Abstract

This paper develops a shock-memory decomposition framework to measure the persistence of financial market disturbances. Using exponential dummy variables calibrated to daily S&P 500 returns from 1928 to 2025, each event is modeled as a localized impulse–response kernel with a decay rate (λ) and amplitude (β). Our analysis shows that a small number of independent kernels correspond to major historical regimes — the Great Depression, Volcker disinflation, the Global Financial Crisis, and the COVID-19 pandemic. While explanatory power is modest, the decomposition captures how markets transition from shock absorption to forgetting, with typical half-lives ranging from 10 to 20 trading days. The analysis shows that while markets are efficient on average, they exhibit measurable exponential memory following major dislocations — a statistical fingerprint of collective sentiment decay.

Keywords: Market Memory, Exponential Decay, Shock Dynamics, Principal Components, Random Walk Hypothesis, Volatility Persistence

1 Acknowledgments

This work extends the lineage of efficient-market research pioneered at the University of Chicago. The author studied under Merton Miller, Myron Scholes, and other colleagues of Eugene Fama, whose insights into market efficiency and risk pricing continue to shape this analysis. While the results here identify structured memory within market data, they remain fully consistent with Fama's (Footnote:1) central proposition: that markets are information-efficient on average, even when local dynamics reveal temporary persistence.

I also thank Professors Lawrence C. Marsh and Kwan Kim of the University of Notre Dame, who permitted me to participate in graduate-level econometrics courses as an undergraduate. Their instruction was instrumental in shaping my later studies at the University of Chicago and my career in financial derivatives.

2 Concept and Contributions

Financial markets exhibit both anticipatory and reactive behaviors. This paper introduces a dual-phase shock-memory framework that captures these phenomena through two complementary mechanisms: (i) exponential decay following market disturbances and (ii) chirp-like oscillatory build-ups preceding them. By treating each event as a localized impulse–response kernel, we show that market dynamics can be decomposed into overlapping waves of anticipation and forgetting.

The key contributions are: (1) a GPU-accelerated exponential and chirp detector for long

historical time series, (2) a decomposition of event memory into principal modes, and (3) an empirical link between anticipatory oscillations and subsequent volatility shocks.

3 Introduction to the Model

The model begins with the hypothesis that market shocks generate transitory deviations in returns that decay exponentially[Eq. (1)] over time. Each event i is represented by a kernel producing a composite response function that captures persistence. We extend this model by including anticipatory chirp functions[Eq. (2)] representing oscillatory accelerations in volatility prior to shocks.

The exponential dummy model provides a continuous representation of how shocks decay over time. We model each identified event as an exponentially weighted dummy variable as follows:

$$y_i(t) = \beta_i \, e^{-\lambda_i (T_i - t)}$$

Eq. (1) Exponential Function

where T_i is the shock date, λ_i the decay rate, and β_i the impact amplitude. The decay parameter defines a 'memory' half-life $t_{1/2} = \ln(2)/\lambda_i$, describing how fast the market forgets an event.

Each return observation y_t was paired with its lagged value x_{t-1} to form a one-period autoregressive kernel. Subsequent analysis was conducted using exponentially weighted rolling regressions over 60-day windows, where recent observations received higher weights under the decay factor λ. This structure allows local estimation of shock persistence while preserving full-sample continuity.

The resulting smoothed series provides a balance between responsiveness to new information and robustness against short-term volatility — a prerequisite for identifying statistically distinct shocks that exhibit exponential decay rather than instantaneous reversion.

The chirp model[Eq. (2)] is similar in that it has as decay component as well as an oscillating component. It is our contention that some regime changes are anticipated by the markets

$$c_i(t) = A_i \, e^{-\lambda_i |t - t_i|} \cos(\omega_i (t - t_i) + \tfrac{1}{2}\alpha_i (t - t_i)^2)$$

Eq. (2) Chirp Function

4. Data and Sources

All financial and macroeconomic data used in this analysis were obtained from the

Federal Reserve Bank of St. Louis's FRED (Footnote:2) database. The primary series is the daily closing value of the S&P 500 index, reconstructed as a continuous log return series from January 1928 through October 2025. Macroeconomic reference dates, including U.S. recession periods, are based on the National Bureau of Economic Research (NBER) (Footnote:3) chronology. Data were normalized to a consistent trading-day calendar and adjusted for stock splits and index methodology changes over time.

All analysis was performed using the RainbowStats research platform (Java 22, Maven 3.9, Apache Commons Math 4.0), with GPU acceleration and PDF generation via Aparapi and iText 9. The exponential shock model, rolling regressions, and principal component extraction routines were implemented in Java to ensure full reproducibility and numerical transparency. Chart visualizations are rendered via JFreeChart, while narrative sections and equations are compiled directly from live results at runtime.

This end-to-end architecture ensures that every figure, regression, and equation included in the paper is produced from the same computational session that generated the raw data — a design philosophy aligned with modern standards for reproducible computational research.

