How is CCM useful?

1 Example System

The continuous system is

$$\frac{dI}{dt} = \frac{V(t)}{L} - \frac{R(t)}{L}I, \tag{1}$$

where I is the current at time t, $V(t)$ is the voltage at time t, $R(t)$ is the resistance at time t, and L is the inductance (which is also constant in these examples), and it can be approximated as

$$\dot{I} = \frac{V(t)}{L} - \frac{R(t)}{L}I \Rightarrow I_{t+1} - I_t = \frac{V_t}{L} - \frac{R_t}{L}I_t. \tag{2}$$

Rearranging leads to

$$I_{t+1} = \frac{V_t}{L} + I_t\left(1 - \frac{R_t}{L}\right), \tag{3}$$

$$V_t = L\left(I_{t+1} - I_t\left(1 - \frac{R_t}{L}\right)\right), \tag{4}$$

and

$$R_t = L\left(I_t - I_{t+1} + \frac{V_t}{L}\right). \tag{5}$$

All of the plots of I seen below are produced by using MATLAB's *ode45* to solve Eqn. 1 (i.e. not using the discrete approximation shown). The time series $V(t)$ and $R(t)$ are created by defining values at fixed points and using linear interpolation (i.e. MATLAB's *interp1*) to find the time steps required by the ODE solver (i.e. MATLAB's *ode45*).

2 Changing V(t)

Consider the situation where $R(t)$ is constant.

Physical intuition is that V drives I, so we expect to find V CCM causes I ($C_{VI} > C_{IV}$).

For this example, the voltage is described by

$$V(t) = A_v \sin(f_v t + \phi_v) + O_v, \tag{6}$$

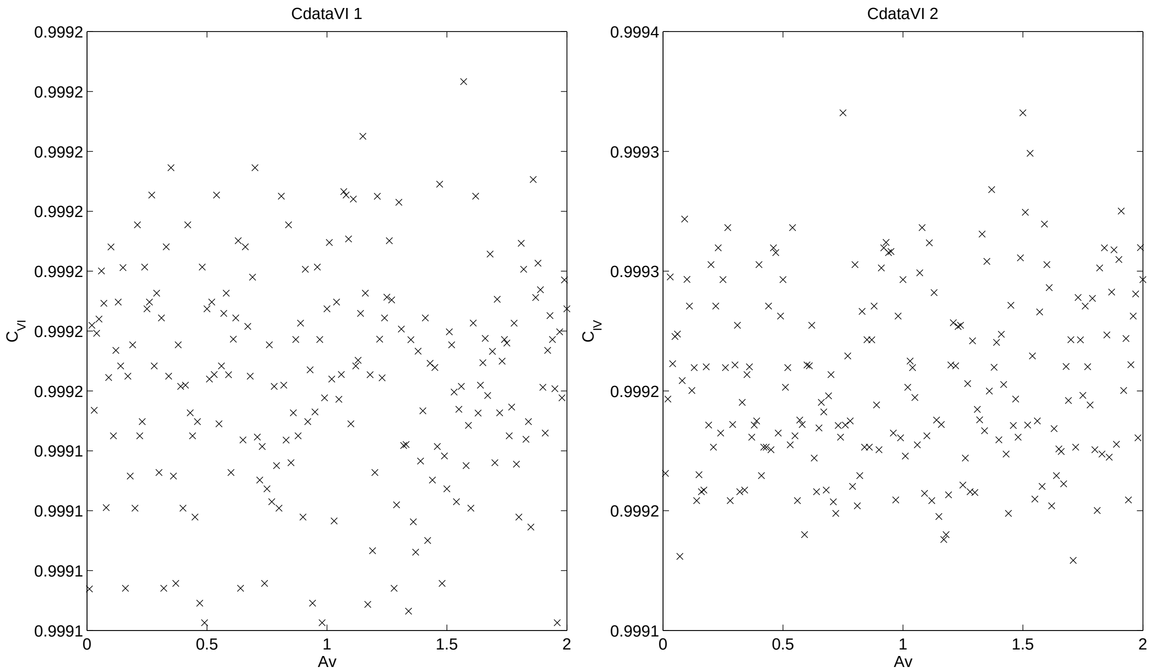
where A_v is the amplitude, f_v is the frequency, ϕ_v is the phase, and O_v is the offset voltage.

2.1 Changing A_v

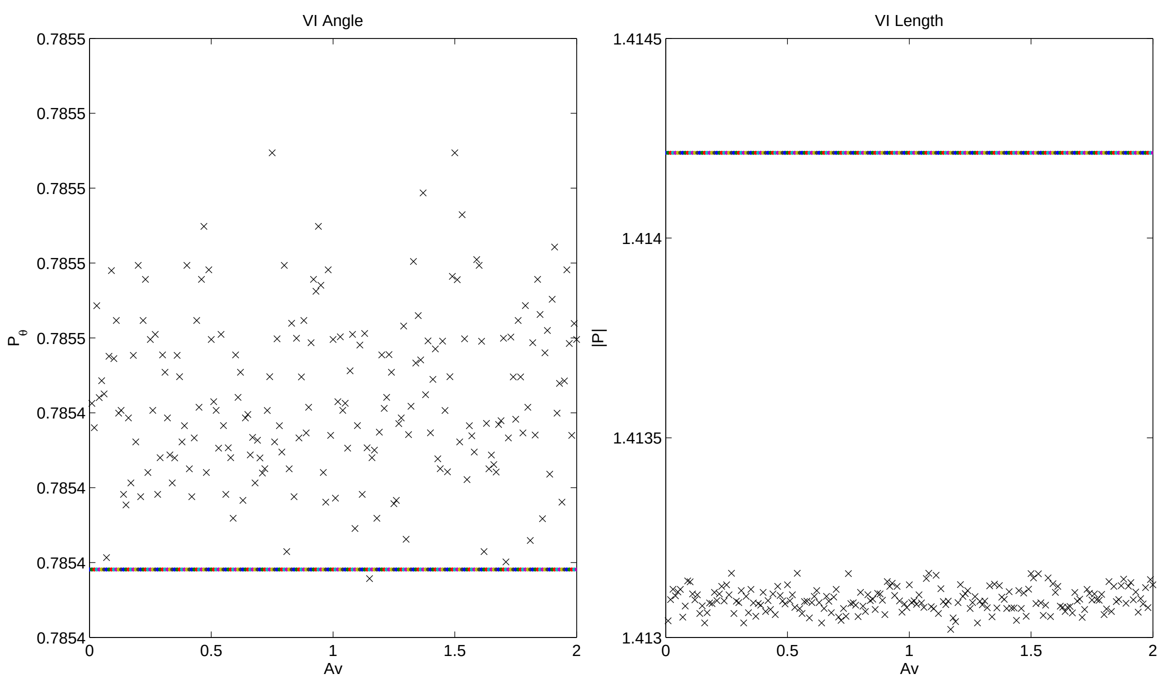
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $A_v \in [0.01, 2.0]$ in steps of 0.01. For reference, both V(t) and I(t) are plotted for different A_v in Figure 1.

Figure 1: Reference plots for changing A_v.

The CCM correlations are each plotted in Figure 2 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

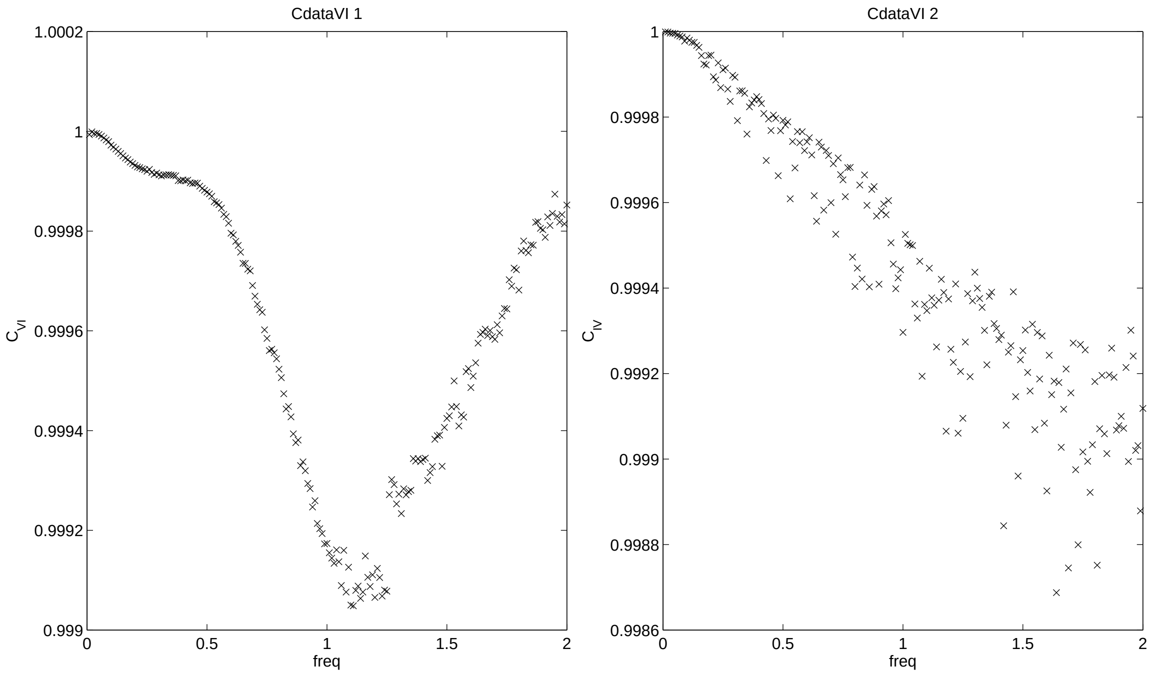
Figure 2: Changing A_v.

