Now you see it, *Now you don't!*

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Highly deviated wellbores sometimes suffer from a cyclic variation in borehole size. And ***although the caliper oscillations may be relatively small (+/- 1/4" for example), when combined with a salty mud the composite can severly compromise the borehole wireline data***. ***Curiously, it may be the deepest reading tool (resistivity) which suffers the largest degradation,*** with the pad bulk density data being less affected than the mandrel neutron porosity: Figure 1.

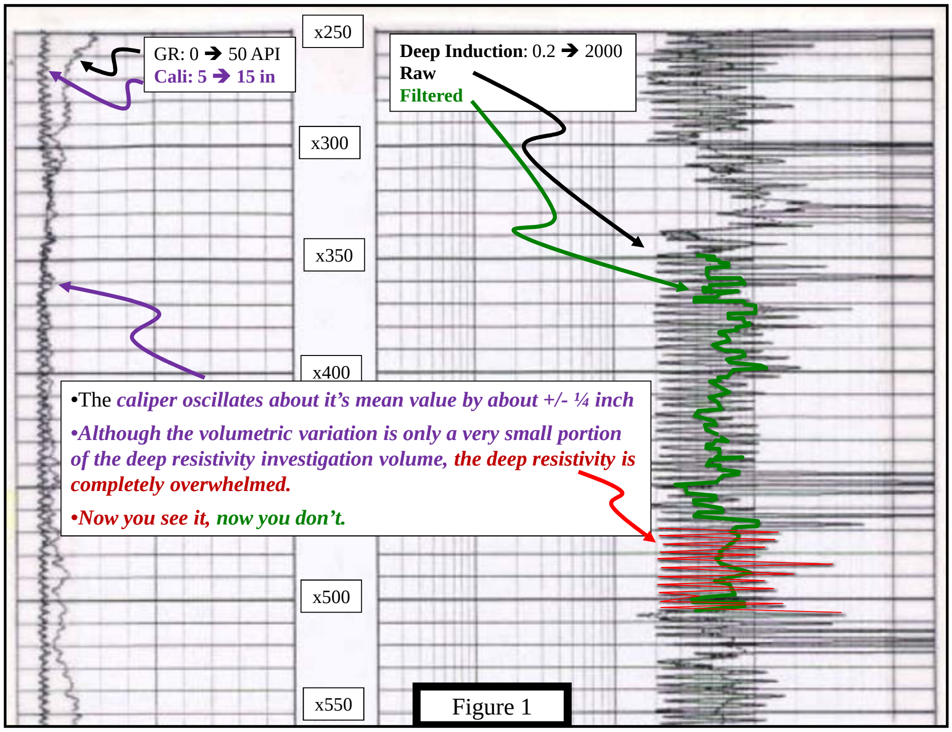
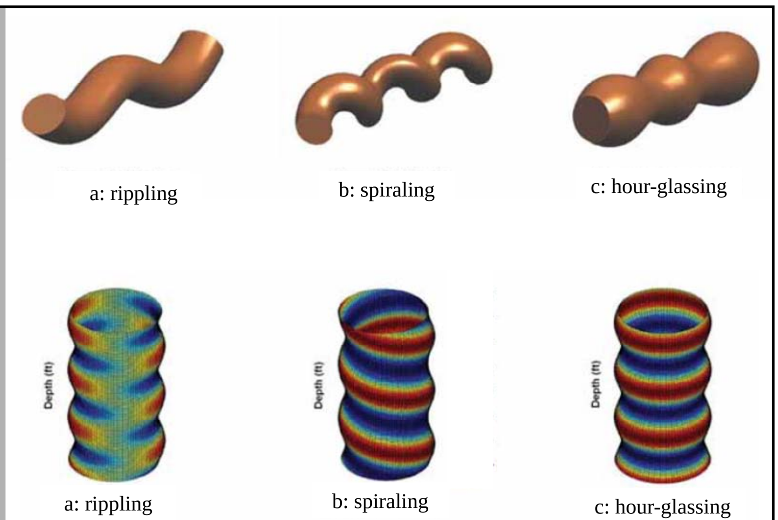


Figure 1

Figure 2

The Fourier Transform of the caliper log, across the interval of cyclic wellbore, will contain a peak at the frequency (depth wavelength) corresponding to the cyclicity of the hole size.