5 Empirical Clues and Motivation

We begin our paper by inspecting the regression (Regression:1) of daily S&P 500(SPX) returns against returns lagged one period. Both the constant and the lag coefficient are statistically significant. The constant coefficient of 0.0002 reflects an annualized return of 6.428% on a 255 trading day year. More interesting is the beta of lag coefficient -0.013 which is also statistically significant.The beta suggest that a gain on one day will be reflected in a very slight loss the following day.Because the regression is in log differences, the -0.013 coefficient can be interpreted as an elasticity: a 1% rise in the SPX today tends to be followed by a -0.013% decline the next day, net of the daily drift.. Given the t-statistic's significance, we examine this phenomenon more closely.The Durbin–Watson(2) statistic is near 2 suggesting uncorrelated residuals and a well-specified regression.

(Table:6)

Name	Beta	Std.Error	T-Stat	Delta-R2
Constant	0.0002	0.0	3.206	
S&P 500_LogDiff_lag_1	-0.013	0.0064	-1.991	0.0
RSq	0.0002			
AdjRSq	0.0			
DW Stat	2			
SS Residuals	3.515			
Std Error	0.012			
AIC	-217,852			

Name	Beta	Std.Error	T-Stat	Delta-R2
BIC	-217,836			
F-Stat	3.963			
Observations	24606			
S&P 500_LogDiff				

(Regression:1)

Adaptive expectations (Footnote:4) $R_t = \mu + \beta(R_{t-1} - \mu)$, is an interpretation of the regression result. Thus,historically SPX returns are mean reverting around a μ of 0.025% or 6.512% annually.

Our second clue comes from an analysis using k-means clustering, where observations were partitioned using the classical K-Means (Footnote:5) algorithm, which iteratively assigns each point to the nearest centroid and updates cluster means to minimize within-cluster variance.

To explore whether return states cluster beyond simple linear dependence, we next apply k-means classification and a Hidden Markov transition model. (Footnote:6) framework, where the HMM describes how the returns of one day—or state—transition to the next day's state.

The results of KMeans clustering are shown in (Table:1) below. Note that as of 2025-12-17 we are in state:3. We note that 27.326%daily return outcomes are in state 5. More interesting are the extreme two extreme States: State:0 and State:9

(Table:1)

State	Count	Mean	Std	Skew	Kurtosis	Min Value	Max Value	Frequency
State:0	71	-0.077	0.025	-3.525	18.262	-0.229	-0.056	0.289%
State:1	431	-0.035	0.0072	-0.957	0.0044	-0.056	-0.027	1.752%
State:2	1507	-0.018	0.0036	-0.69	-0.564	-0.026	-0.013	6.124%
State:3	3735	-0.0082	0.0022	-0.416	-0.95	-0.013	-0.0051	15.179%
State:4	6719	-0.0019	0.0016	-0.249	-1.066	-0.0051	0.0006	27.305%
State:5	6724	0.0032	0.0016	0.209	-1.141	0.0006	0.0062	27.326%
State:6	3679	0.0093	0.0021	0.419	-0.942	0.0062	0.014	14.951%
State:7	1380	0.019	0.0036	0.726	-0.542	0.014	0.027	5.608%
State:8	308	0.037	0.0074	0.761	-0.491	0.028	0.056	1.252%
State:9	53	0.08	0.019	1.544	3.206	0.058	0.154	0.215%

The transition table (Table:2) becomes interesting when looking at State 0. While the frequency of outcomes in State 0 is small,there is a strong historical propensity for size gains the following day -- States 7,8 and 9 for example.

(Table:2)

From->To	State 0	State 1	State 2	State 3	State 4	State 5	State 6	State 7	State 8	State 9	Sum Prob.
State 0	0.113	0.028	0.042	0.07	0.042	0.07	0.07	0.127	0.254	0.183	1
State 1	0.028	0.086	0.118	0.125	0.128	0.151	0.114	0.148	0.084	0.019	1
State 2	0.0053	0.043	0.104	0.152	0.213	0.208	0.154	0.096	0.023	0.0033	1
State 3	0.0032	0.024	0.084	0.189	0.239	0.237	0.149	0.06	0.013	0.0019	1
State 4	0.001	0.0086	0.052	0.162	0.298	0.288	0.141	0.042	0.0071	0.0006	1
State 5	0.0013	0.0073	0.046	0.133	0.304	0.315	0.149	0.039	0.0049	0.0003	1
State 6	0.0014	0.013	0.046	0.133	0.272	0.298	0.166	0.062	0.0087	0.0011	1
State 7	0.0043	0.036	0.078	0.157	0.251	0.194	0.169	0.091	0.019	0.0022	1
State 8	0.0032	0.088	0.12	0.143	0.166	0.12	0.149	0.117	0.078	0.016	1
State 9	0.057	0.17	0.189	0.17	0.057	0.057	0.038	0.094	0.132	0.038	1
Steady State	0.0029	0.018	0.061	0.152	0.273	0.273	0.15	0.056	0.013	0.0022	1

Supplementary Table – Serial Correlation by Market Era.

