the output.

Summary

In this document we have discussed directional well drilling for oil and gas and the common telemetry used to transmit data from the BHA to the surface. The main topic of this document is the MP telemetry, Introduction to Mud Pulse Telemetry explains how a unique pulse sequence is used to synchronize timing between the tool and the surface. We go on to show that decoding the timing of each pulse relative to the timing of the header is crucial for good MP decoding and the nuances that exist in decoding the timing of each pulse correctly. Finally, we present the multi-decoder show how it samples data from various places on the rig and filter each data stream via multiple combinations of filter-decoder settings to produce various results, the results are then consolidated into a single data stream. In addition, the multi-decoder includes and AI system that monitor the performance of the different filter-decoder combinations and from time to time may remove poorly performing filter-decoders to introduce new combinations that work better.