A filter, designed to eliminate the spurious frequency peak observed in the caliper data, is applied to the other data, thereby removing the anomaly and leaving the valid formation response.



Pastusek et al described *the three most common forms of borehole oscillations as: a) Rippling b)Spiraling c) Hour-glassing*.

Pastusek, Paul et al. A Model for Borehole Oscillations. SPE 84448, 2003.

Sugiura, Junichi et al. The Use of the Industry's First 3-D Mechanical Caliper Image While Drilling Leads to Optimized Rotary-Steerable Assemblies in Push- and Point-the-Bit Configurations. SPE Annual Technical Conference and Exhibition. Sept 2008, Denver, CO, USA

The situation may be understood, and a remedy devised, within the context of the Fourier Transform. The Fourier Transform of the caliper log, across the interval of cyclic wellbore, will contain a peak at the frequency (depth wavelength) corresponding to the cyclicity of the hole size: Figure 2.

A filter, designed to eliminate the spurious frequency peak

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observed in the caliper data, is applied to the other data, thereby removing the anomaly and leaving the valid formation response. That is, ***the manifestation of the basic problem appears in the caliper log, and it is the caliper log which determines the filter specification appropriate for the correction of the effects in the other logs: Now you see it, now you don't.***

The Fourier Transform concept can further be used to quantify logging tool boundary resolution, at various logging speeds and/or with special processing. For example, the Gamma Ray and Neutron are often pulled to surface through pipe, after completion of the open-hole job, and we would like that uphole logging speed to be a fast as possible. A comparison of Fourier Transforms, at various logging speeds, will quantify the differences in associated vertical tool resolutions. Alternatively, or additionally, the open-hole interval may require an increased vertical resolution (thin beds, for example), and we can evaluate (compare) the different service company options via their respective Fourier Transforms.

The Fourier Transform

The Fourier Transform determines the frequency content of a periodic function (typically cyclic in time, but in the current case cyclic in depth), ***thereby allowing that function to be represented as a series of sine and cosine expressions.***

The wireline logs are said to be the "depth domain" representation with the Transform being the "frequency domain" expression.

In the case of an example square wave of periodicity 20 ft, the cosine terms drop out (integrate to zero) because the square wave has value zero at the origin, and only the sine terms are required: Figure 3.

The ***Fourier Transform concept*** revolves around ***representing any periodic function as the sum of various sine and cosine components***, with ***the coefficient amplitude reflecting the corresponding frequency content of that signal***.

In the case of an ***illustrative square wave***, the ***cosine components are zero*** since the square wave is of amplitude zero at the origin, and ***the various, individual sine wave components are as at right.***

Figure 3

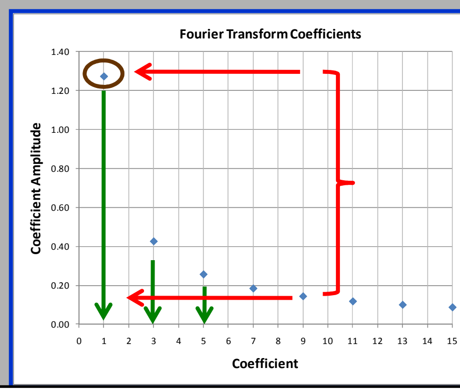
$$x_{\text{square}}(t) = \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{\sin\left((2k-1)\pi f t\right)}{(2k-1)}$$
$$= \frac{4}{\pi}\left(\sin(\pi f t) + \frac{1}{3}\sin(3\pi f t) + \frac{1}{5}\sin(5\pi f t) + \cdots\right)$$

The ***coefficient amplitude indicates the relative contribution of that specific frequency to the net response.***

In the case of a square wave, one observes

- ***Only odd integers contribute***
- ***The most important component is the basic sine wave: k = 1***
- ***Beyond k = 7, the coefficient amplitude is less than about 1/10 the base amplitude***

http://en.wikipedia.org/wiki/Square_wave



The magnitude of the various frequency coefficients reflects their respective importance in the composition of the actual (original) measurement.