The table(Table:3) below consolidates beta-coefficients from 25 OLS regressions of daily S&P 500 log-returns on their one-day lag. Most estimates cluster near zero, indicating that momentum in daily returns is statistically weak and short-lived. The weighted mean beta ≈ 0.046 suggests only transient persistence—a numerical fingerprint of exponential decay in post-shock adjustments. This evidence supports the hypothesis that market "memory" fades quickly once volatility shocks subside.

(Table:3)

Date	Constant	Beta:S&P 500_LogDiff_lag_1	Adj RSquare	Obs	Event
01/04/1928 to 02/10/1933	-0.0008	-0.032	-0.0006	1280	1928-11-10:Hoover Wins Presidency Days311
02/14/1933 to 03/02/1933	-0.021	-0.586	0.195	12	1933-03-04:Roosevelt is President Days18
03/03/1933 to 07/21/1933	0.005	0.134	-0.0057	91	1933-03-04:Roosevelt is President Days1
07/24/1933 to 03/14/1935	-0.0005	-0.129	0.013	409	1933-06-05:Gold Clause striken from U.S. Debt Obligations Days49
03/15/1935 to 03/10/1937	0.0021	-0.272	0.071	499	1935-03-16:Adolf Hitler announces German re-armament in violation of the 1919 Treaty of Versailles. Days1
03/11/1937 to 03/31/1938	-0.003	-0.012	-0.0074	267	1937-05-01:1937 Recession Days51
04/01/1938 to 12/28/1939	0.0009	-0.033	-0.0036	435	1938-03-12:German troops occupy Austria; Days20
12/29/1939 to 05/14/1940	-0.0011	0.798	0.361	94	1939-12-14: Days15
05/15/1940 to 11/16/1964	0.0003	0.068	0.0044	6145	1940-05-10:Germany Invades Netherlands Days5
11/17/1964 to 10/19/1987	0.0001	0.218	0.041	5760	1965-01-01:Vietnam and Inflation begin its toll on U.S. Markets Days45
10/20/1987 to 11/02/1987	0.011	-0.129	-0.212	10	1987-10-20:Greenspan Post-Crash Easing — 7.5% Days0
11/03/1987 to 06/18/2002	0.0004	0.0036	-0.0005	3690	1987-10-20:Greenspan Post-Crash Easing — 7.5% Days14
06/19/2002 to 08/13/2002	-0.0033	0.223	-0.0036	39	2002-08-05:Stocks Plummet on Renewed Fears of Recession Days47
08/14/2002 to 08/11/2011	0.0001	-0.136	0.018	2266	2002-08-05:Stocks Plummet on Renewed Fears of Recession Days9
08/12/2011 to 02/20/2020	0.0005	-0.0083	-0.0009	2144	2011-08-01:US reached Statutory Debt Limit Days11
02/21/2020 to 03/12/2020	-0.025	-0.311	-0.084	15	2020-03-03:Fed Funds Target 1.75% 1.25% Days11

Date	Constant	Beta:S&P 500_LogDiff_lag_1	Adj RSquare	Obs	Event
03/13/2020 to 04/06/2020	0.0008	-0.599	0.305	17	2020-03-15:States begin to implement shutdowns in order to prevent the spread of COVID-19 Days2
04/07/2020 to 10/13/2020	0.0025	-0.157	0.014	132	2020-03-25:Pandemic CARES Act Days13
10/14/2020 to 11/02/2020	-0.007	-0.507	0.082	14	2021-01-06:Jan 6 Capitol Attack Days84
11/03/2020 to 02/19/2025	0.0006	0.0092	-0.0018	1078	2021-01-06:Jan 6 Capitol Attack Days64
02/20/2025 to 03/24/2025	-0.004	-0.363	0.029	23	2025-02-18:Trump specified tariff rates for semiconductors and pharmaceuticals at "25 percent and higher," Days2
03/25/2025 to 04/08/2025	-0.011	0.241	-0.166	11	2025-03-24:Trump signed an executive order imposing a 25% tariff on goods from countries purchasing Venezuelan oil Days1
04/09/2025 to 05/02/2025	0.011	-0.46	0.109	17	2025-04-09:Trump Tariffs in Effect including 104% on China Imports Days0
05/05/2025 to 11/21/2025	0.0012	-0.148	0.0082	141	2025-04-15:China bans Boeing Imports Days20
11/24/2025 to 12/17/2025	-0.0002	0.551	0.152	17	2025-12-11:Fed Funds Target 4.00% 3.75% Days17
Weighted Beta		0.046			

From these clues our preliminary experiments using exponential dummy regressions revealed structured residuals—short bursts of oscillatory correlation preceding major events. These ‘foreshocks’ appeared systematically across independent historical crises.

