Using PIETA to Map Echo Train Coherence Pathways

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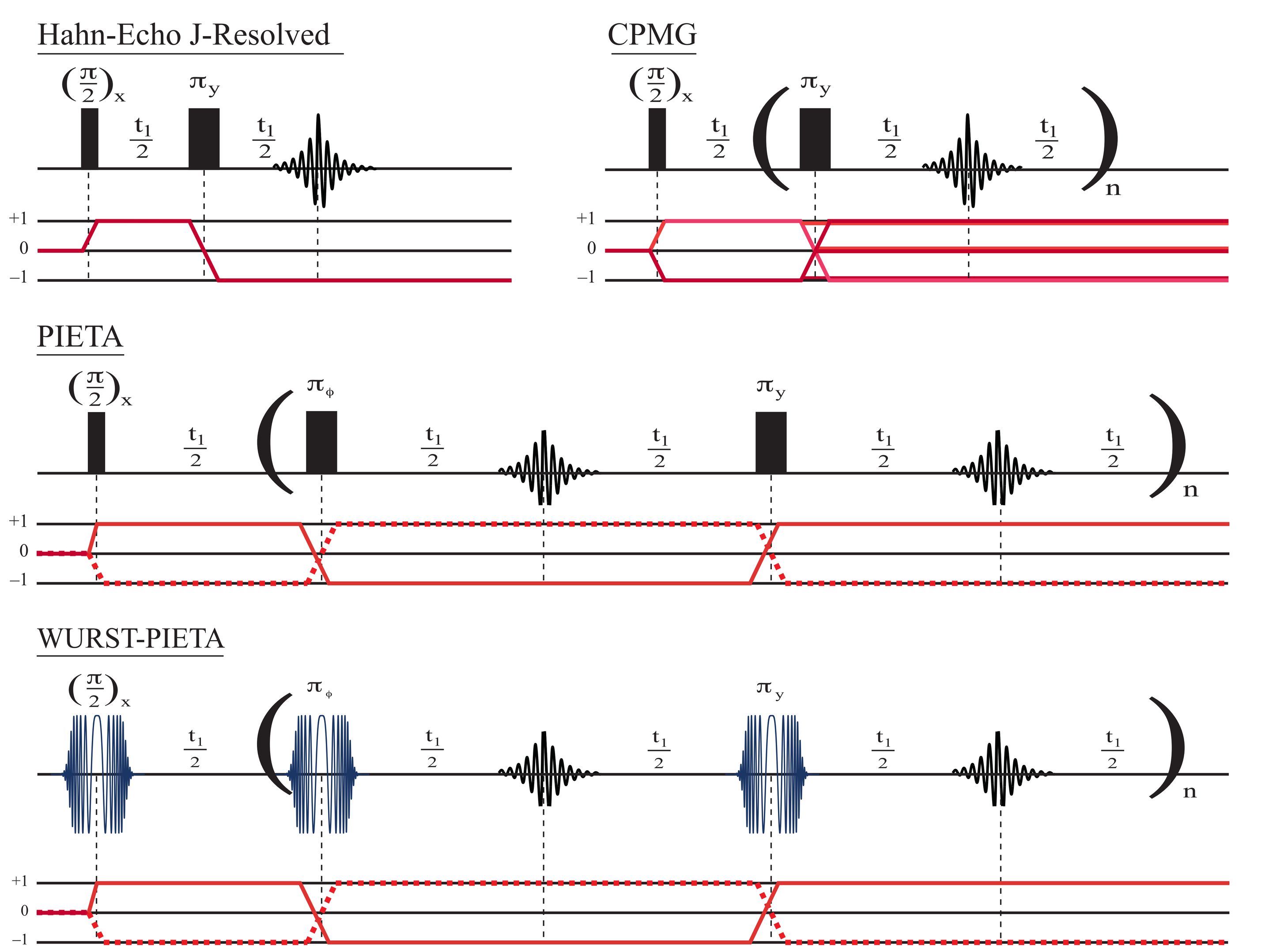
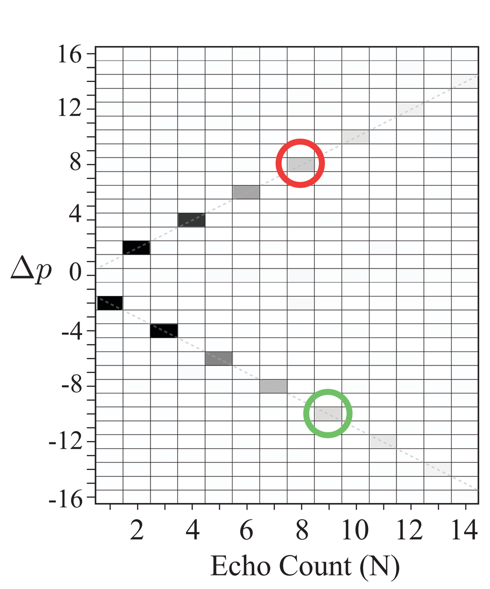
Background