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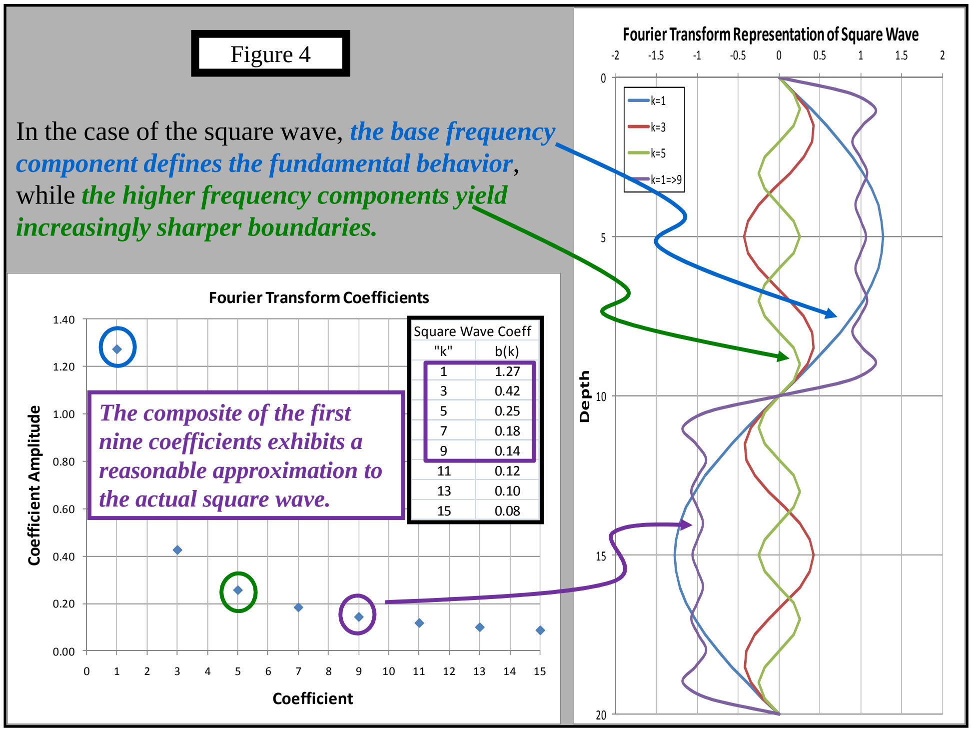
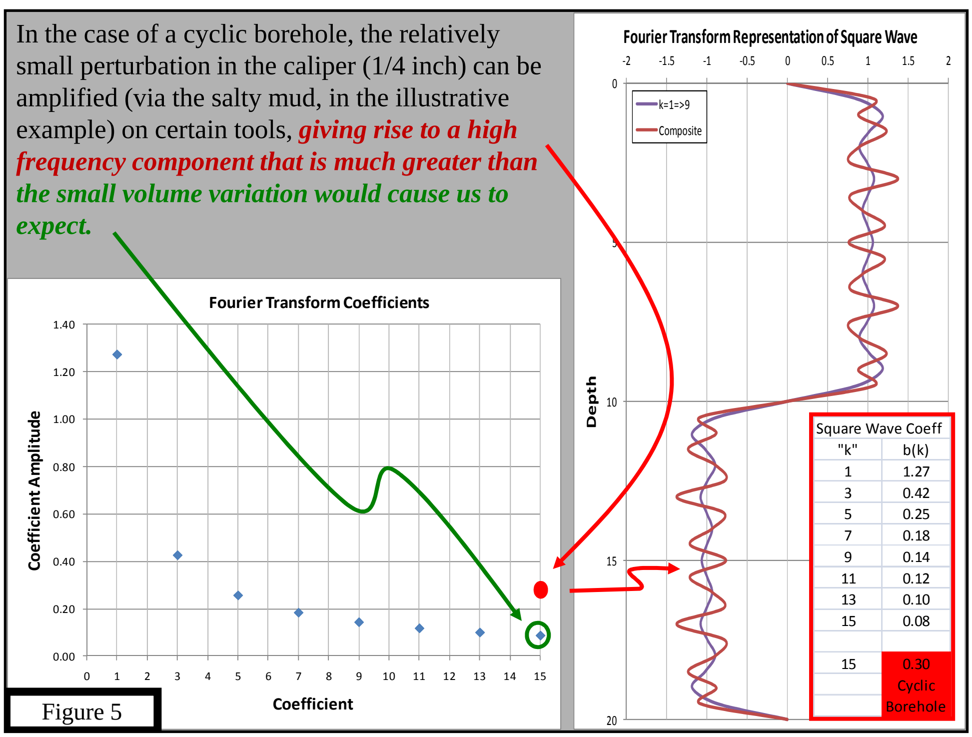


Convergence (decreasing coefficient amplitude) can be surprisingly rapid. In the case of a square wave, we find that a basic sine wave (first term in the series expression) is clearly approaching the desired square wave, when the first nine terms are summed: Figure 4.