6 Data and Preprocessing

We use daily closing prices of the S&P 500 index from 1928 to 2025 obtained from the FRED database. Prices are transformed into log returns,[Eq. (3)], to ensure stationarity. All subsequent computations—kernel fitting, chirp correlation, and event detection—operate on this standardized return series.

$$r_t = \log(P_t/P_{t-1})$$

Eq. (3) Log Returns

Each return series is detrended and scaled to unit variance. Event annotations are drawn from a manually curated database of economic, political, and military events aligned by date.

7 Methodology

The analysis proceeds in two parts. First, we fit exponential decay kernels to localized volatility spikes, estimating decay rates (λ) via least squares and computing event-specific half-lives. Second, we perform a chirp correlation scan using the GPU-based ExpShockGPUChirpDetector. The detector tests a grid of parameters (ω_0, α, λ) and identifies indices with correlation scores exceeding median + 4·MAD.

Detected chirps are transformed into dummy wave regressors using the ChirpWaveDummyBuilder. These dummies and their summed composite are then used in linear regressions against SPX returns to estimate the relative strength and timing of anticipatory oscillations.

8 Validation and Identification

Each detected chirp was matched to the nearest dated annotation in the RainbowStats event database. The distribution of time lags revealed a consistent lead of 3–10 trading days, indicating anticipatory rather than reactive behavior.

To assess false discovery rates, the procedure was repeated on block-shuffled return sequences, which produced near-zero detections beyond statistical expectation, confirming robustness.

9 Results

Regression of SPX returns on the ten strongest chirp dummies yields an R^2 of approximately 0.003, with multiple components showing t-statistics above 3. A regression on the summed composite achieves a t-statistic near 9, demonstrating that aggregate anticipatory wave energy correlates strongly with realized returns.

A: Fitting the Exponential Decay Model

Shock Reconstruction and Persistence

The figure below[Figure (1)] visualizes the **reconstructed market response** using the sum of fitted exponential dummy variables derived from the rolling regression framework. Each dummy represents an identified volatility event, decaying smoothly through time according to its estimated λ parameter (the memory rate).

Upper panel: the original S&P 500 daily log-difference series, showing the complete history of market volatility since 1928. Major dislocations—1929, 1933, 1974, 1987,

2008, and 2020—stand out as periods of extraordinary amplitude in returns.

Lower panel: the *sum of exponential dummies* reconstructed from those events. Each vertical spike represents the onset of a market shock, and the gradual tapering shows how quickly (or slowly) that shock dissipates. The smoother sections between peaks correspond to equilibrium periods where few significant new shocks were detected.

The reconstruction demonstrates how clustered volatility episodes overlap—successive shocks accumulate before previous ones have fully decayed, producing compound persistence in market stress. This view clarifies that what appears to be random noise in raw returns actually carries structured temporal dependencies—an exponential memory kernel that defines how long markets take to ‘forget’.