2.2 Changing f_v

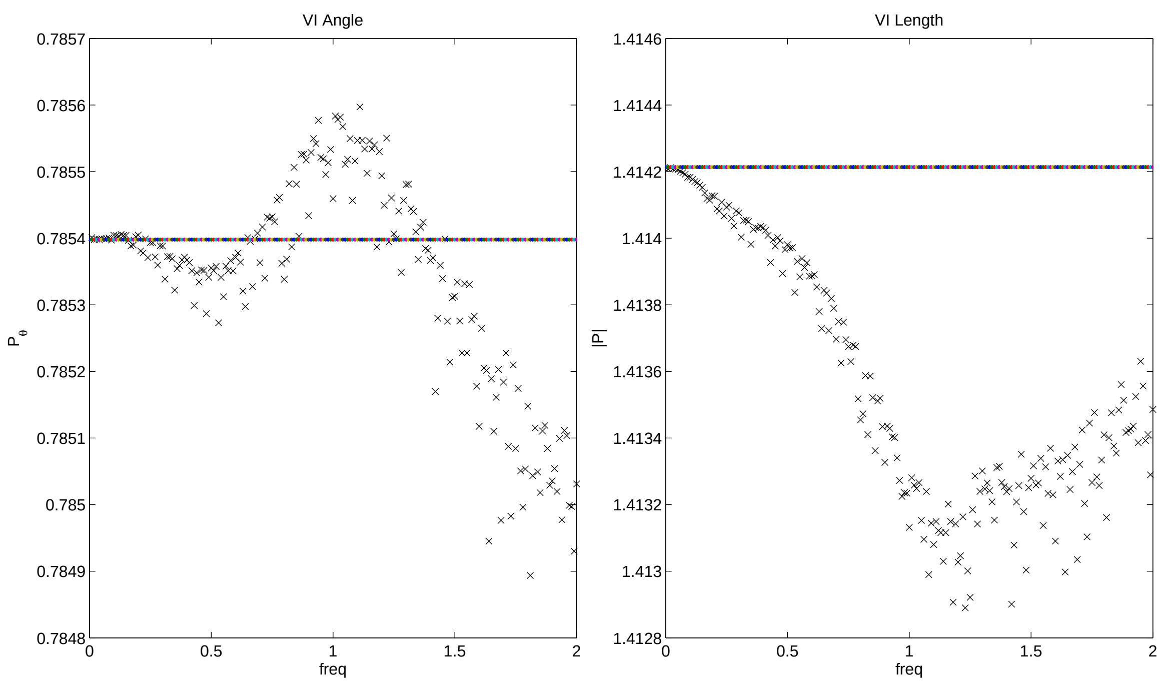
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $f_v \in [0.01, 2.0]$ in steps of 0.01. For reference, both V(t) and I(t) are plotted for different f_v in Figure 3.

Figure 3: Reference plots for changing f_v.

The CCM correlations are each plotted in Figure 4 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

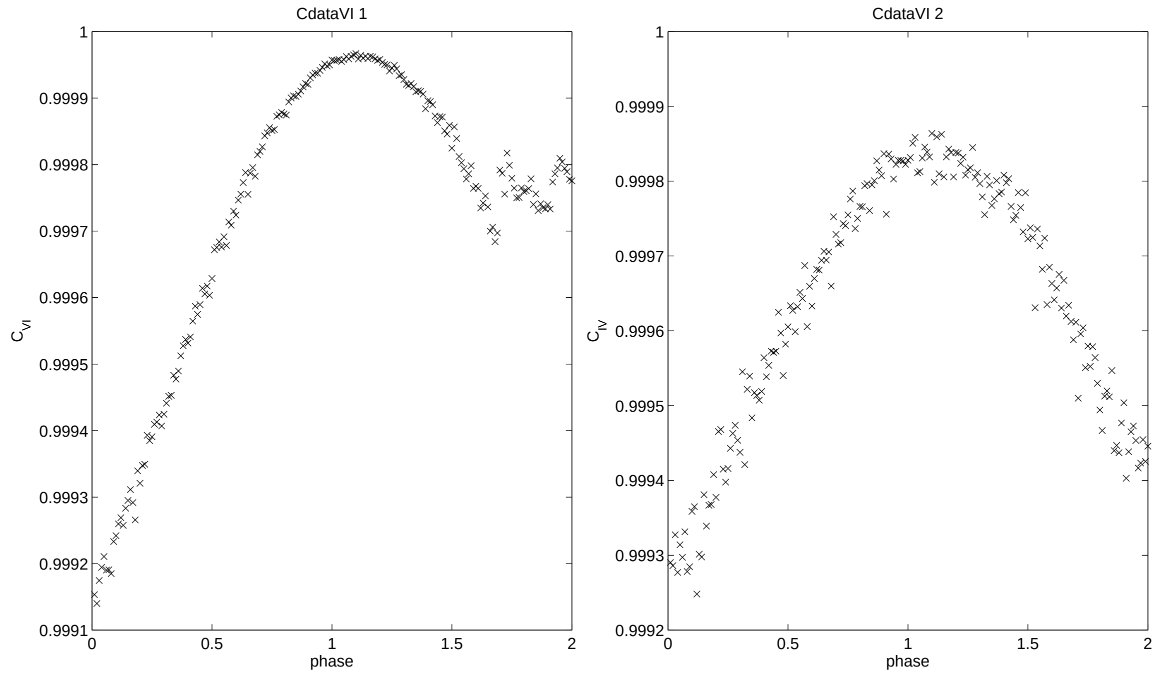
Figure 4: Changing f_v.

2.3 Changing ϕ_v

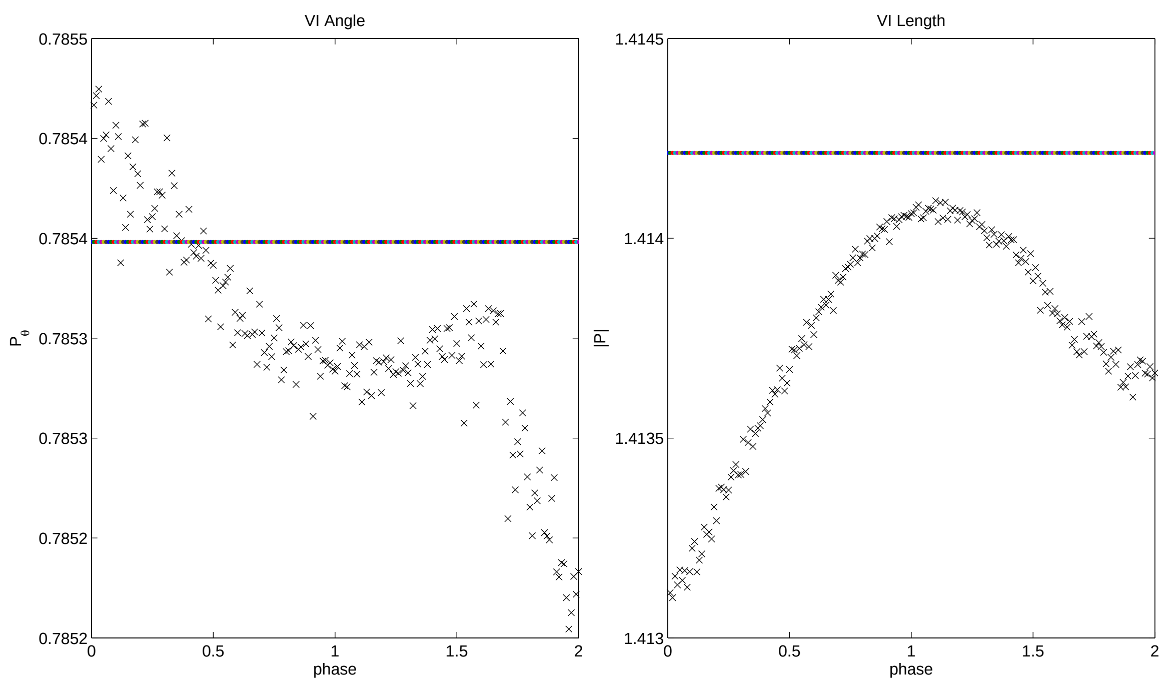
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $\phi_v \in [0.01, 2.0]$ in steps of 0.01. For reference, both V(t) and I(t) are plotted for different ϕ_v in Figure 5.