- Echo train acquisition (and CPMG in particular) is used in many different applictions.
  - Measurement of diffusion
  - Sensitivity enhancement
  - Relaxation weighted imaging
  - Low field relaxation studies (e.g. core samples, oil well logging)
  - Relaxation dispersion experiments
- In cases where the echo dimension contains information (all of these except for sensitivity enhancement) the coherence pathway for the signal is important for modeling and normally is expected to be an alternating ±1 producing Hahn echo signals
- Pulse imperfections, offset effects and pulse length errors lead to production of stimulated rather than Hahn echo signals in many cases mentioned above
- PIETA allows us to map the portion of signal that follows the correct pathway

Pulse Sequences and Coherence Pathways



Coherence Maps with PIETA

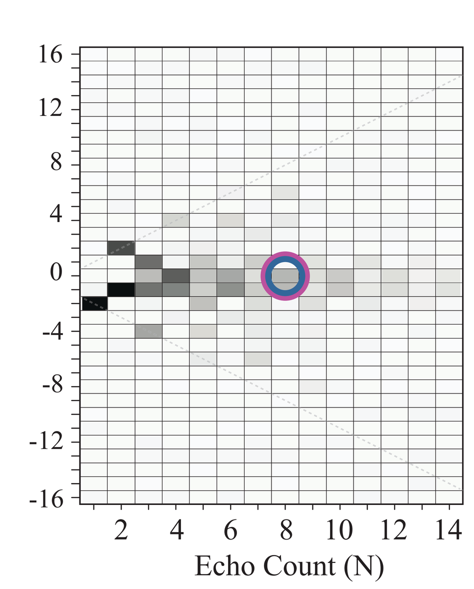


$$S_N(\Delta p) = \int e^{-i\phi_P \Delta p}\, e^{iP_N(\phi_P)}\, d\phi_P$$

$$P_N(\phi_P) = \sum_n^N \Delta p_n\, \phi_n$$

$$\phi_n = \begin{cases} 0 & \text{odd } n \\ \phi_P & \text{even } n \end{cases}$$

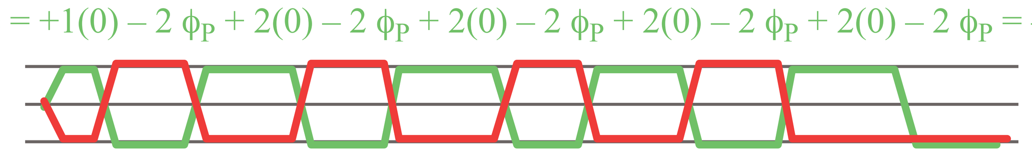
$$-1 = \sum_n^N \Delta p_n$$



For good pulses (left map) the most intense echoes from unique pathways occur at

$P_8(\phi_P) = -1(0) + 2\,\phi_P - 2(0) + 2\,\phi_P - 2(0) + 2\,\phi_P - 2(0) + 2\,\phi_P - 2(0) = +8\,\phi_P$

