CAFE

CLS ANN FFCF Extractor

GUI Documentation (v1.1)

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I. What is CAFE?

CAFE is a tool that takes an experimentally determined Center Line Slope (CLS) decay of 2D spectra and a corresponding linear FWHM and returns the underlying Frequency-Frequency Correlation Function (FFCF). In particular, it takes the parameters of a CLS decay fit to the form:

$$\text{CLS}(T_w) = A_\infty + \sum_i A_i \exp\left(-T_w / \tau_i\right). \tag{1}$$

Here the A's are dimensionless amplitudes and τ's are time constants. CAFE returns the parameters for the FFCF, $C(t)$:

$$C(T_w) = \frac{\delta(T_w)}{T_2} + \Delta_\infty^2 + \sum_i \Delta_i^2 \exp\left(-T_w / \tau_i\right) \tag{2}$$

Where Δ's are frequency amplitudes, T_2 is the dephasing time, $\delta(t)$ is the Dirac delta function, and τ's are time constants that are identical to those in Eq. 1. T_2 can also be described as a homogeneous line width, $\Gamma = (\pi T_2)^{-1}$.

As the relationship between the CLS amplitudes and FFCF frequency amplitudes can be highly nonlinear and depends on both the values of the time constants and the width of the underlying peak, the FFCF parameters are calculated using a set of artificial neural networks (ANN). These networks were trained on a large set of parameters from simulated 2D spectra and can be thought of as functions that take combinations of the CLS parameters (A's, τ's, and the linear FWHM) as inputs and returns an FFCF frequency amplitude, Δ. After all of the Δ's are determined in this way, the homogeneous component is calculated by inputting the known Δ's and τ's into the one-dimensional response function, and increasing the homogeneous component,

Γ, until the simulated 1D spectrum has the correct FWHM. The complete algorithm typically takes not more than a few seconds to run. A complete description of the underlying algorithms can be found in the related publication.

II. Installation Notes

Windows 64-bit

The CAFE GUI is currently only available for Windows 64-bit. To use the software, the MATLAB Runtime Environment v9.7 (for MATLAB 2019b) is required and is available as a free download at the Mathworks website:

https://www.mathworks.com/products/compiler/matlab-runtime.html

After the MATLAB Runtime is installed, the CAFE GUI can be run from the executable file that is downloadable from our website:

https://web.stanford.edu/group/fayer/CAFE.html

On certain displays, the GUI will be rendered incorrectly, with the input and output tables squished and not readable. This can be generally solved by right-clicking on the CAFE.exe file, selecting **Properties** -> **Compatibility** -> **Change high DPI settings,** checking the box for **Override high DPI scaling behavior** and selecting **System**.

III. How to use CAFE

The Inputs

All that is needed is the set of CLS fit parameters and the FWHM of the linear spectra (e.g. from FTIR). The CLS parameters can be entered by hand to the **CLS Parameters** table or loaded from a plain text delimited file by selecting **Load Parameters**. The parameter file can be either in a single row or in columns similar to what is presented in the CAFE GUI. The plain text document does not need to have values for all 7 parameters. If the plain text document does not contain Std. Errors, uncheck the **Load Errors** checkbox and it will only load parameter values. The parameters are ordered to match the default output of the OriginPro ExpDec fitting functions, with the offset first. The **FWHM** and associated error must be entered by hand in the associated table. CAFE assumes that the CLS is a monotonically decreasing function that does

not go below zero. Accordingly, all of the input parameters must be greater than or equal to zero. As the CLS is also normalized, the sum of the amplitudes cannot exceed one.

CAFE offers multiple ways of propagating uncertainty of the resulting FFCF parameters. The default is **Estimate from Std. Error**, which makes mild assumptions about how the CLS parameters are correlated with each other to determine the FFCF Std. Errors. This uses just the visible Std. Errors in the input fields and is typically reasonably accurate. If the user does not wish to propagate error, selecting **NN Error Only** reports just the error from the NN calculation itself. The most accurate method is **Use Covariance Matrix**, which explicitly considers the covariance of the CLS fit parameters as determined from the fitting software. For example, in OriginPro, the covariance matrix can be found in the following options of the fit dialog (**Advanced**->**Quantities**->**Covariance matrix**) and appears in the fit output as follows:

Summary

	y0		A1		t1		A	
	Value	Standard Error	Value	Standard Error	Value	Standard Error	Value	St
B	5.51698E-4	0.00104	0.14923	0.04432	0.37188	0.12556	0.1288	

ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
	Regression	4	0.05464	0.01366	2369.8149	6.16048E-47
B	Residual	40	2.30567E-4	5.76418E-6		
	Uncorrected Total	45	0.12932			
	Corrected Total	44	0.05487			

At the 0.05 level, the fitting function is significantly better than the function y=constant.