Figure 5: Reference plots for changing ϕ_v.

The CCM correlations are each plotted in Figure 16 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

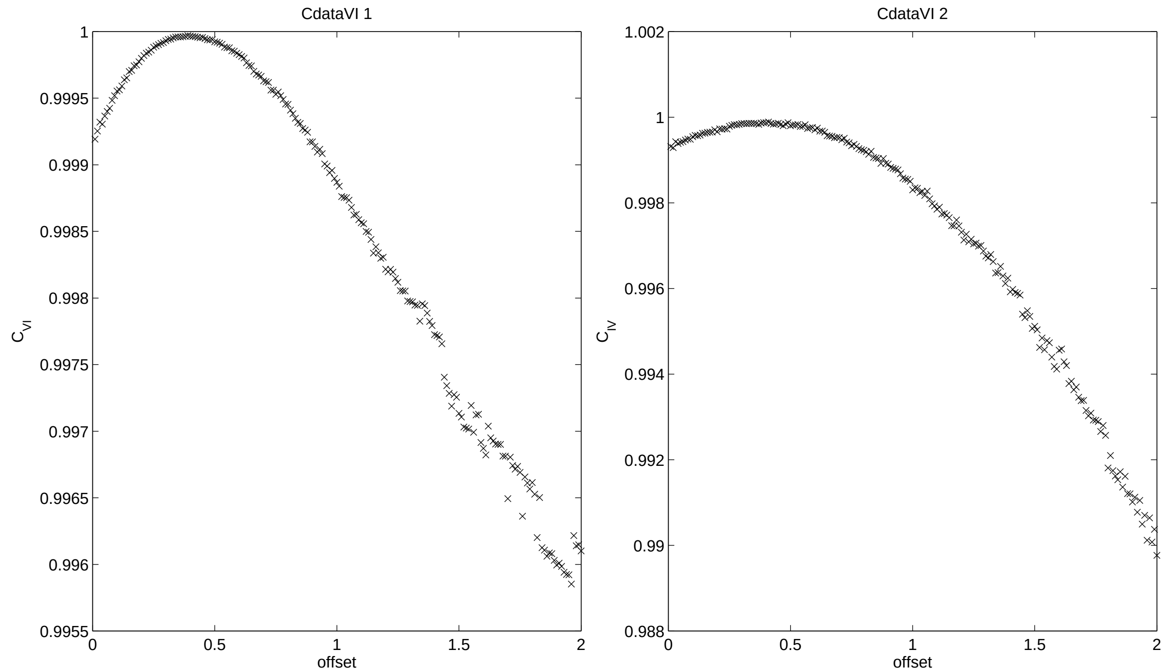
Figure 6: Changing ϕ_v.

2.4 Changing O_v

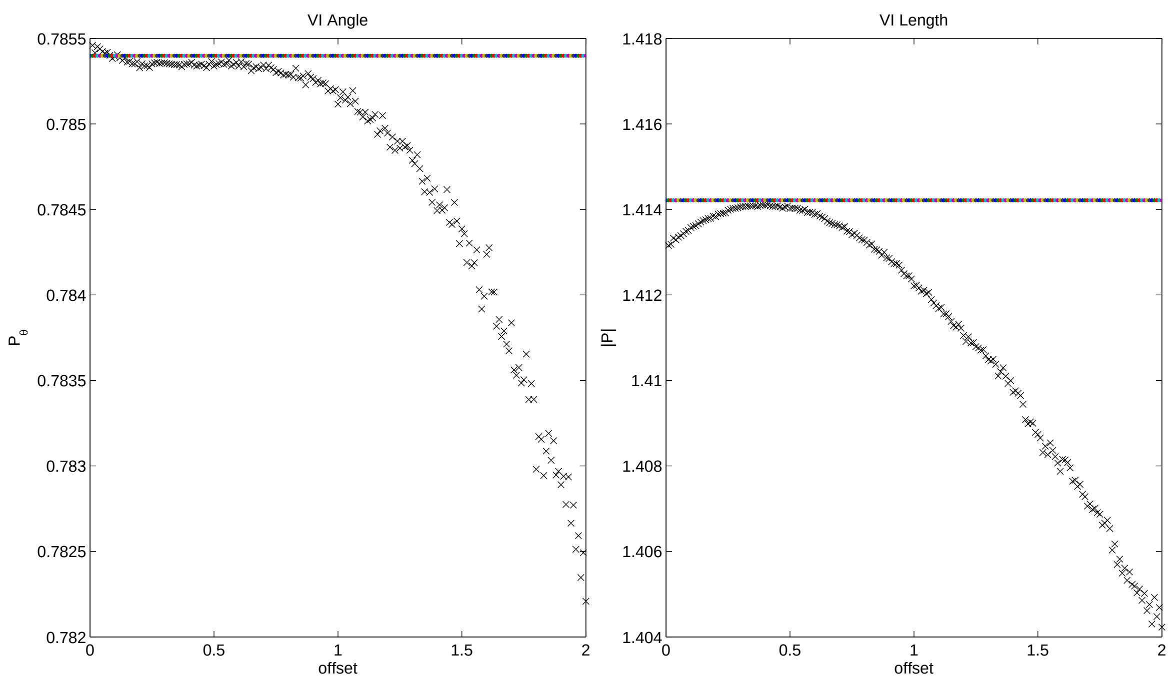
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $O_v \in [0.01, 2.0]$ in steps of 0.01. For reference, both V(t) and I(t) are plotted for different O_v in Figure 7.

Figure 7: Reference plots for changing O_v.

The CCM correlations are each plotted in Figure 8 along with the corresponding PAI elements P_θ and $|P|$.