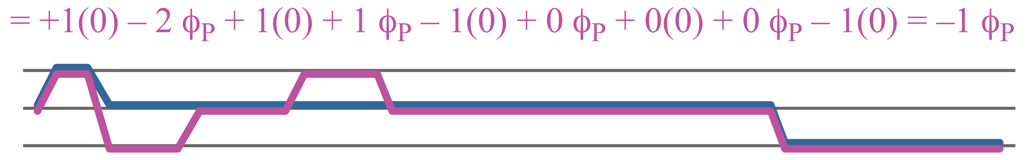
$P_8(\phi_P) = +1(0) - 2\,\phi_P + 2(0) - 2\,\phi_P + 2(0) - 2\,\phi_P + 2(0) - 2\,\phi_P + 2(0) = -10\,\phi_P$



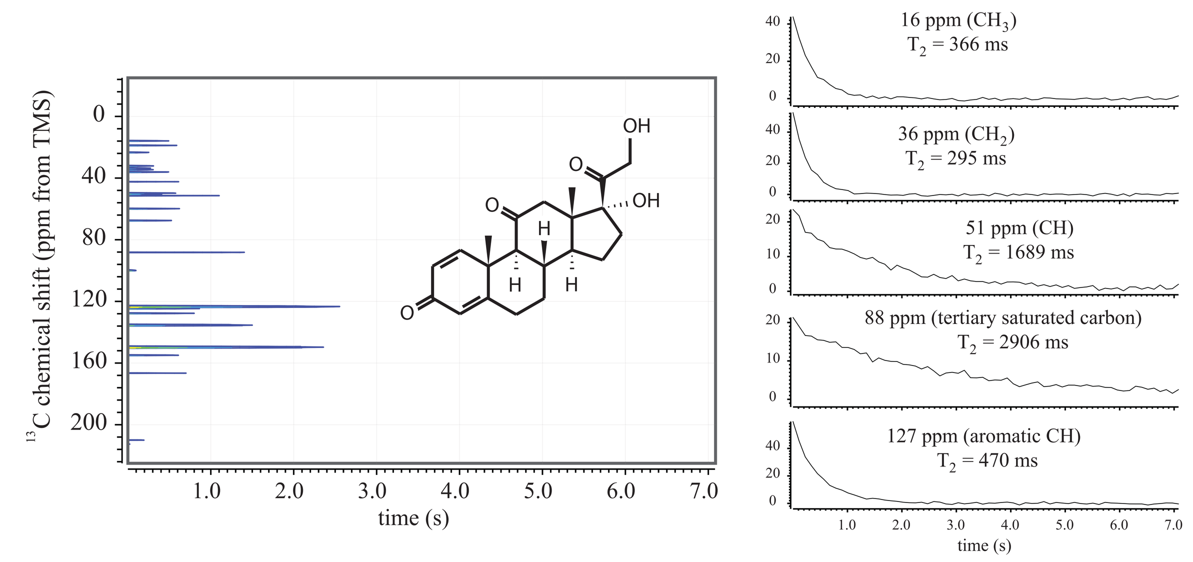
For bad pulses (right map) the most intense echoes occur from many non-unique pathways

$P_8(\phi_P) = +1(0) - 1\,\phi_P + 0(0) + 0\,\phi_P + 0(0) + 0\,\phi_P + 0(0) + 0\,\phi_P - 1(0) = -1\,\phi_P$

$P_8(\phi_P) = +1(0) - 2\,\phi_P + 1(0) + 1\,\phi_P - 1(0) + 0\,\phi_P + 0(0) + 0\,\phi_P - 1(0) = -1\,\phi_P$