In the field example to be discussed next, ***the carbonate reservoir is relatively uniform as compared to the periodicity of the cyclic borehole variation, and the combination of a cyclic borehole and salty mud have given rise to an unusually large higher frequency component***: Figure 5.



Our approach is to Transform the caliper log, which is the physical manifestation of the issue, and identify the frequency band that needs to be eliminated from wireline data. In doing this, we expect of course, to find the frequency consistent with the observed depth period in the caliper log.

Because the reservoir is relatively uniform at the scale of the wellbore cyclicity, ***a properly designed low pass filter will yield the frequency spectrum of the basic underlying formation response***, and when that spectrum is transformed back into the depth domain, we can be said to have "recovered lost data in the frequency domain".

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Illustrative Example

Upon occasion, the bottom-hole drilling assembly in a deviated well can yield a cyclic borehole which has small (+/- 1/4") oscillations about the mean wellbore radius, but results in large variations in wireline tool responses.

In the case at hand the problem arises when changing from sliding to rotating drilling modes. ***While sliding, the bent housing steerable mud motor produces an in-gauge hole, but when one switches to rotating (in order to drill ahead faster), the bent assembly can interact with the stabilizer, to produce alternating hole sizes with the period of the oscillation determined by the bit-to-stabilizer length.***

While the volumetric variation is extremely small in comparison to the total volume seen by the deep resistivity tool (or even the porosity logs), the periodic nature of the caliper oscillation can yield a log anomaly (noise) which nearly overwhelms the basic formation response.

By transferring the issue to the frequency domain it is possible to characterize the "noise" via a Fourier Transform of the caliper log, which is the physical manifestation of the problem. And to then design a low-pass filter which may be applied to the remainder of the logs. ***In effect, one removes from the resistivity and porosity data, those spatial frequencies which correspond to the "noise" found in the caliper log, leaving the basic formation response:*** Figure 6.

The Fourier Transform of the ***'raw' caliper exhibits a strong peak at about 0.28 ft $^{-1}$***, ***corresponding to a periodicity of 3.6 ft***, which is that observed in the depth oriented display.

The ***objective is to define a filter which will remove the cyclic borehole effects from the caliper (and other logs),*** and this ***may be done with either a 'notch' or 'high cut' filter.***

In this example, ***a 'high cut' filter yields the green distribution.***

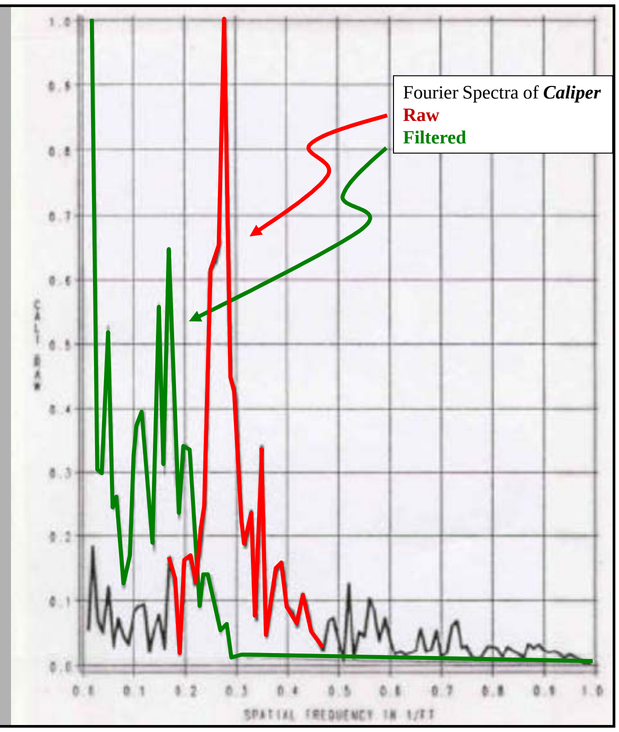

Figure 6

We have typically encountered the problem in highly deviated wells, but it has been observed at much smaller angles. In the illustrative example herein, the formations of interest are relatively thick and nearly horizontal; true formation variations in the historical sense (along the wellbore) are then gradual. As a result, the high cut filter designed by examination of the caliper Fourier spectra, does not seriously compromise the resulting evaluation.