Covariance

B

	y0	A1	t1	A2	t2
y0	1.08138E-6	7.7888E-6	-5.81916E-5	1.13088E-5	-1.30738E-4
A1	7.7888E-6	0.00196	-0.00465	5.05347E-4	-0.0035
t1	-5.81916E-5	-0.00465	0.01576	-0.00226	0.01813
A2	1.13088E-5	5.05347E-4	-0.00226	3.7601E-4	-0.00321
t2	-1.30738E-4	-0.0035	0.01813	-0.00321	0.02968

The covariance matrix must be uploaded from a delimited text file with the **Load Covariance Matrix** button. It is critically important that the order of parameters loaded parameters and the order of parameters in the covariance matrix are the same. If the upload is successful, the filename will display below the button.

The Outputs

After the CLS and FWHM parameters are input, the FFCF parameters can be determined by clicking the **Calculate FFCF** button. If no errors occur, the resulting FFCF parameters should appear in the corresponding **FFCF Parameters** table, and a set of decay curves will be plotted. The blue curve is the experimental CLS as derived from the CLS input parameters. The red points are the CLS of simulated 2D spectra using the resulting FFCF parameters and the CLS time constants. The residual of these two curves is plotted below in blue points. A high quality result should have the **Max Residual** at $\leqslant 0.02$, which is about the maximum underlying uncertainty in the CLS measurement itself. If the result is not high quality, it is possible that the CLS parameters are in a regime that was not well sampled by the neural network training data.

The green curve is the "Gaussian approximation" of the FFCF. It is a visual indicator of how partially motionally narrowed a line shape is. The Gaussian approximation uses the same τ's as the FFCF and CLS, but it uses normalized amplitudes that go as:

$$\alpha_j = \frac{\Delta_j^2}{\left(1/T_2\right)^2 + \sum_i \Delta_i^2}. \tag{3}$$

If there is not substantial partial motional narrowing, the green curve will be relatively close to the blue curve. If there is substantial partial motional narrowing, the green curve will tend to be much larger than the blue curve. The three curves can be saved as a text delimited file by pressing **Save CLS Decays**. The order of output columns are:
[T_w, Sim. CLS, FFCF Gaussian, Exp CLS].

The simulated 1D and 2D spectra for the calculated FFCF can also be examined using the **Plot 1D Spectrum** and **Plot 2D Spectrum** buttons. Different T_w's of the 2D spectrum can be examined by selecting different items in the **Tw** drop-down menu. These can also be saved as delimited text files: **Save 1D Spectrum** saves a single file with the columns [ω, 1D spectrum]. **Save 2D Spectra** saves all of the calculated spectra to a folder. The first row and column of each file is a frequency axis, and the rest of the file is the table of values for each initial and final frequency.

The FFCF parameters can also be saved as a delimited text files by pressing **Save FFCF Pars**. In the default **Row** option, the output structure of the file is as follows: [Δ_∞ Δ_1 τ_1 Δ_2 τ_2 Δ_3 τ_3 Γ T_2]. If the **Save Errors** box is selected, the error term will be adjacent to the corresponding

parameter. If **Col** is selected, the text file will have the same ordering of parameters, but with the values and errors in separate columns.

"Calculated linewidth exceeds experimental FWHM"

Due to partial motional narrowing, not every CLS is possible for any given FWHM. This effect is illustrated in Fig. 6 of the associated publication. If CAFE determines the CLS is not possible for the given linewidth, it will return the error: "Calculated linewidth exceeds experimental FWHM." This can be resolved manually by using CLS fit parameters with smaller amplitudes and/or longer time constants or increasing the input FWHM.

CAFE can attempt to use the covariance matrix of the CLS fit to automatically correct this error (v. 1.1 only). The covariance matrix encodes how every other fit parameter will vary under small perturbations of another fit parameter. The CAFE program will slowly increase the value of τ_1 (generally the fastest way to approach a valid CLS for a given linewidth) while modifying the other CLS input variables accordingly. If a solution is found, the FFCF will be calculated using these new parameters. The new time constants can then be found in the output FFCF values by selecting the "Save FFCF Pars" button.

It should be noted that such corrections will necessarily result in an FFCF with a homogeneous linewidth that is approximately zero, as that will be the closest valid CLS. As a result, the standard errors for Γ and T_2 will likely be very large and ill-defined, as the error in the terms are clearly not symmetric when Γ is near zero (since Γ must be greater than zero). The standard errors for these terms should likely be discarded as poor approximations in these cases.