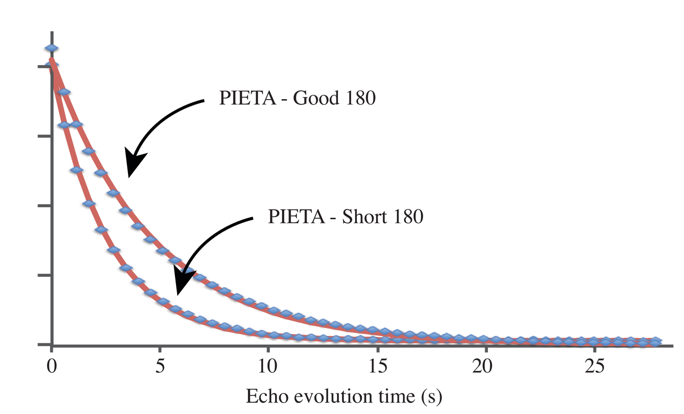


^{13}C Relaxation Measurements



- Contour plot shows longer contours (lines) for longer T_2 decay curves
- T_2 measurements may be done with PIETA but offset and pulse width effects lead to faster decays for the peaks that are farther from the center.
- In CPMG, many of these off-resonance peaks show very long decays that are indicative of long T_1 rather than long T_2

^1H Pulse Length Experiments: T_2 from TMS



$$S_{IDEAL}(\tau) = A\, e^{-\tau/T_2}$$

$$S_{REAL}(\tau) = A\, e^{-\tau/T_2^*} = A\, e^{-\tau/T_2}\, e^{-\tau/k}$$

$$\frac{1}{T_2^*} = \frac{1}{k} + \frac{1}{T_2}$$

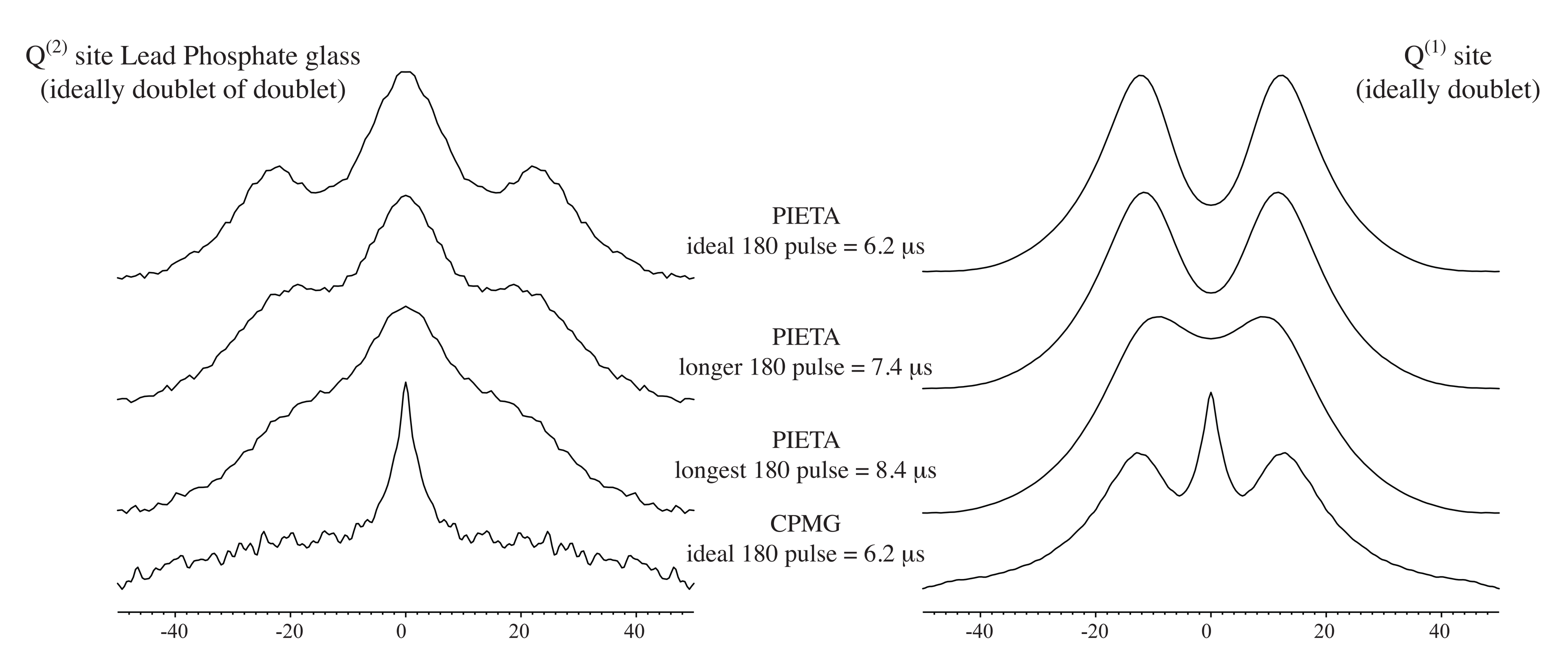
$$f = \sin^2\frac{\phi}{2}$$

$$k = \frac{-dw_{echo}}{\ln f}$$