The porosity logs are filtered with the exact same filter which was specified from, and tested with, the caliper log.

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The porosity logs are filtered with the exact same filter which was specified from, and tested with, the caliper log.

The Fourier Transform of the ***'raw' density exhibits a peak at about 0.28 ft*** $^{-1}$, ***corresponding to a periodicity of 3.6 ft***, ***but that peak is not so dominant as was the case with the caliper, suggesting that the cyclic borehole has relatively less effect (bulk density vs deep resistivity).***

The 'high cut' filter yields the green spectra, which is basically the formation density, absent the cyclic borehole effects.

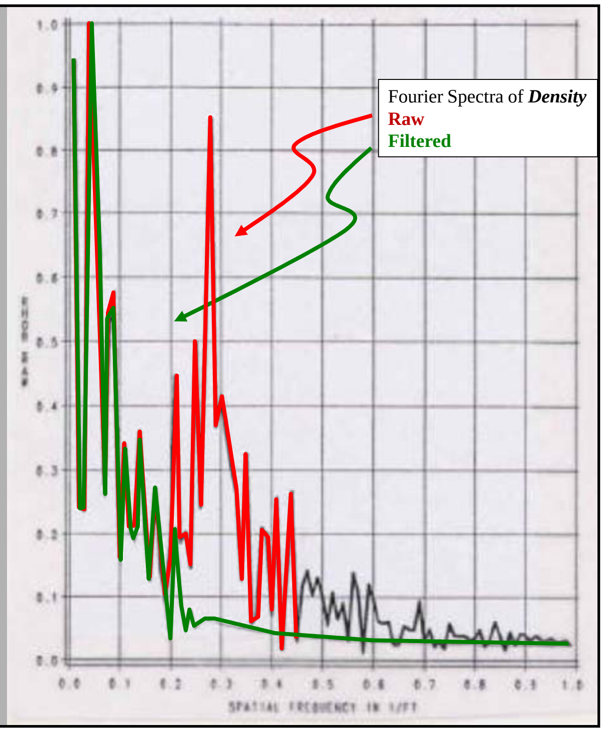

Figure 7

The Fourier Transform of the 'raw' density exhibits a peak at about 0.28 ft $^{-1}$, corresponding to a periodicity of 3.6 ft, but that peak is not so dominant as was the case with the caliper, suggesting that the cyclic borehole has relatively less effect (bulk density vs deep resistivity): Figure 7.

The 'high cut' filter results in a spectrum that is essentially the same as the 'raw' spectra, below the cyclic borehole frequency. This is then the basic formation bulk density, absent the cyclic borehole effects, now available for evaluation.

As expected from the depth oriented display, the Fourier Transform of the neutron log also exhibits a peak at about 0.28 ft $^{-1}$, and now that peak is larger in magnitude than the lower frequency components (compare to bulk density results, Figure 7): Figure 8.

That is, ***while the neutron log is mandrel, as compared to the pad density, and even though the borehole volume variations are less of the total volume investigated by the neutron as compared to the density log, the effect upon the neutron is larger***. This is likely due to the salty mud and associated environmental effects on the neutron, a relatively minor issue with the density log.

The porosity logs are filtered with the exact same filter which was specified from, and tested with, the caliper log.

The Fourier Transform of the ***'raw' neutron exhibits a peak at about 0.28 ft*** $^{-1}$, with a periodicity of 3.6 ft, ***and is less dominant than was the case with the caliper, but more obvious than with the bulk density log (likely due to the very salty mud, and associated environmental effects).***

The 'high cut' filter yields the green spectra, whose pattern basically tracks the 'raw' spectra, but absent the cyclic borehole effects.