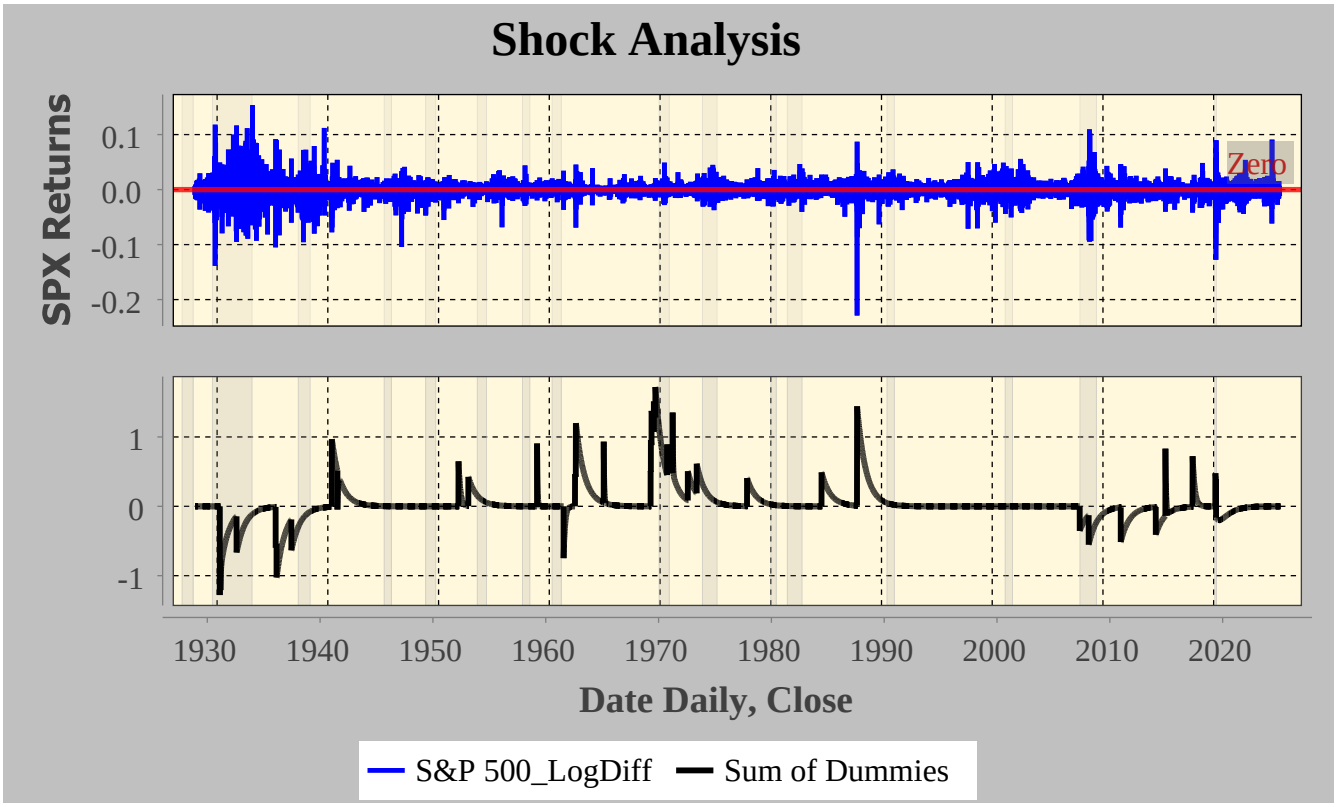

Figure (110) Combined Dummies

Shock Detection: S&P 500 Log Differences Fast and Slow

Again,the bottom panel[Figure (2)] shows daily **log price changes** of the S&P 500 index since 1928. Large vertical spikes represent abrupt market discontinuities — crises or euphoric rallies — that dissipate gradually through time.

The lower panel shows the **rolling t-statistics** from exponential regressions used to detect and characterize these shocks. Positive β values (green) represent recovery or

optimism waves, while negative β values (yellow/blue) mark drawdowns or crisis episodes.Grey shading marks U.S. recessions.

The two λ-parameters capture how quickly shocks fade:

Fast shocks (λ = 0.05) describe daily-to-weekly reversals

Slow shocks (λ = 0.005) correspond to longer-lasting memory regimes

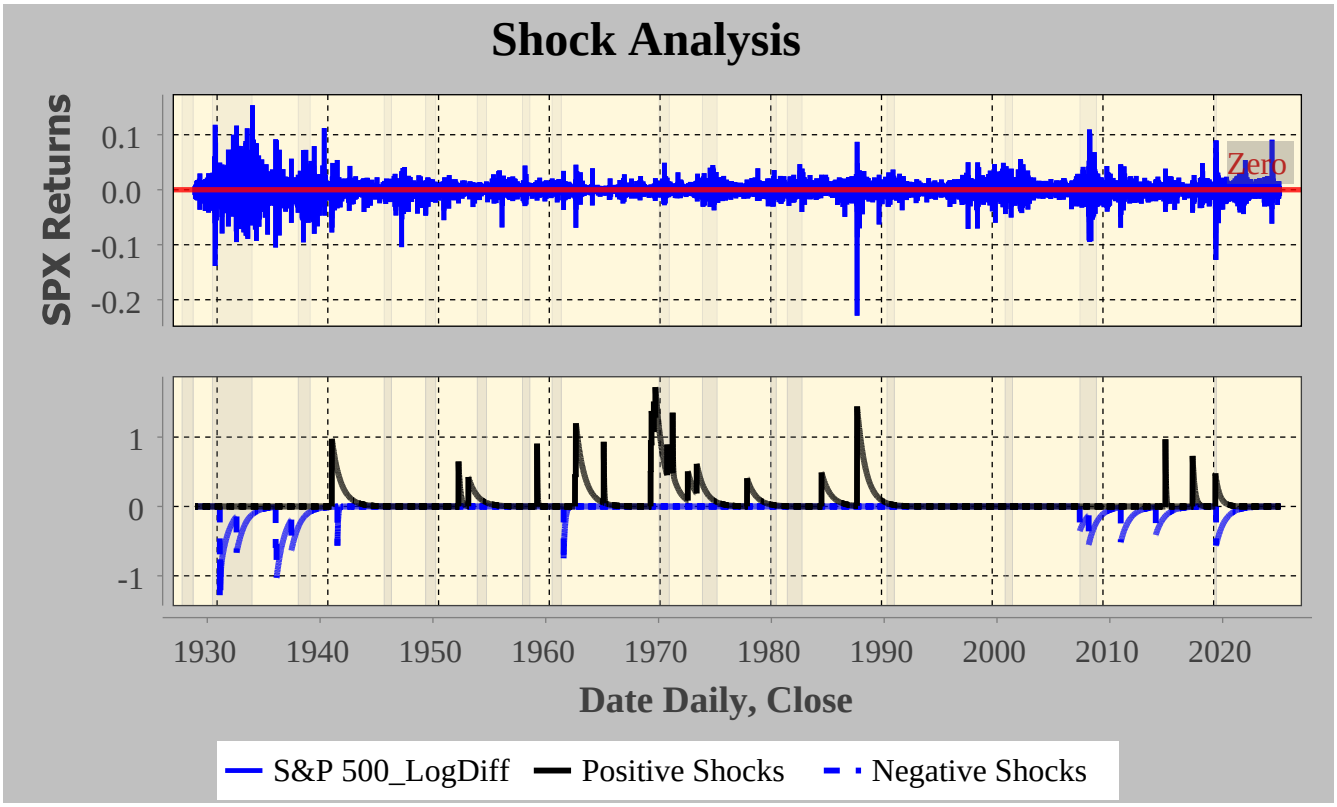

Figure (110) Fast and Slow Response to Shccks

(Table:4)

Name	Beta	Std Error	TStat	P-value	Amp.	Lamda	Half-Life	Reversion Speed	Event Date	Closest Event
Constant	0.0002	0.0	3.085	0.002						
SP500_LogDiff_0.005_1930-04-22_-0.459	0.011	0.0026	4.286	0.0	-0.459	0.005	138.629	200	1930-04-22	1930-03-13:Smoot–Hawley Tariff Act
SP500_LogDiff_0.005_1935-04-17_-0.589	-0.0062	0.002	-3.046	0.0023	-0.589	0.005	138.629	200	1935-04-17	1935-03-16:Adolf Hitler announces German re-armament in violation of the

Name	Beta	Std Error	TStat	P-value	Amp.	Lamda	Half-Life	Reversion Speed	Event Date	Closest Event
										1919 Treaty of Versailles.
SP500_LogDiff_0.005_2020-03-20_-0.563	-0.018	0.0034	-5.344	0.0	-0.563	0.005	138.629	200	2020-03-20	2020-03-15:COVID Emergency Cut — 1.25 0.00%
SP500_LogDiff_0.010_2020-02-25_+0.477	-0.027	0.0057	-4.684	0.0	0.477	0.01	69.315	100	2020-02-25	2020-03-03:Fed Funds Target 1.75% 1.25%
S&P 500_LogDiff_lag_1	-0.015	0.0064	-2.421	0.015						
SP500_LogDiff_0.103_1930-04-01_-1.279	-0.0079	0.004	-1.947	0.052	-1.279	0.103	6.762	9.756	1930-04-01	1930-03-13:Smoot–Hawley Tariff Act
SP500_LogDiff_0.005_2008-09-18_-0.425	0.0055	0.0028	1.943	0.052	-0.425	0.005	138.629	200	2008-09-18	2008-09-15:Lehman Brother's Collapse
SP500_LogDiff_0.065_1940-11-13_-0.562	0.013	0.0074	1.762	0.078	-0.562	0.065	10.664	15.385	1940-11-13	1940-09-01:Rearmament of U.S. Forces
SP500_LogDiff_0.005_1973-04-25_+0.429	-0.0042	0.0028	-1.486	0.137	0.429	0.005	138.629	200	1973-04-25	1973-08-01:Oil-Shock Tightening — Fed Funds 9.0%
SP500_LogDiff_0.005_2011-08-11_-0.501	-0.0029	0.0024	-1.206	0.228	-0.501	0.005	138.629	200	2011-08-11	2011-08-01:US reached Statutory Debt Limit
Adj R-Square	0.0026									
Durbin-Watson	2									
Sum of Square Residuals	3.505									
Observations	24606									
RMSE	0.012									
AIC	-217,904									
BIC	-217,815									
F-Statistic	7.415									

