Technical Note

Multi-frequency NMR Logging

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EXECUTIVE SUMMARY

Magnetic Resonance (NMR) geophysical logging was developed for use in the oil industry in the 1990s. Nearly all modern NMR logging tools have the ability to perform NMR measurements at multiple frequencies during a single logging run. This multi-frequency measurement capability provides many critical operational benefits, including improving the signal-to-noise ratio of the measurements and enabling faster logging (Coates *et al.*, 1999).

Vista Clara's full line of Javelin and Dart magnetic resonance (NMR) logging probes offer this capability, operating at multiple frequencies to offer the following important benefits:

1. **Operation in a wider range of wells and boreholes**: Multi-frequency logging probes are like having multiple probes in one, so a multi-frequency probe can satisfy a wider range of conditions than any single-frequency probe.
2. **Faster logging and improved signal-to-noise ratio**: Multi-frequency logging improves the time efficiency of data collection by allowing measurements at multiple frequencies to overlap in time. These efficiency gains permit more measurements in the same time interval compared to single-frequency logging. This allows faster logging than a single-frequency system, or improved signal-to-noise ratio the same logging speed.
3. **Resilience to EM interference:** Multi-frequency NMR logging increases the likelihood of obtaining usable data in environments with high levels of electromagnetic interference (EMI), where single-frequency logging can yield unusable data.
4. **Multiple Radial Distances:** Multi-frequency logging provides independent information at multiple radial distances from the logging probe. This offers the ability to assess borehole conditions and drilling disturbance, thereby offering a quality control metric and process that is unavailable with a single-frequency NMR logging tool.

The benefits of multi-frequency NMR logging come with no downsides. In no circumstances does properly collected multi-frequency logging provide inferior or lower fidelity data compared to single-frequency logging. If single-frequency operation is desired for any reason, all Javelin and Dart logging systems can optionally be operated in single-frequency mode, yielding identical results to a single-frequency logging system.

INTRODUCTION

NMR logging was developed for application in the oil industry, where it has been in routine commercial use for decades. All major oilfield service companies offering NMR logging services rely on the advanced capabilities and features that multi-frequency logging provides. Vista Clara is proud to be the only provider of multi-frequency NMR logging systems for groundwater, environmental, and geotechnical engineering applications and we are excited to offer these capabilities to our customers.

The primary motivation for multi-frequency logging is to provide NMR measurements at multiple radial distances from the probe.

The physical phenomenon of nuclear magnetic resonance occurs at a unique frequency of precession (the Larmor frequency) for a given atomic nuclei. The Larmor frequency (f) is given by:

$$f = \frac{\gamma B_0}{2\pi}$$

where γ is the gyromagnetic ratio and γ/2π=42.58MHz/tesla for hydrogen. Thus, *f* is linearly related to B_0, which is the static background magnetic field. For NMR logging, B_0 is determined by the permanent magnets in the logging probe. Because the magnetic field strength of the permanent magnets decreases with distance, performing NMR excitation at different frequencies excites the NMR response in hydrogen nuclei at different discrete radial distances from the probe. Thus, operating at a specific frequency causes the NMR measurement to occur in a discrete, cylindrical sensitive volume at a known, fixed radius from the center of the tool.

The Vista Clara Javelin and Dart logging systems contain advanced electronics to rapidly switch between transmit frequencies, permitting the system to perform NMR excitation at multiple frequencies during a single logging run with no time lost or decrease in signal fidelity.