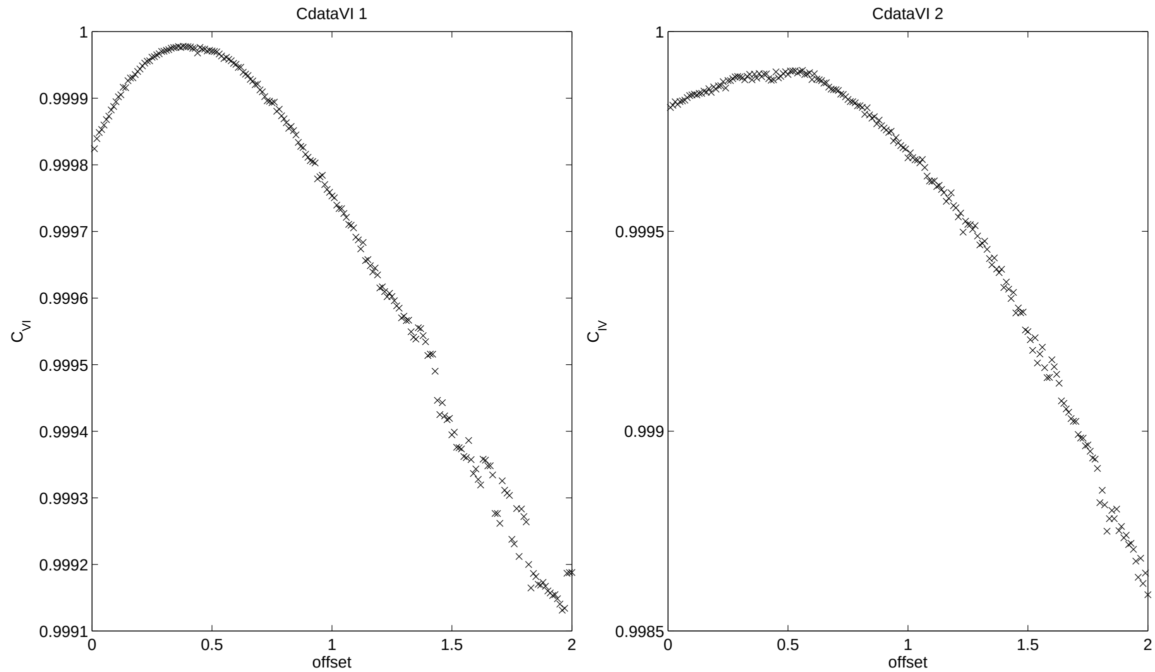
(a) C_{VI} and C_{IV}



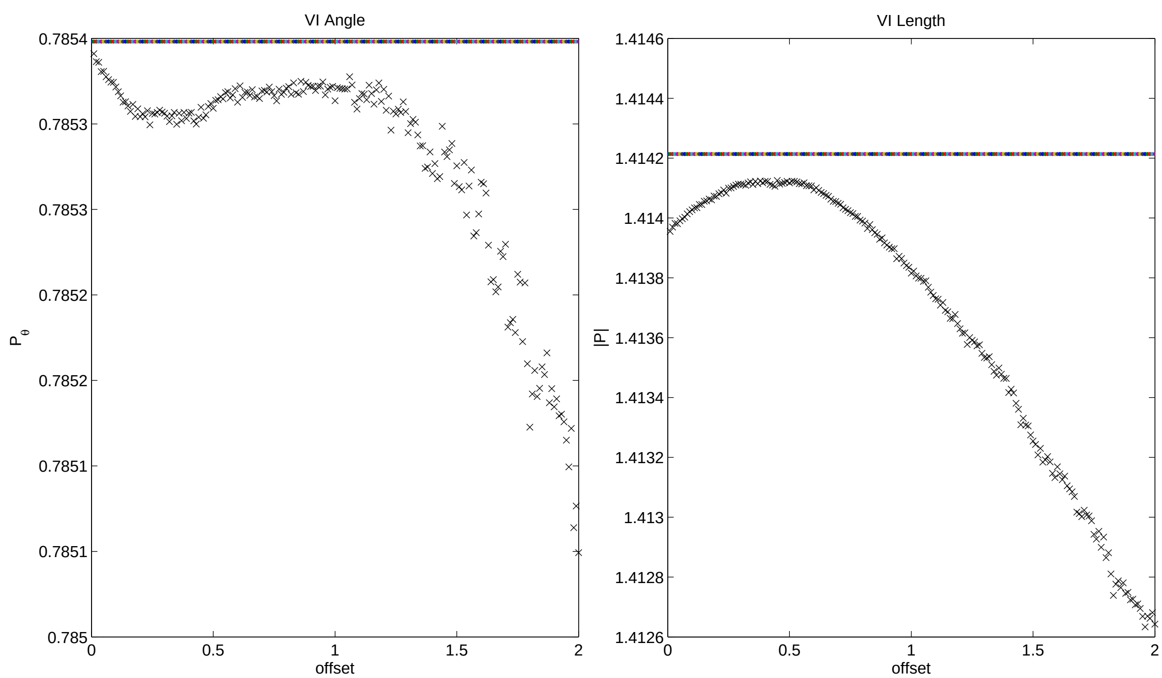
(b) P_θ and $|P|$

Figure 8: Changing O_v.

Figure 9 shows the effect of increasing the library length from 2×10^3 (i.e. `tspan = [0:0.5:1000];`) to 10^4 (i.e. `tspan = [0:0.5:5000];`), and Figure 10 extends the above plots to $O_v \in [0.01, 10.0]$ in steps of 0.05.

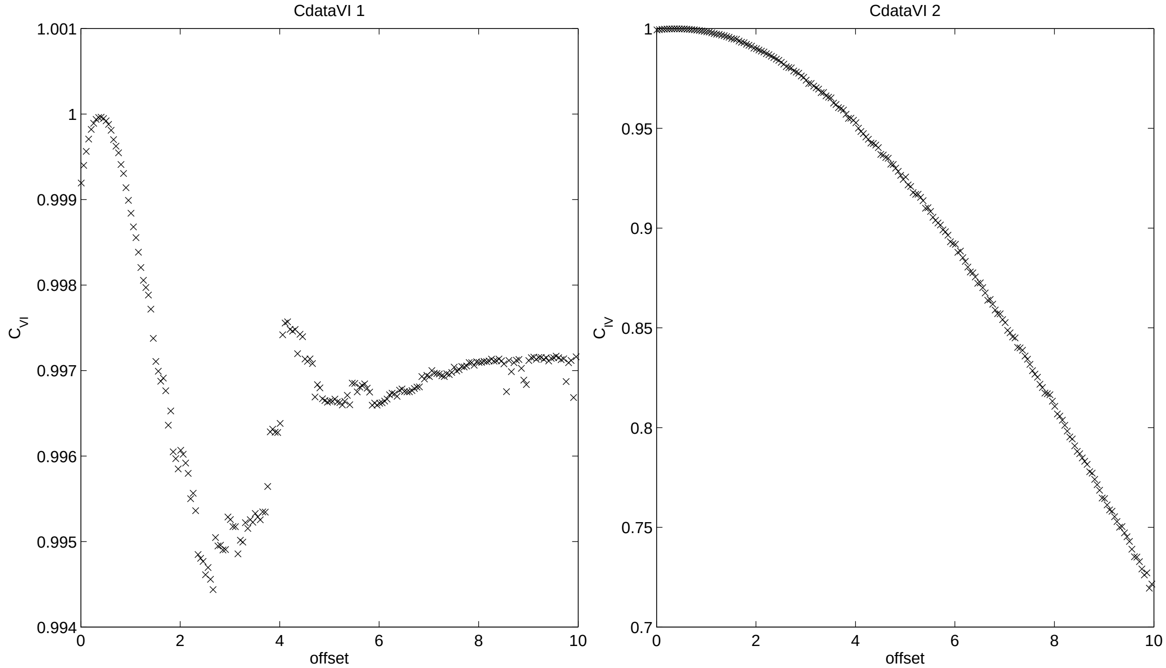


(a) C_{VI} and C_{IV}

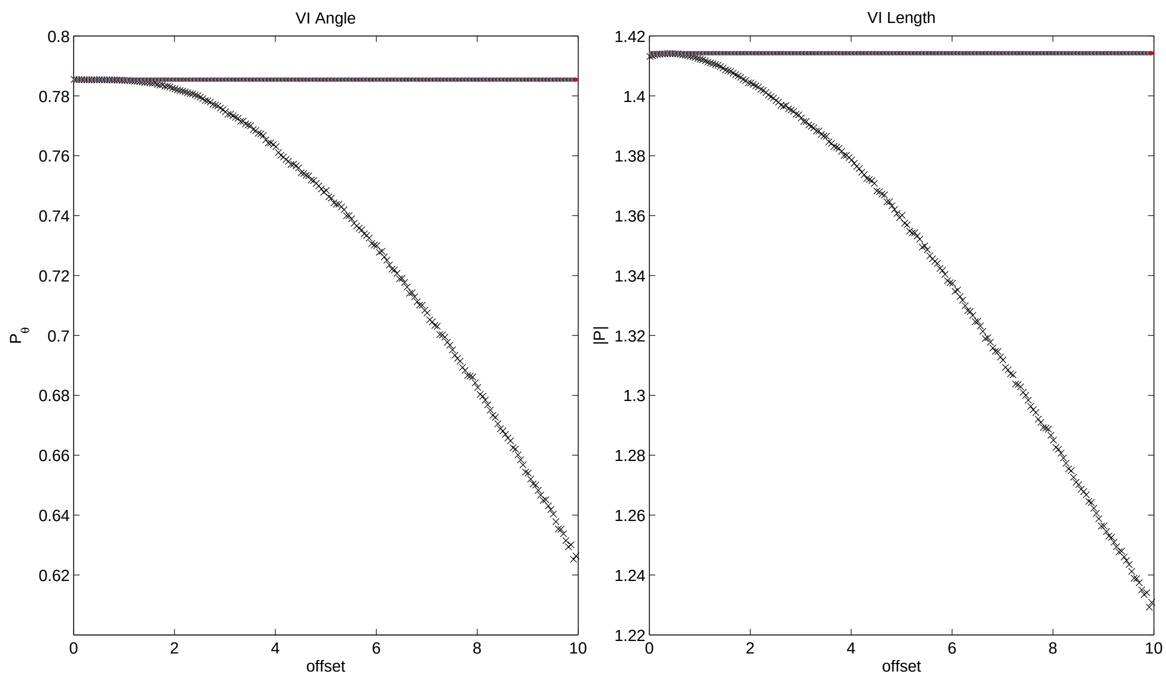


(b) P_θ and $|P|$

Figure 9: Changing O_v (longer library length).