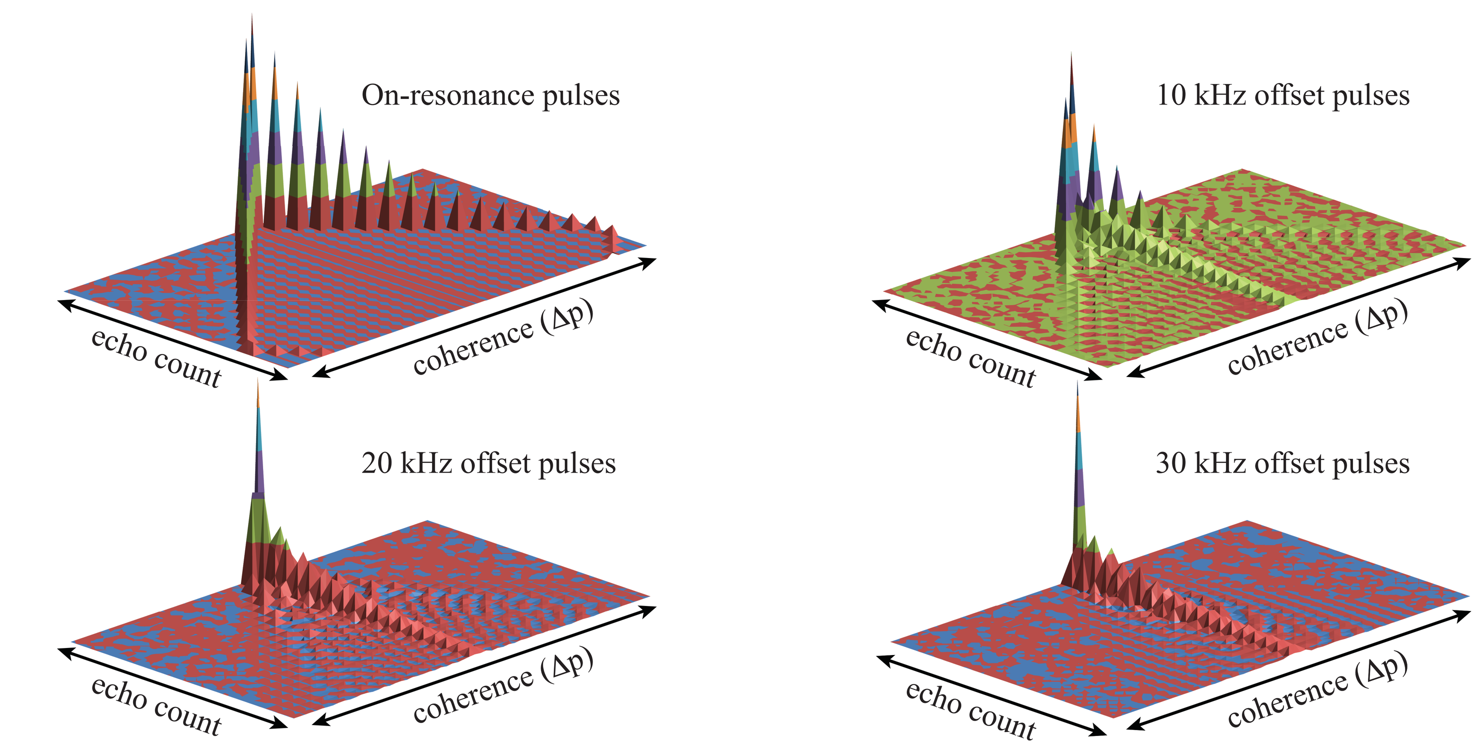
- Measured on-resonance T_2 using PIETA with variable pulse lengths gives exponential decay
- The factor f represents the fraction of signal which gets Δp = ±2 from a ϕ pulse
- Given that each echo data point has an addition 180 pulse, there is an additional real decay added to the PIETA ideal decay and may be accounted for if you know the pulse lengths
- In CPMG this same effect occurs but the lost signal may come back as stimulated echo signal versus the PIETA where it never comes back
- In cases where T_2 is similar to T_1, the CPMG will give an effective decay that looks correct for improper 180 pulses but is in-fact only so due to the T_1 and T_2 signal decay equivalence