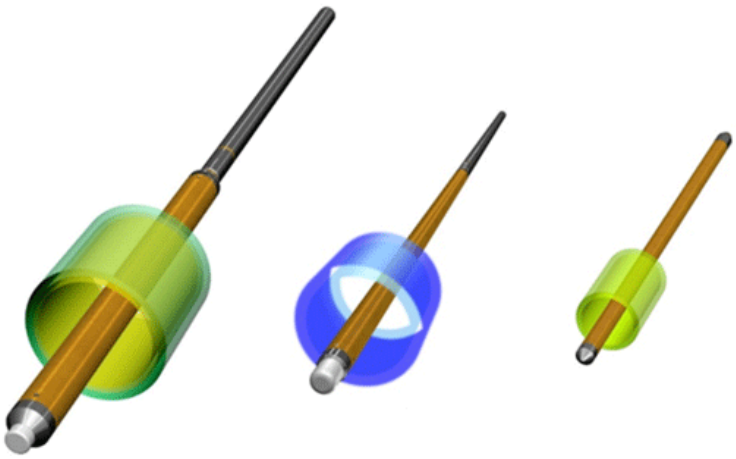

Figure 1: Multiple logging shells of a selection of probes from the Javelin and Dart product line. Left: Javelin Max with 5.25-inch (OD) three-frequency NMR probe with three measurement shells at diameters of 16, 18.5 and 21 inches. Center: Javelin Slim with 2.38-inch (OD) two-frequency NMR probe with two measurement shells at diameters of 9 and 11 inches. Right: Dart 1.75-inch (OD) two-frequency NMR probe with two measurements shells at diameters of 5 and 6 inches.

The NMR measurements at each frequency, and correspondingly at each radial distance, are completely independent and interleaved in time. In a Javelin or Dart log, the system alternates between measurements at each frequency over the course of the log, yielding independent logs for each radial distance from a single logging run. These separate logs can be analyzed independently and/or merged into a combined log that represents the average hydrologic properties across the radial measurement zones.

If desired, multi-frequency capabilities can be disabled by the operator at acquisition time, and the Javelin will collect at a single frequency, operating identically to a single-frequency-only system. In practice however, it is almost always beneficial to acquire NMR data at multiple frequencies. The reasons for this are described next.

Benefit #1: Operate in a Wider Range of Wells and Boreholes

The multiple logging shells of a multi-frequency NMR probe have varied characteristics: shells with a smaller radius have higher signal-to-noise ratios and shorter echo spacing, permitting faster logging and improved characterization of bound water, while shells with a larger radius have the ability to see past large annular spaces, drilling disturbance, and washouts. With a single-frequency logging system, operators must choose which of these characteristics they want, or must use multiple tools and perform multiple logging runs to achieve both objectives.

Multi-frequency logging systems put all these capabilities into a single probe. When drilling diameters are small and conditions permit, all logging shells can be used, taking advantage of the high signal-to-noise ratio and short echo spacing of the inner shell. In marginal conditions (e.g., large drilling diameters, washouts, extensive drilling disturbance), the larger shell can be relied upon to deliver results.

For example, Vista Clara's Javelin Max JPX525T probe has three logging shells, with diameters of 16in, 18.5in, and 21in. This probe is appropriate for use in 7-8in open hole borings, in which case all three shells can be used, *and* is appropriate for use in 17-18in open hole borings, in which case only the 21in shell intersects the native formation.

Operators can easily select which shells to acquire during logging, or can acquire all shells and select which ones to use in Vista Clara's powerful, user friendly analysis software.

Don't miss out: with single-frequency systems, operators must choose between having high signal-to-noise and short echo spacing, or having a large diameter of investigation.

Benefit #2: Faster Logging

NMR measurements require a wait time of several seconds between excitations to allow complete longitudinal relaxation of the hydrogen spin moments before initiating a new NMR response. With a multi-frequency system, measurements at one frequency can be conducted during the wait time of the other frequency (or frequencies). This provides more measurements per time interval than a single-frequency tool, improving the signal-to-noise ratio, with little to no time penalty.

After excitation and measurement of the NMR response, water in larger pores takes a longer time to relax back to equilibrium than water in small pores. This relaxation rate is called T1 relaxation, and water in coarse sands and gravels can exhibit T1 relaxation constants of one second or longer. The T1 relaxation times of water in the largest pores in each logging environment determines the shortest repetition frequency that can be used at any single frequency. If an NMR

measurement is performed before the T1 relaxation process has had time to complete, the water content in large pores will be significantly underestimated. For this reason, there is a mandatory wait time, typically three seconds or longer, between successive measurements at a single frequency.