(a) C_{VI} and C_{IV}



(c) P_θ and $|P|$

Figure 10: Changing O_v (larger domain for O_v).

3 Changing R(t)

Consider the situation where $V(t)$ is constant.

Physical intuition is that R drives I, so we expect to find R CCM causes I ($C_{RI} > C_{IR}$).

For this example, the voltage is described by

$$R(t) = A_r \sin(f_r t + \phi_r) + O_r, \tag{7}$$

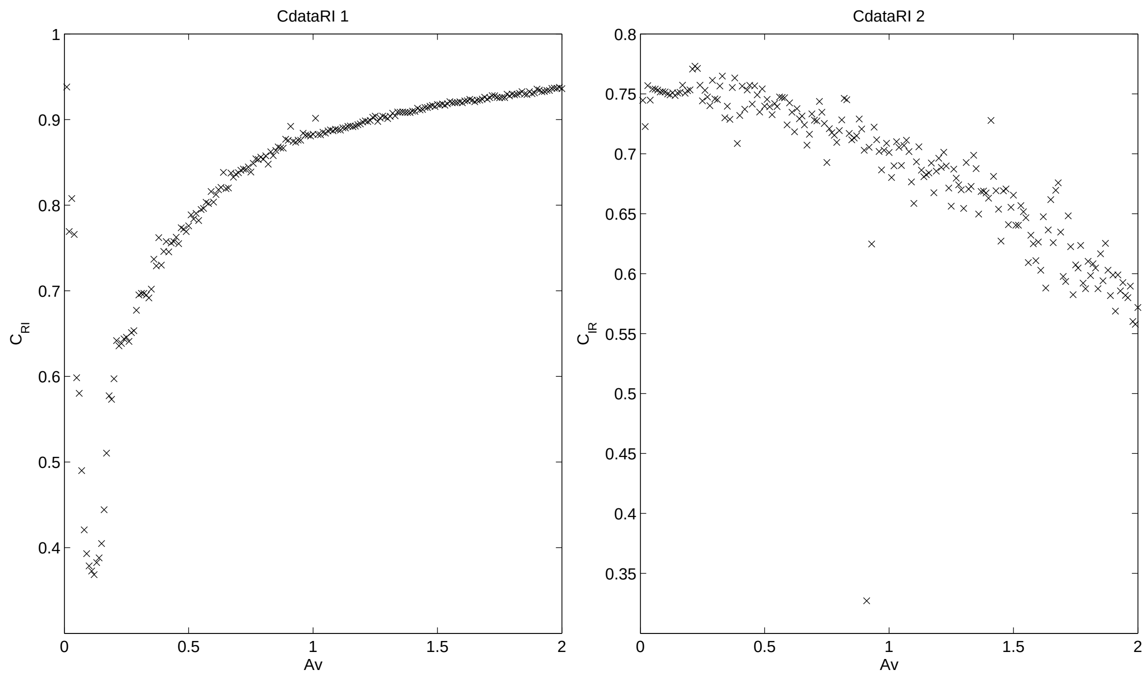
where A_r is the amplitude, f_r is the frequency, ϕ_r is the phase, and O_r is the offset voltage.

3.1 Changing A_r

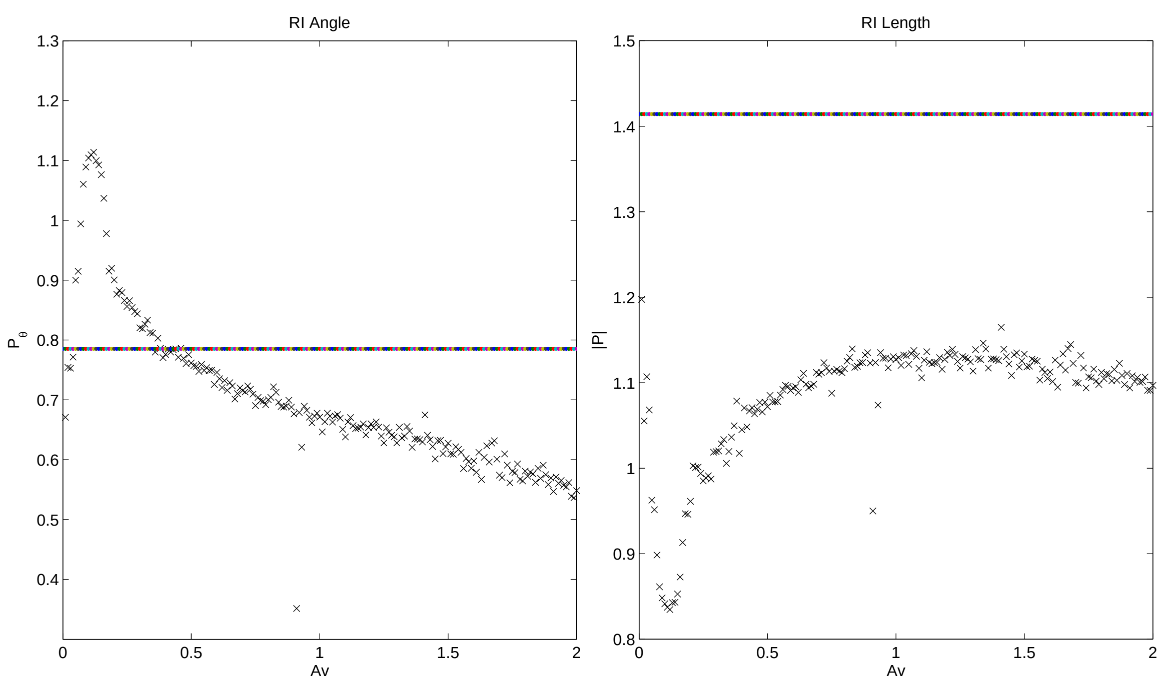
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $A_r \in [0.01, 2.0]$ in steps of 0.01. For reference, both R(t) and I(t) are plotted for different A_r in Figure 11.

Figure 11: Reference plots for changing A_r.

The CCM correlations are each plotted in Figure 12 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

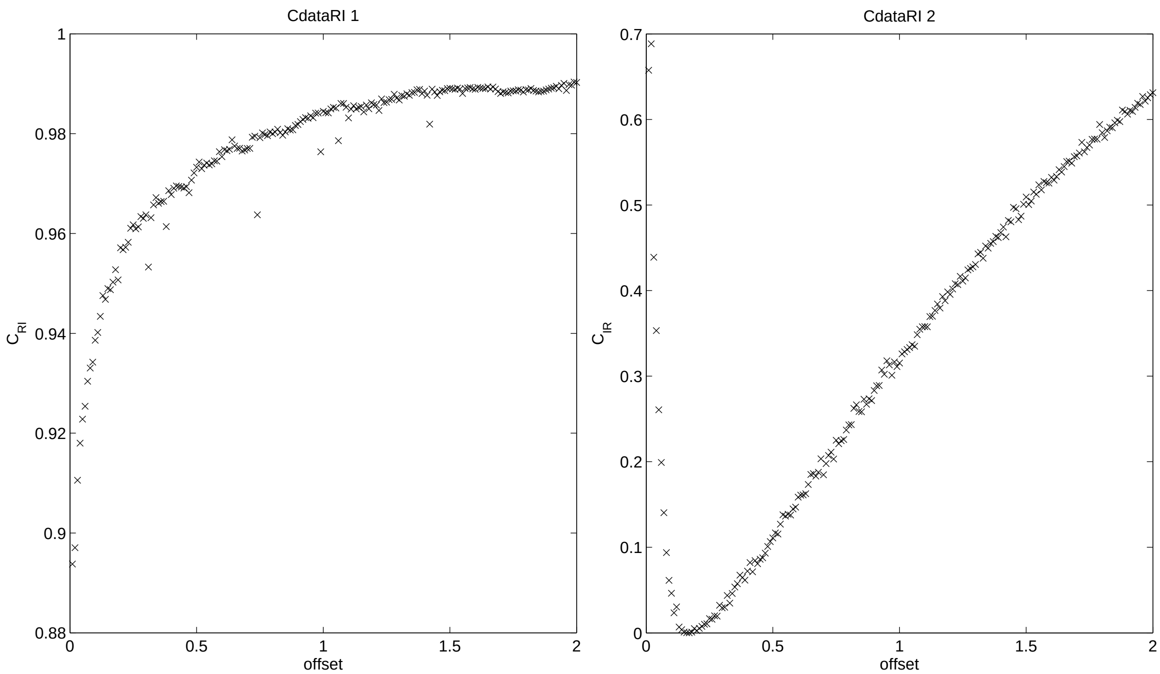
Figure 12: Changing A_r.