180 Pulse	CPMG (T_2^*)	PIETA (T_2^*)	Scaled PIETA (T_2)
10 μs	5.78 s	0.58 s	4.40 s
15 μs	5.65 s	1.40 s	4.13 s
18 μs	5.43 s	2.60 s	4.34 s
20 μs	5.24 s	3.51 s	4.09 s
22 μs	4.63 s	4.70 s	Nearly ideal T_2
25 μs	5.28 s	3.10 s	3.99 s

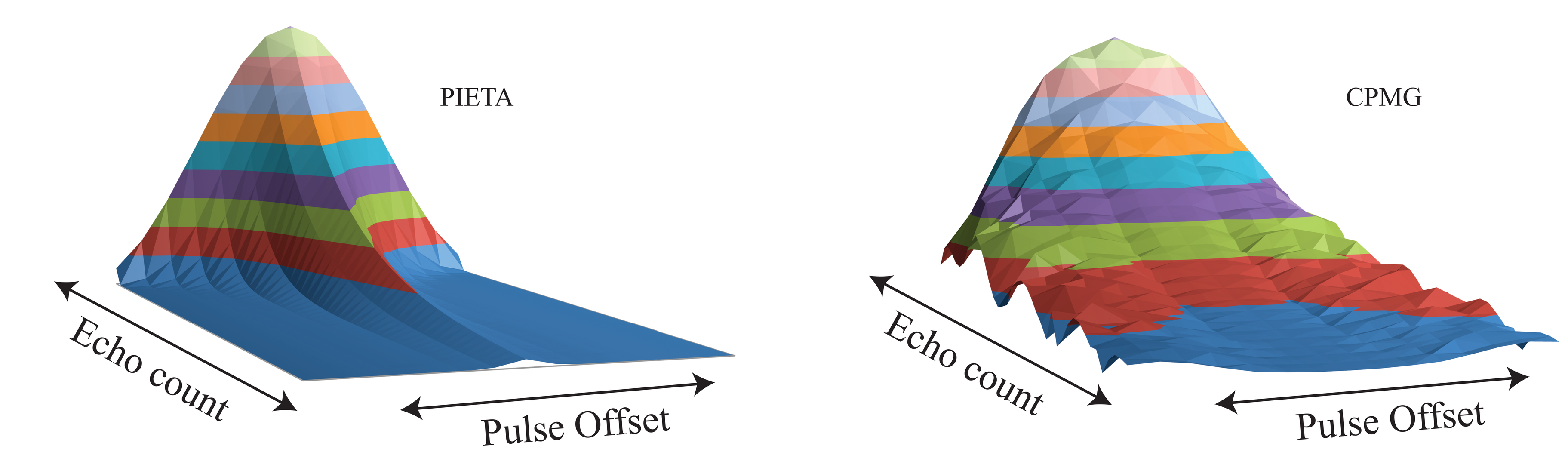
^{31}P Pulse Length Experiments: Homonuclear J-Coupling