Multi frequency tools turn this limitation into a strength by acquiring data at multiple frequencies interleaved in time. Due to significant separation between operating frequencies, and limited bandwidth of the transmitted RF energy, the measurement at one frequency does not disturb the T1 relaxation process at other frequencies. This enables multi-frequency NMR logging tools to collect 2x or even 4x as much data for any time interval compared to a single-frequency NMR tool.

The NMR measurements at each frequency in multi-frequency Javelin logging are completely independent of one another: the NMR excitation and relaxation taking place at one frequency and distance from the probe is unaffected by the excitation and relaxation occurring at a different frequency and distance from the probe. The regions of excited groundwater are physically isolated and non-overlapping. This means that an NMR measurement can be made at one frequency and distance during the time that the hydrogen nuclei are recovering from a previous measurement at a different frequency and distance. This creates significant time savings, allowing equivalent logs (same resolution and signal-to-noise) to be completed faster than with a single-frequency system (Coates *et al.*, 1999).

Equivalently, this time efficiency can be exploited to collect more samples in the same amount of time compared to a single-frequency system, yielding a log with a higher resolution, an improved signal-to-noise ratio, or both.

Don't miss out: with single-frequency systems, operators must log slower or at coarser resolution to obtain the same signal-to-noise ratio as a multi-frequency Javelin system. Multi-frequency NMR logging tools provide both options in a single tool.

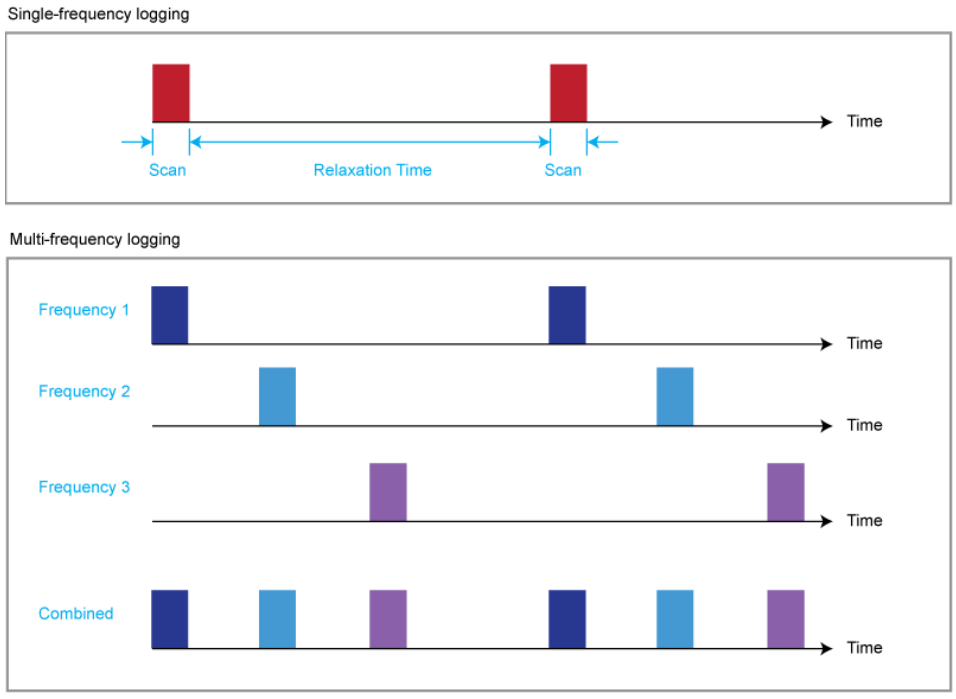

Figure 2: Top: Single-frequency logging tools are inactive during the mandatory relaxation time between consecutive measurements. This is lost time. Bottom: Multi-frequency logging uses the relaxation time at each frequency to perform measurements at different frequencies, increasing the data density over time, thereby improving the signal-to-noise ratio and allowing faster logging.