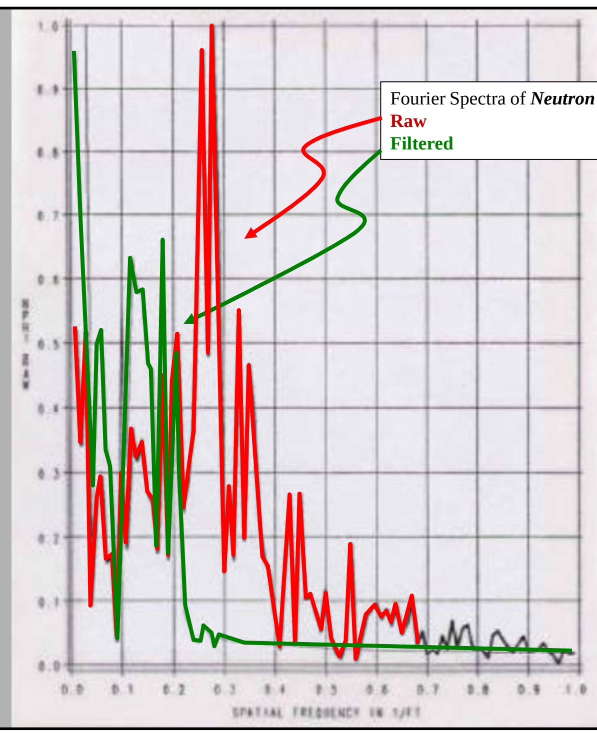

Figure 8

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The raw and filtered (before and after) data are seen in Figure 9.

Again, in the illustrative example herein, the filter is determined directly, and only, from the caliper log, which is the actual physical manisfestation of the problem. ***In the case of the deep resistivity, the salty mud (R_{mf} = 0.04 ohm-m @ 75 F) has led to a cyclic borehole component that completely over-whelms the formation response***: Figure 10.

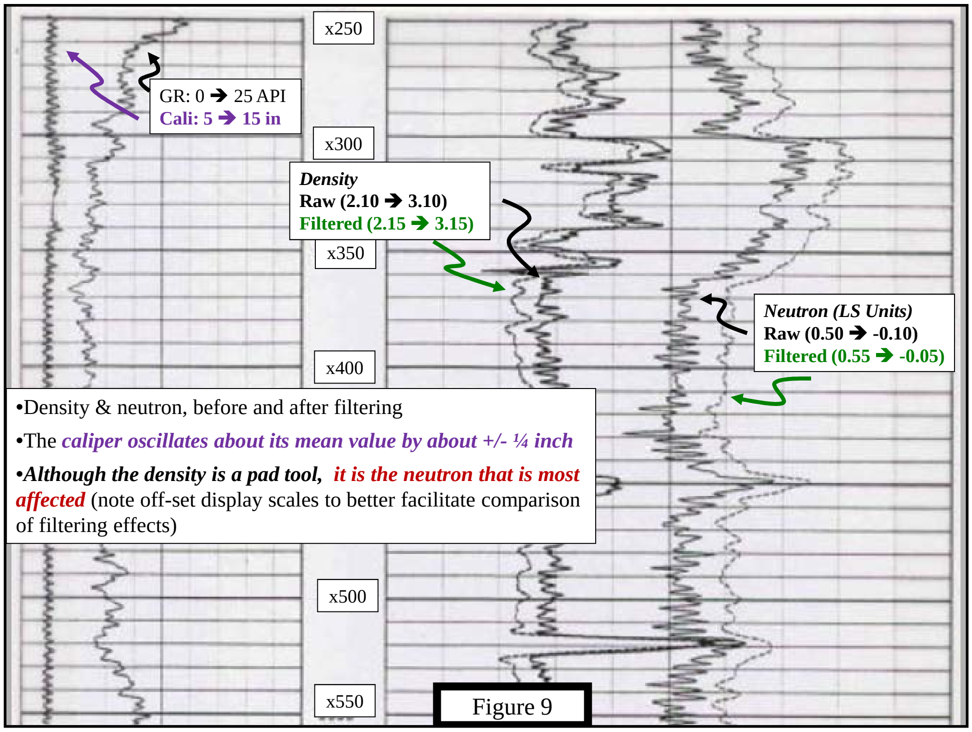

Figure 9

The deep resistivity is filtered with the same filter that was specified from, and tested with, the caliper log.

The Fourier Transform of the ***'raw' data exhibits a strong peak at about 0.28 ft*** $^{-1}$, with a periodicity of 3.6 ft, ***which is even more dominant than was the case with the neutron (again, likely due to the very salty mud, and associated environmental effects).***

The 'high cut' filter yields the green spectra, which tends to tracks the 'raw' spectra, but absent the cyclic borehole effects.