3.2 Changing O_r

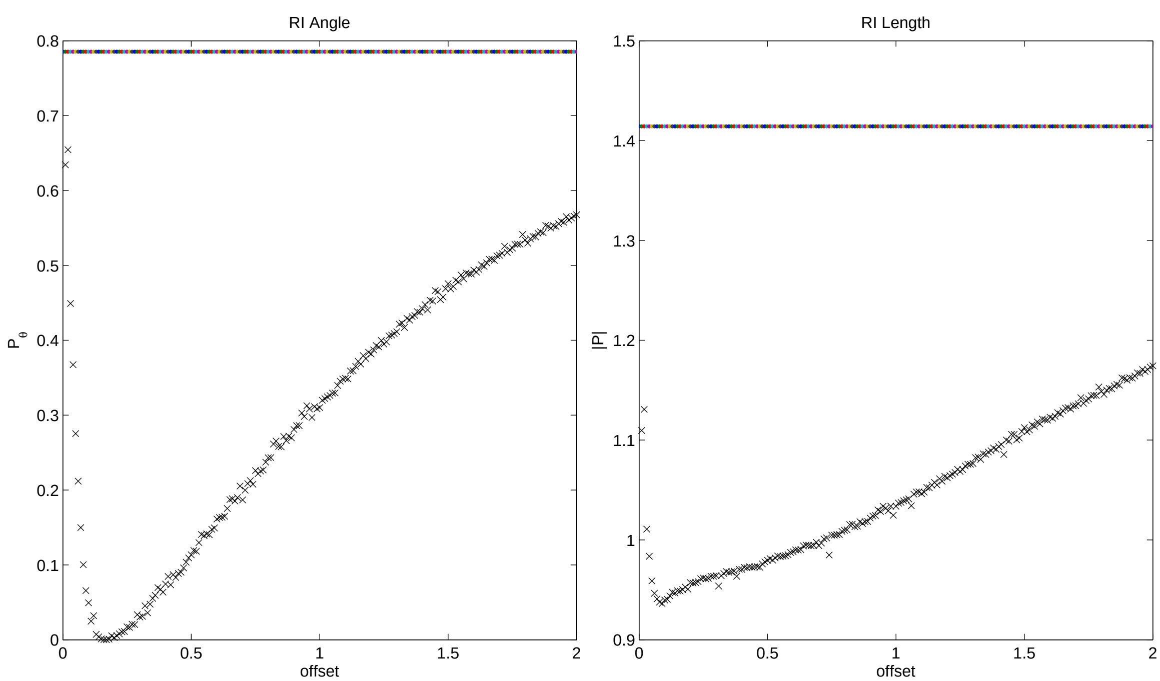
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $O_r \in [0.01, 2.0]$ in steps of 0.01. For reference, both R(t) and I(t) are plotted for different f_v in Figure 13.

Figure 13: Reference plots for changing O_r.

The CCM correlations are each plotted in Figure 14 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

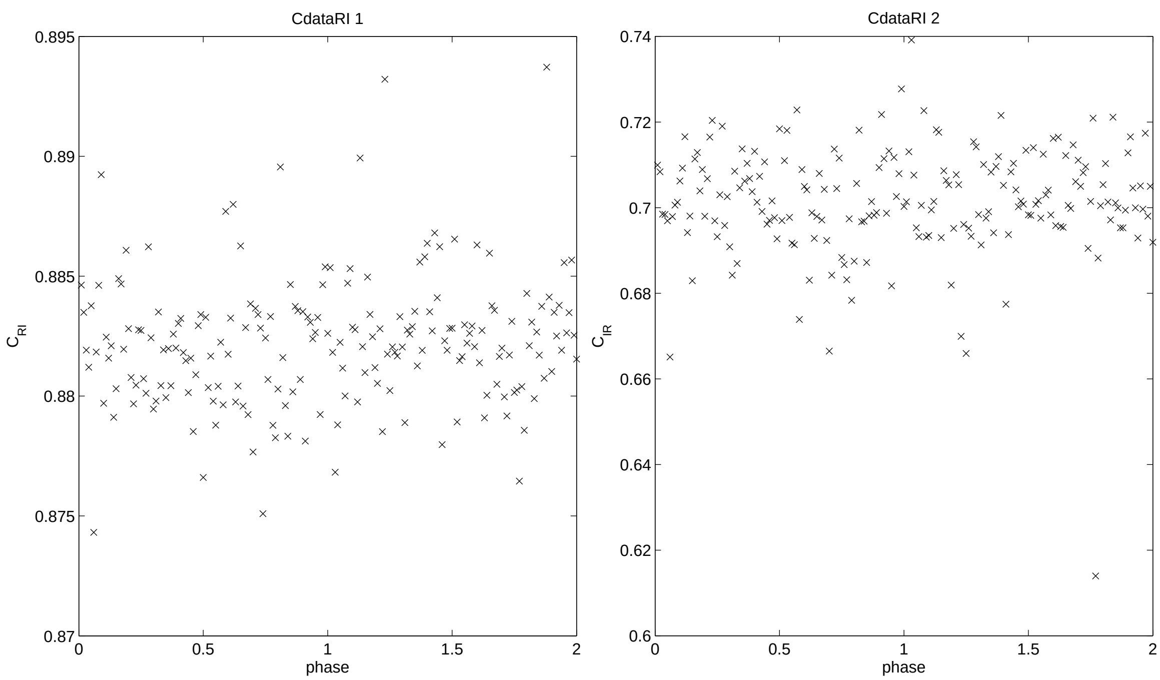
Figure 14: Changing O_r.

3.3 Changing ϕ_r

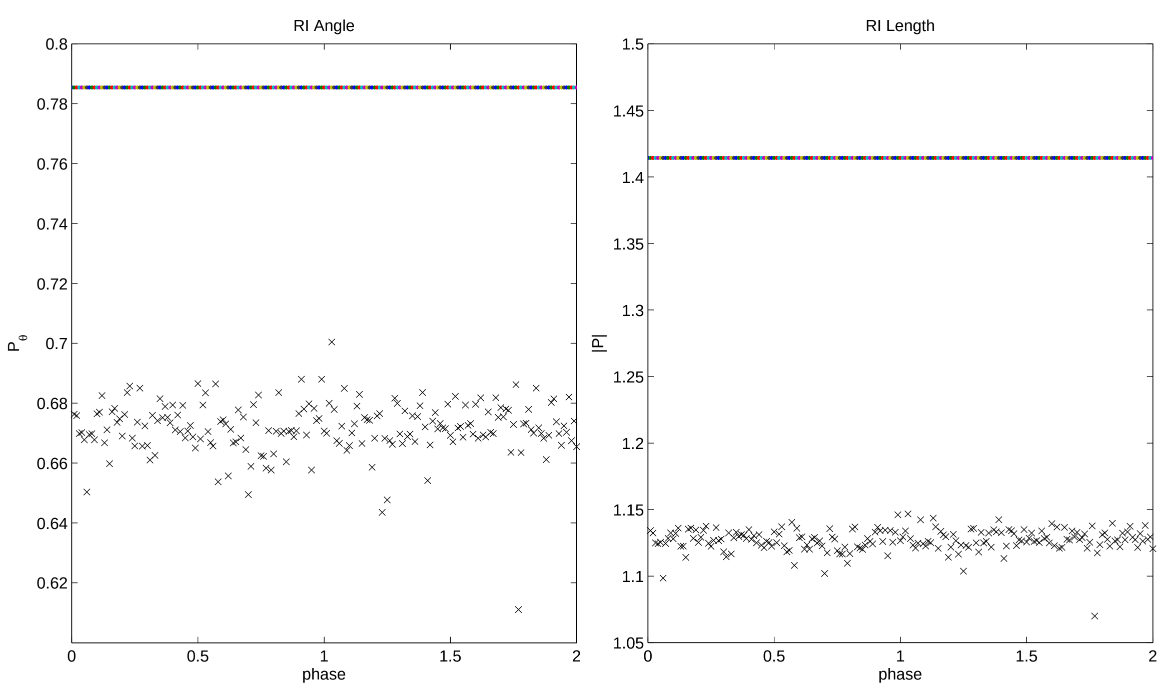
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $\phi_r \in [0.01, 2.0]$ in steps of 0.01. For reference, both R(t) and I(t) are plotted for different ϕ_r in Figure 15.