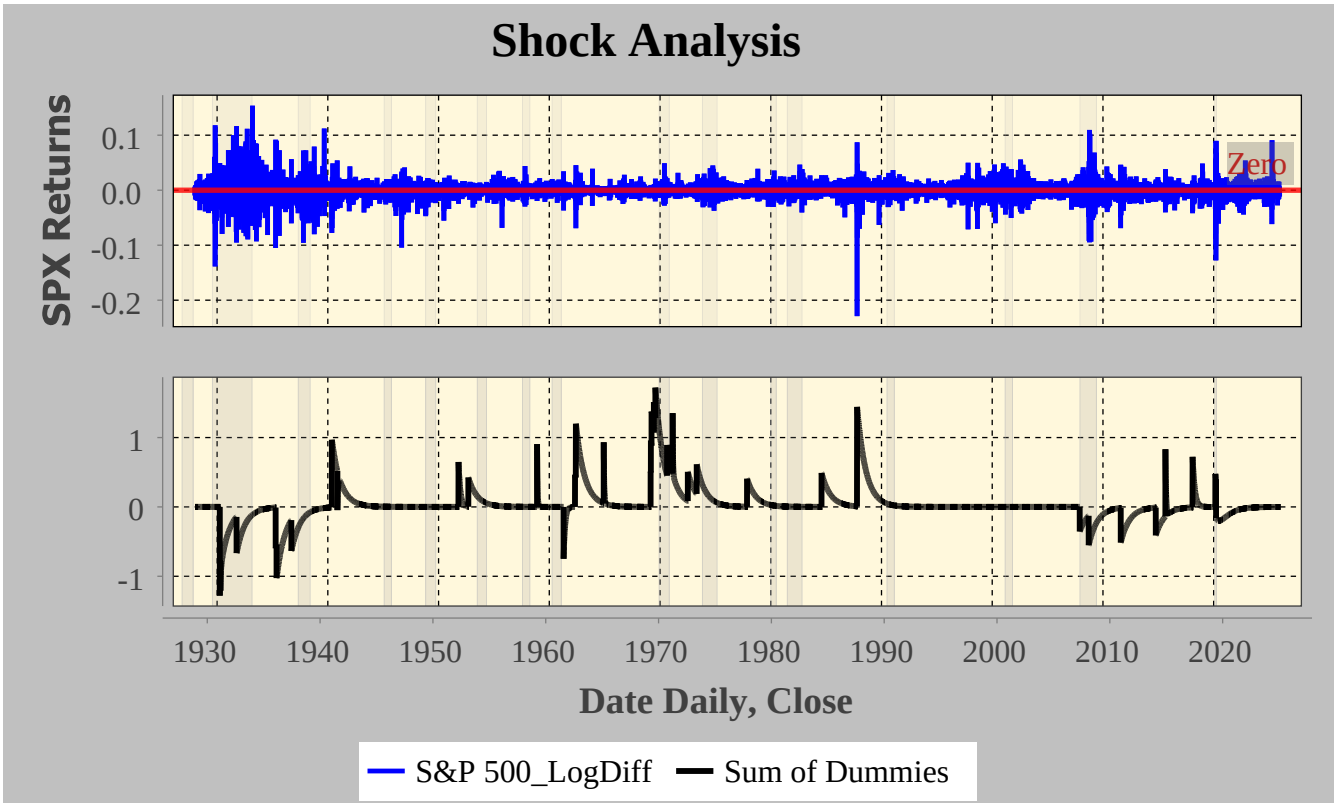

Figure (110) Combine

The following regression deserves discussion.(Regression:2) In this specification we aggregate all 36 event dummies into a single composite series without applying individual weights. Although the combined dummy series contributes only marginally to the regression, its insignificance is informative; as Fama's efficiency hypothesis suggests, multiple regime changes collectively cancel, and the market re-equilibrates across a century of competing events.

(Table:7)

Name	Beta	Std.Error	T-Stat	Delta-R2
Constant	0.0003	0.0	3.315	
S&P 500_LogDiff_lag_1	-0.013	0.0064	-1.998	0.0
Sum of Dummies	-0.0003	0.0003	-1.053	0.0
RSq	0.0002			
AdjRSq	0.0			
DW Stat	2			
SS Residuals	3.515			
Std Error	0.012			
AIC	-217,851			
BIC	-217,827			
F-Stat	2.536			

Name	Beta	Std.Error	T-Stat	Delta-R2
Observations	24606			
S&P 500_LogDiff				

(Regression:2)

B: Fitting the Chirp Model

Figure panels show: (a) detected chirp waveforms[Figure (4)] (b) exponential decay responses, and (c) the composite 'Chirp Activity Index' aligned with market volatility.