BENEFIT #3: RESILIENCE AGAINST EM INTERFERENCE

All NMR logging is sensitive to electromagnetic interference (EMI), which can be conducted into the system from connected electronics (e.g., inverters or switching power supplies) or radiated in from the environment (e.g., electrical storms, power lines, or submerged pumps). EM interference is especially prevalent in shallower borehole logging conditions common to groundwater, environmental, and geotechnical applications. Some sources of EMI may be broadband, but many are narrowband and occur at isolated frequencies. It is often impossible to predict or anticipate the frequencies at which harmful narrowband interference will occur for any project or location.

Logging with a single-frequency NMR system means a single point of failure for data collection: if high levels of EM interference exist at the NMR excitation frequency used by the system, data can be rendered significantly compromised or wholly unusable (e.g., Pehme *et al.*, 2022).

Logging with a multi-frequency Javelin system means a greater likelihood of operating at a frequency or frequencies clear of destructive interference. Because measurements at each frequency yield independent data sets, any data collected at a frequency impacted by interference can be down-weighted or discarded and only the data from unaffected frequencies considered. Vista Clara's Javelin Pro processing software automatically produces a noise-weighted average of the NMR signals from the different logging shells to produce a weighted average with optimal signal-to-noise ratio.

Although multi-frequency logging improves the odds of collecting data unaffected by EM interference, it does not guarantee it. It is possible for EM interference to occur at each of the Javelin or Dart operating frequencies, resulting in compromised or unusable data for an entire log. However, with each additional operating frequency added to the system, the statistical odds of achieving unaffected data necessarily improve.

Don't miss out: with single-frequency systems, local EM interference occurring at the detection frequency will render the data unusable.

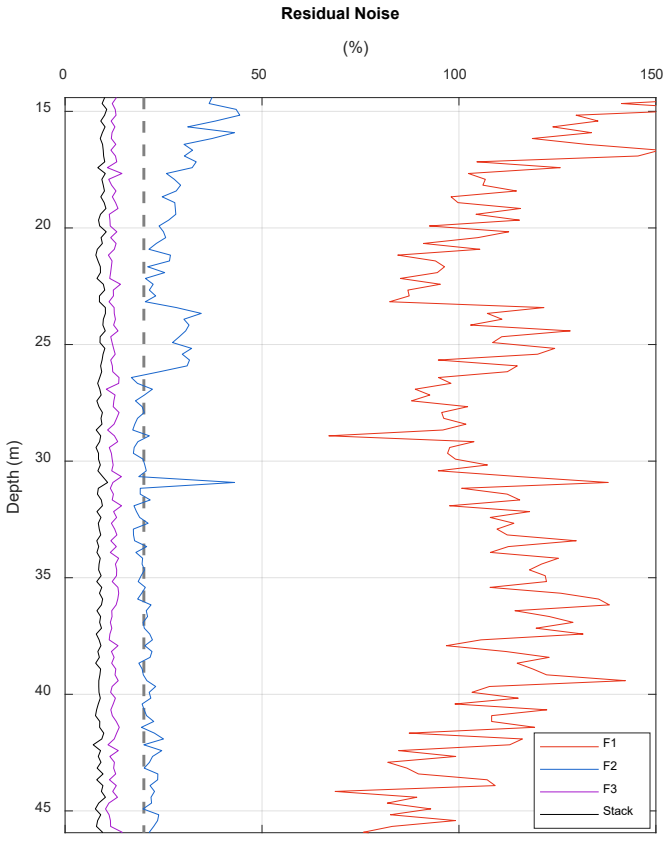

Figure 3: Real data example of EM interference levels (expressed as Residual Noise Percentage). Noise levels greater than 20% on this scale can result in unreliable data. In this log, Frequency 1 suffered excessive interference, resulting in completely unusable data. Frequency 2 had marginal-to-unacceptable levels of interference. Only Frequency 3 yielded data that was unaffected and fully usable. With a single-frequency system operating at Frequency 2 or Frequency 3, no usable data could be obtained from this log. With a Javelin multi-frequency system, high quality data was obtained.