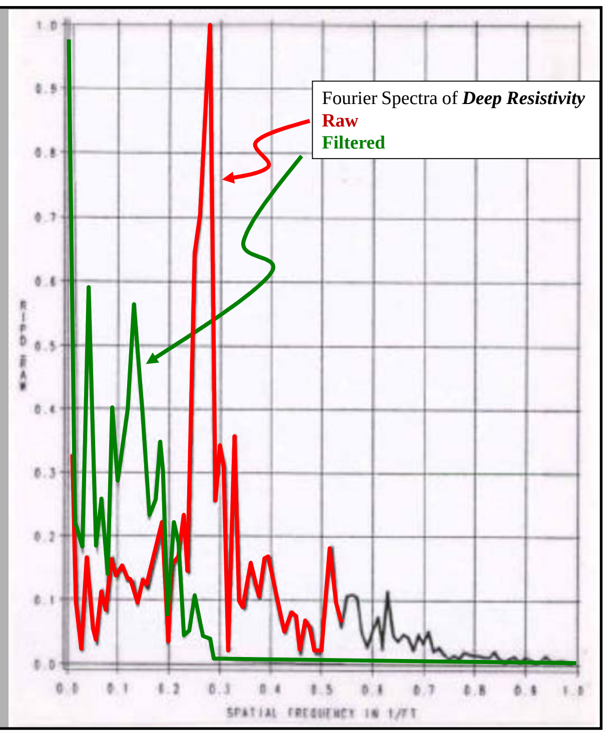

Figure 10

Paradoxically, the tool with greatest volume of investigation as compared to the density and neutron, is the one most affected by the relatively small borehole volume variations.

Applying the caliper-based low pass filter to the deep resistivity results brings forward the basic formation response: Figure 1.

Now you see it (the problem), now you don't (cyclic borehole effect is gone).

When working with logarithmic displays, such as commonly used for the resistivity, it is important to remember that while the average of 10.0 and 100.0 is about 60 (ten plus one hundred, divided by two), the average of the two corresponding logarithms is 1.5 (one plus two,

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divided by two). Arithmetic averages do not plot in the middle of the extremal values, when posted to a logarithmic display.

The approach developed here is general, and may be applied in other deviated wells as necessary. The Fourier Transform concept can further be used to quantify bed boundary resolution, at various logging speeds, thereby allowing one to optimize (particularly uphole passes, for correlation purposes) wireline operations (minimizing rig time).

As an example, ***when one Service Company introduced a new bulk density tool, with high resolution options, we ran both the new and old tool in the same wellbore, plus running the new tool in the various increased resolution modes (increased digitization rate plus processing), and then used the Fourier Transform spectra (plus comparison to R_{xo}) to quantitatively document the resolution improvement***.

Acknowledgement

As a young man just home from the Army, and attending Missouri State University, three men sparked my interest in physics, and the mathematical tools with which physical models could be constructed: Dr Larry Banks, Dr Bruno Schmidt and Dr Woodrow Sun.

Like the cyclic borehole discussed herein, life is also cyclic: birth, ascent to maturity, the golden years and death. We lost Dr Banks last year, but just as the borehole cycles reappear, so too does his memory to those who knew and respected him.

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Biography

R. E. (Gene) Ballay's 35 years in petrophysics include research and operations assignments in Houston (Shell Research), Texas; Anchorage (ARCO), Alaska; Dallas (Arco Research), Texas; Jakarta (Huffco), Indonesia; Bakersfield (ARCO), California; and Dhahran, Saudi Arabia. His carbonate experience ranges from individual Niagaran reefs in Michigan to the Lisburne in Alaska to Ghawar, Saudi Arabia (the largest oilfield in the world).

He holds a PhD in Theoretical Physics with double minors in Electrical Engineering & Mathematics, has taught physics in two universities, mentored Nationals in Indonesia and Saudi Arabia, published numerous technical articles and been designated co-inventor on both American and European patents.

At retirement from the Saudi Arabian Oil Company he was the senior technical petrophysicist in the Reservoir Description Division and had represented petrophysics in three multi-discipline teams bringing on-line three (one clastic, two carbonate) multi-billion barrel increments. Subsequent to retirement from Saudi Aramco he established Robert E Ballay LLC, which provides physics - petrophysics consulting services.

He served in the U.S. Army as a Microwave Repairman and in the U.S. Navy as an Electronics Technician: he is a USPA Parachutist, a PADI nitrox certified Dive Master and a Life Member of Disabled American Veterans.

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