Figure 15: Reference plots for changing ϕ_r.

The CCM correlations are each plotted in Figure **??** along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

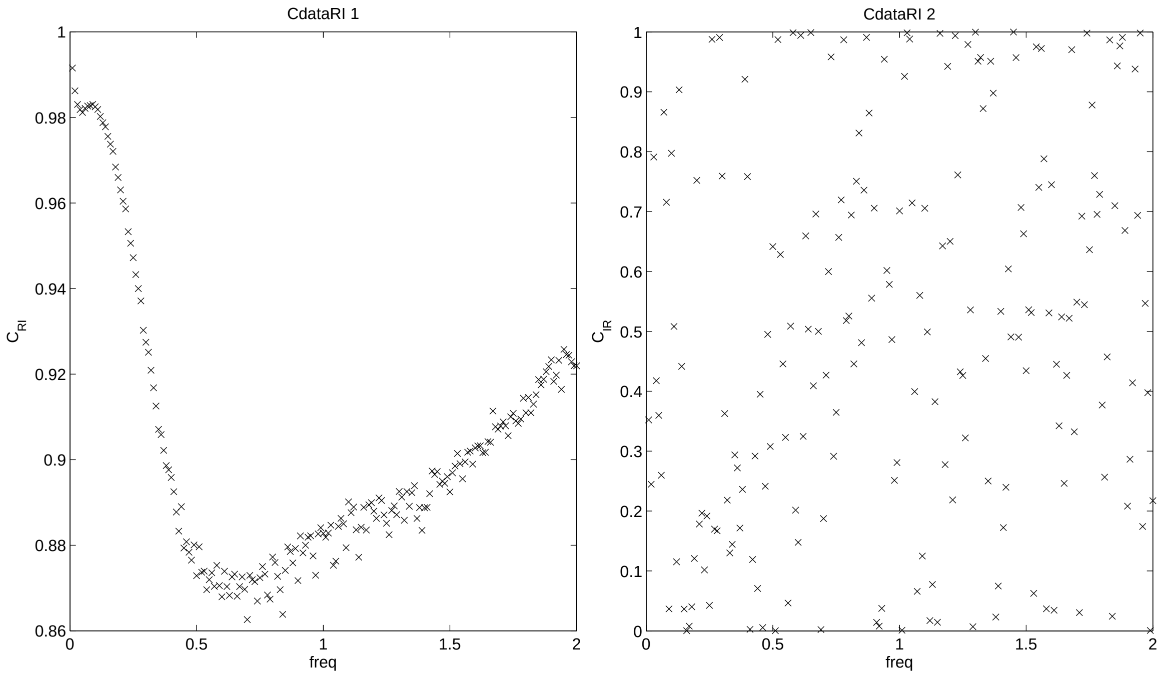
Figure 16: Changing ϕ_r.

3.4 Changing f_r

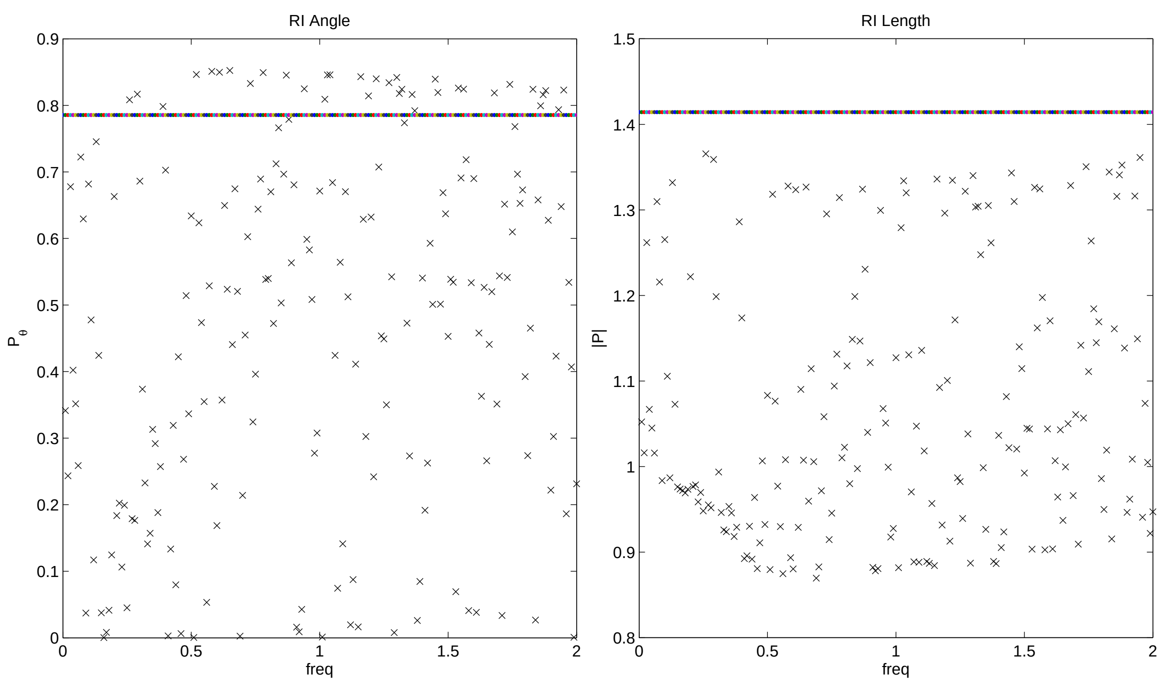
Consider evaluating the CCM correlations C_{VI} and C_{IV} for each $f_r \in [0.01, 2.0]$ in steps of 0.01. For reference, both R(t) and I(t) are plotted for different f_r in Figure 17.

Figure 17: Reference plots for changing f_r.

The CCM correlations are each plotted in Figure 18 along with the corresponding PAI elements P_θ and $|P|$.