BENEFIT #4: RADIAL INFORMATION

The NMR measurement at each frequency in a multi-frequency Javelin system provides an independent measurement at physically distinct radial distances from the probe ("shells"). This provides an opportunity to assess radial variability in the formation or borehole, offering the potential to provide information about borehole or drilling conditions. This can facilitate identification of zones or conditions where interpretation of the collected data is inappropriate, and direct the optimal selection of shells for inclusion in the final NMR data product. For example:

- Washouts or inadequate centralization of the logging probe can be identified by high mobile water contents in the inner shell compared to the outer shell. Failing to recognize these conditions will result in overestimation of mobile water fraction and overestimation or underestimation of hydraulic conductivity.
- Invasion of drilling mud into the formation can be identified by increased bound water fraction in the inner shell compared to the outer shell, due to the mud's short signal decay time compared to water. Failing to recognize these conditions will result in drilling mud being classified as bound water, which would result in a diametrically wrong interpretation of a formation that has large pore spaces and large hydraulic conductivity.

In these situations, affected sections of the well or borehole can be excluded from interpretation, or only the outer shell(s) can be considered. Not all such disturbance may be identifiable over the spatial distance spanned by the different logging shells, but in cases where it does occur, analysis of multiple logging shells provides a powerful quality control metric that is unavailable in single-frequency logging.

If no radial variability is observed between the logs at each distance and all logs are deemed valid, the data from all the measurement shells can be combined at each depth, yielding a single log with an improved signal-to-noise ratio compared to the independent logs.

Don't miss out: with single-frequency systems, there is no ability to identify and confirm effects from drilling disturbance.

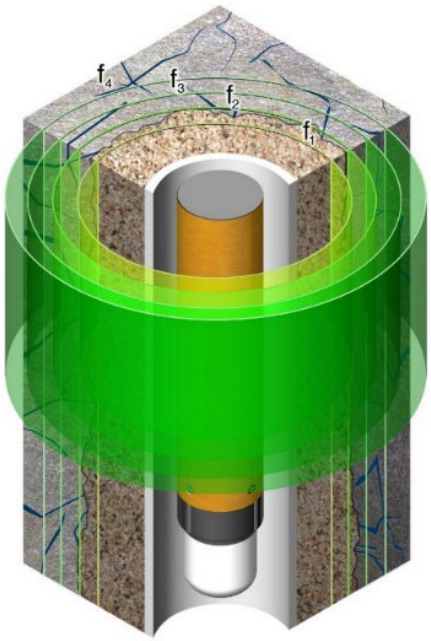

Figure 4: Multiple logging shells provide information about radial variability from the borehole. This information can be used to positively identify washout zones and/or drilling mud invasion, and exclude specific measurement shells from the final data product to avoid mis-characterization of formation properties.

CONCLUSIONS

Multi-frequency NMR logging systems provide numerous important benefits and no drawbacks, making these systems superior to single-frequency tools in all cases. Multi-frequency logging increases signal-to-noise ratio, allowing faster logging and higher-resolution sampling than single-frequency logging. Multi-frequency logging also offers resilience against electromagnetic interference and provides radial information that can help to assess borehole conditions and avoid mis-characterizing formation hydrologic properties. These benefits come with no downsides, making multi-frequency logging a must-have feature for groundwater NMR logging systems.

REFERENCES

Coates, G.R., Xiao, L., Prammer, M.G., 1999. NMR Logging Principles and Applications. Gulf Professional Publishing.

Pehme, P., Crow, H., Parker, B., Russell, H., 2022. Evaluation of slim-hole NMR logging for hydrogeologic insights into dolostone and sandstone aquifers. Journal of Hydrology 610, 127809. https://doi.org/10.1016/j.jhydrol.2022.127809