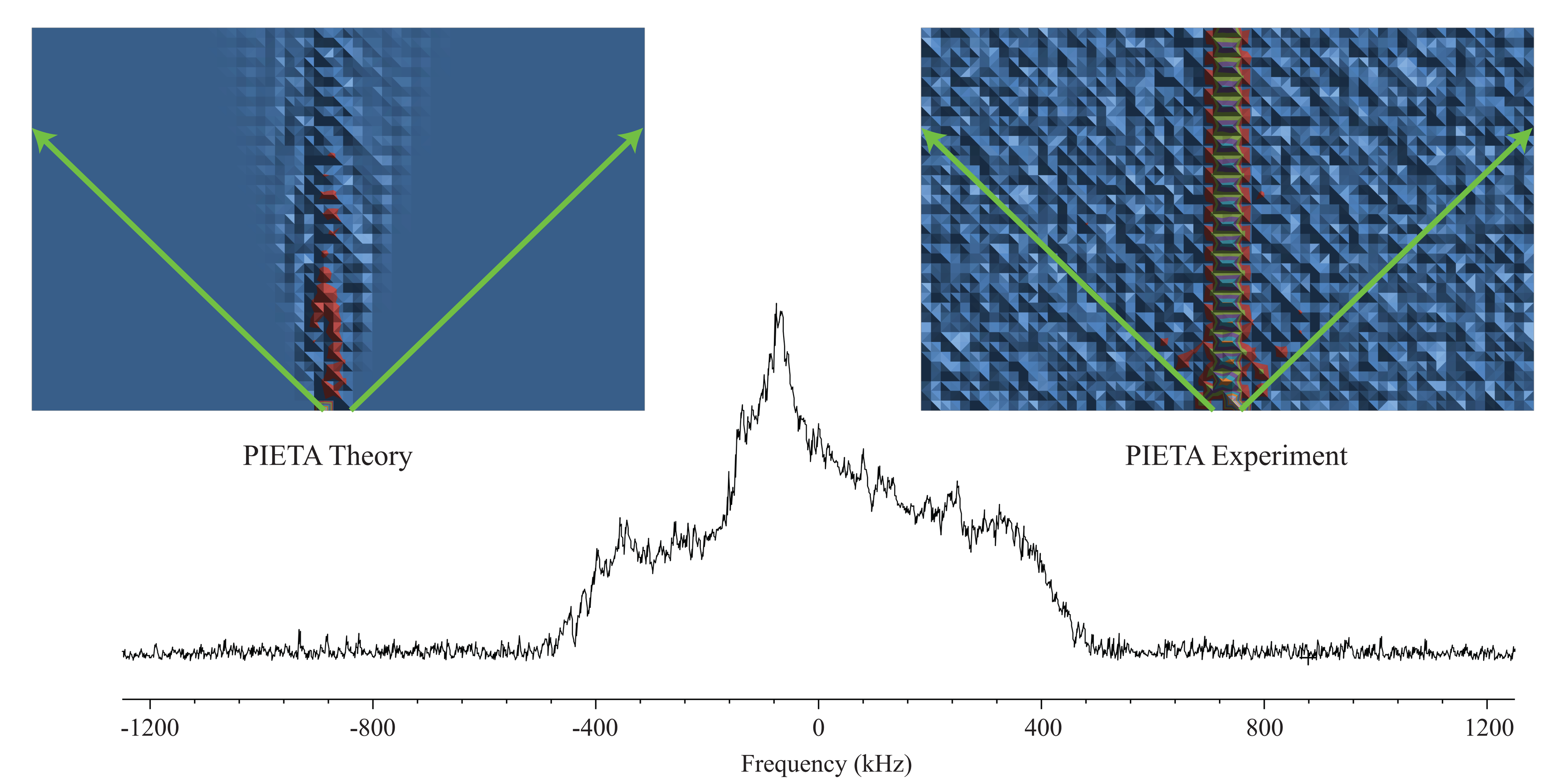
PIETA Pulse Offset Simulation with SpinEvolution



Simulated PIETA and CPMG Decay Curves



WURST-PIETA Pathway Map



- Pathway shows that essentially ALL signal comes from stimulated echoes which is fine as long as no information in the echo dimension is needed other than signal enhnacement
- Given that the decay appears much longer than T_2, finding pulses that give more Hahn echoes should give better overall S/N

Conclusions

The usage of CPMG for situations where the coherence pathways is exected to follow a proper spin echo Δp = ±2 at each step is highly suspect when the offset and inhomogeneity issues are considered.

Using PIETA we may systematically correct for some of the errors in the echo train evolution dimension if we know the pulse strength and offset for a given peak.

References

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