(a) C_{VI} and C_{IV}

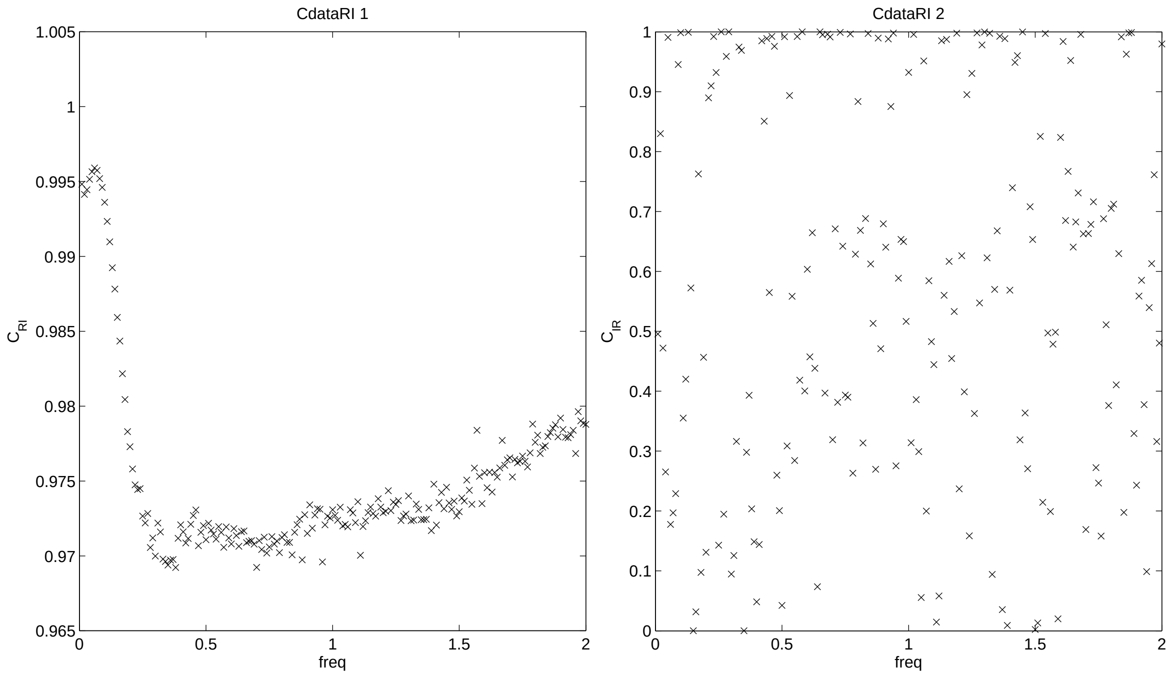


(b) P_θ and $|P|$

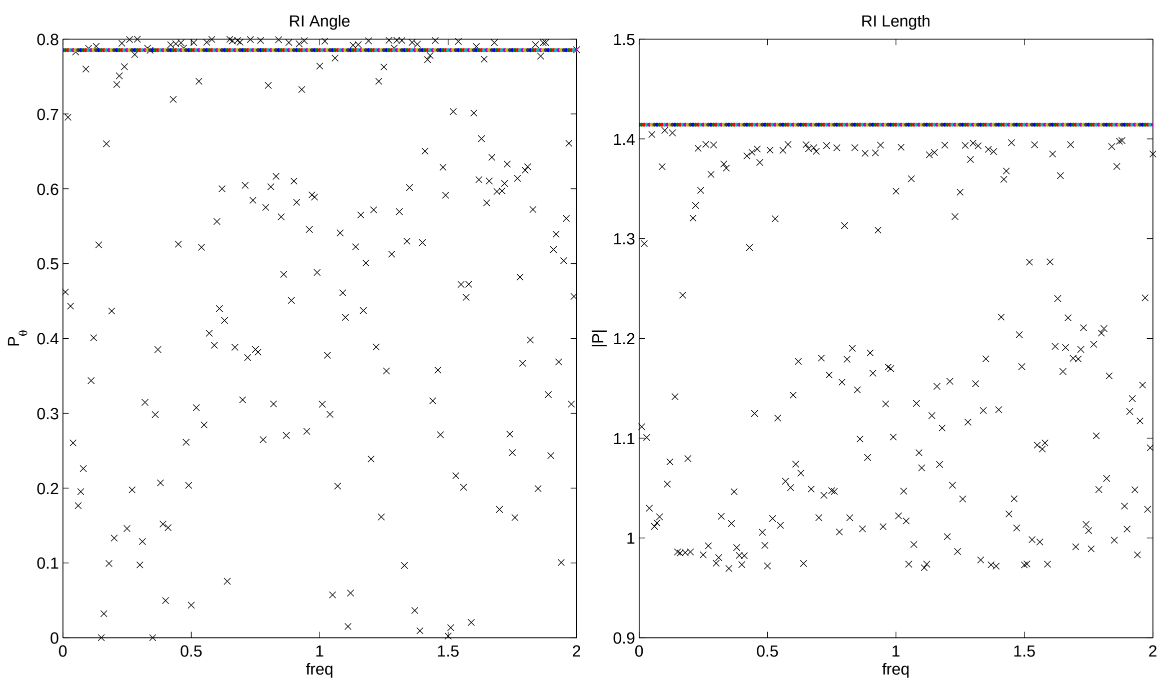
Figure 18: Changing f_r.

Figure 19 shows the effect of increasing the library length from 2×10^3 (i.e. `tspan = [0:0.5:1000];`) to 10^4 (i.e. `tspan =`

`[0:0.5:5000];`), and Figure 20 extends the above plots to $f_r \in [0.01, 10.0]$ in steps of 0.05.

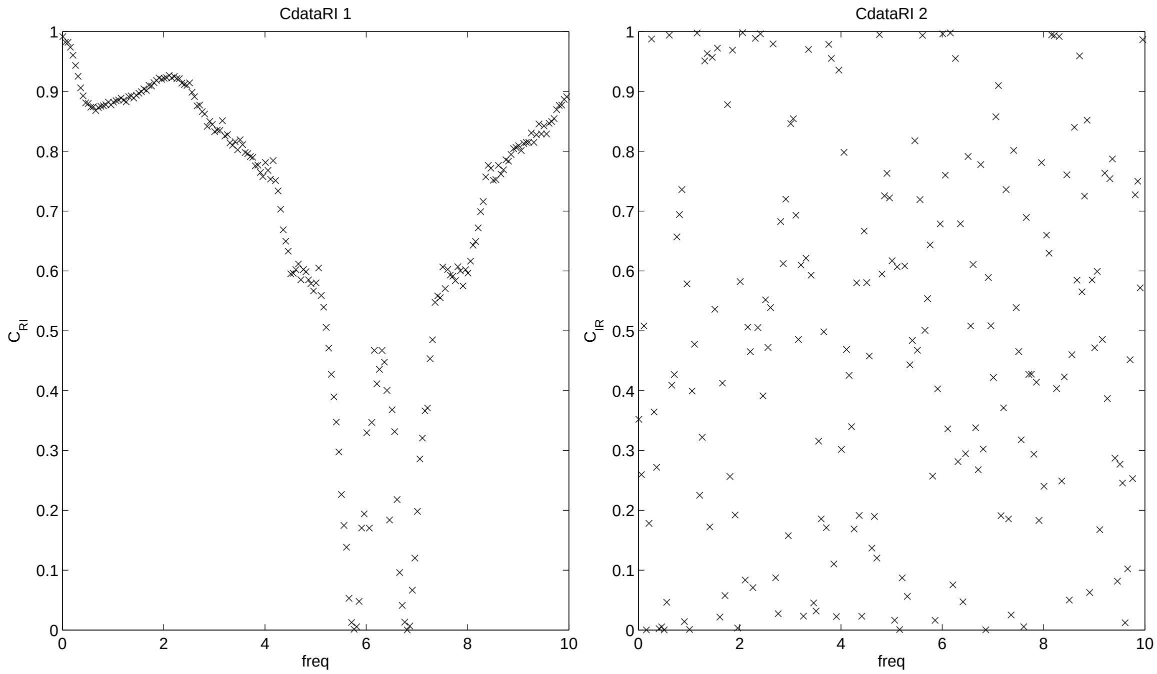


(a) C_{VI} and C_{IV}

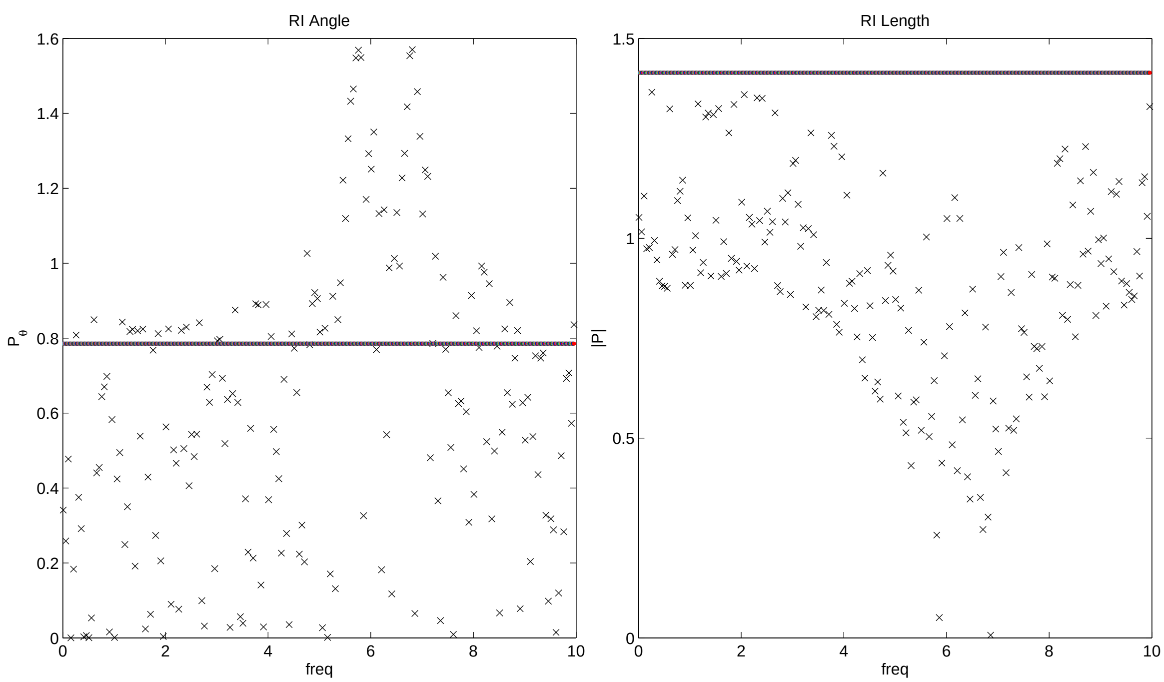


(b) P_θ and $|P|$

Figure 19: Changing f_r (longer library length).



(a) C_{VI} and C_{IV}



(b) P_θ and $|P|$

Figure 20: Changing f_r (larger domain for f_r).