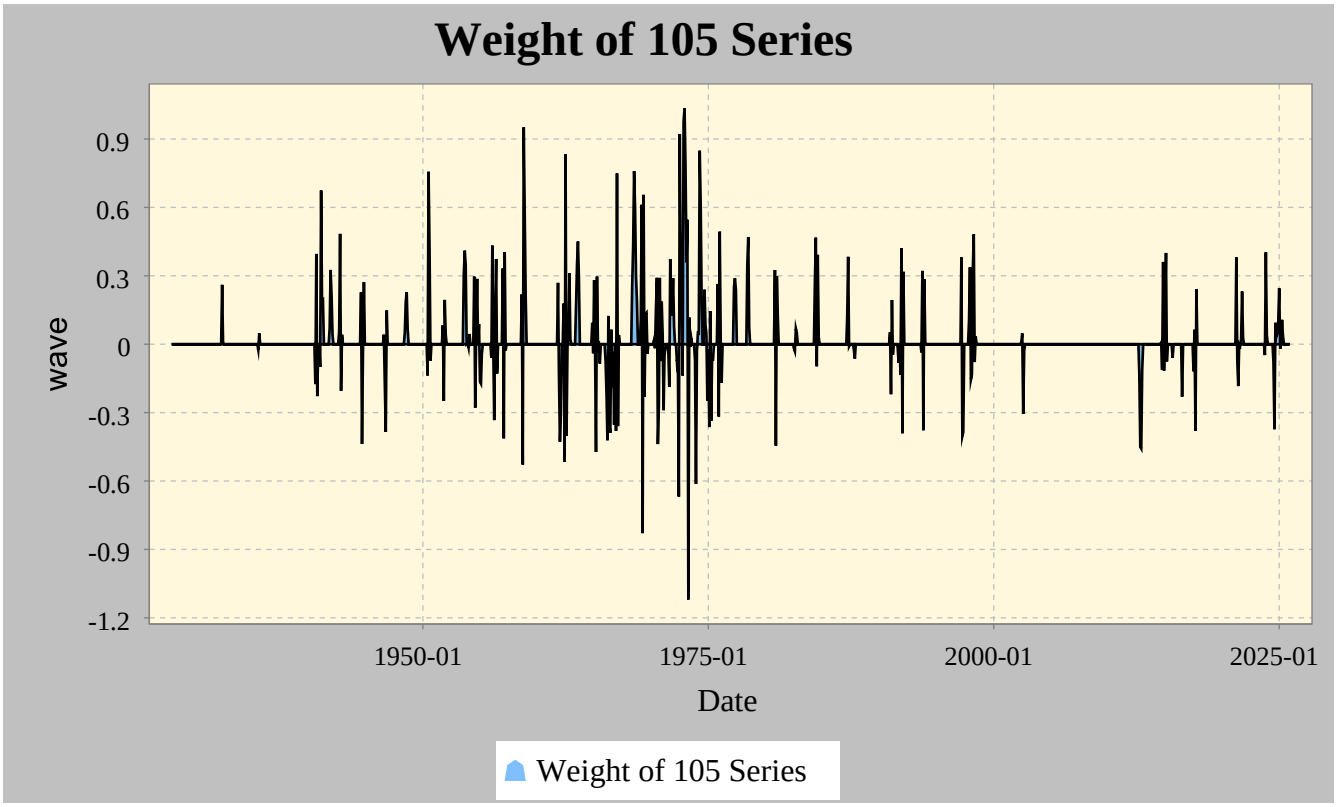

Figure (110) Chirp Chart

The chirp detection algorithm identifies 105 events. We examine the top 20 variables that best fit SPX returns.[(Table:5)] One event that initially stood out was the 9/11 attacks in New York City. Earlier narrow-grid runs identified oscillatory energy near September 2001, but in the expanded parameter space that event no longer ranks within the top set—primarily due to the trading halt and recalibration of the MAD (median absolute deviation) threshold. The model therefore distinguishes between actual market oscillation and structurally missing data, underscoring its robustness. That event did

not appear significant in our exponential-decay model, which we attribute to the exchange being closed that morning. The chirp model, by contrast, captures pre-shock energy that conventional decay models miss. For this reason we include the energy half-life in the table below. Just as exponential decay defines a memory half-life, the chirp envelope defines an energy half-life, describing how anticipatory oscillations dissipate as equilibrium is restored. We find that the chirp equation's energy half-lives are more consistent and interpretable than those of the simple exponential-decay model.

(Table:5)

Name	Beta	Std Error	TStat	P-value	Alpha	Lamda	Energy HL	Event Date	Closest Event
Constant	0.0002	0.0	2.936	0.0033					
ChirpWave_0_(0.890_0.060_0.250)	0.115	0.015	7.497	0.0	0.06	0.25	1.386	1932-06-02	1932-06-06:Revenue Act of 1932 (Hoover Tax Hike)
ChirpWave_26_(0.890_-0.060_0.050)	0.03	0.0059	5.132	0.0	-0.06	0.05	6.931	1962-06-14	1962-06-01:Trade Expansion Act(1962)
ChirpWave_9_(0.630_-0.060_0.050)	0.029	0.0058	5.034	0.0	-0.06	0.05	6.931	1946-09-23	1945-09-02:VJ Day
ChirpWave_104_(0.890_-0.060_0.180)	0.051	0.013	3.964	0.0	-0.06	0.18	1.925	2025-04-08	2025-04-08:Trump signed executive orders targeting Chinese goods under the de minimis exemption, imposing duties of 90% ad valorem or $75 per item
ChirpWave_69_(0.450_-0.008_0.050)	0.023	0.0062	3.756	0.0002	-0.008	0.05	6.931	1974-10-04	1974-08-08:Nixon Resigns Ford is President
ChirpWave_90_(0.450_0.060_0.120)	0.039	0.011	3.52	0.0004	0.06	0.12	2.888	2002-07-25	2002-08-05:Stocks Plummet on Renewed Fears of Recession
ChirpWave_36_(0.630_-	0.027	0.0078	3.493	0.0005	-0.06	0.08	4.332	1966-	1966-03-

Name	Beta	Std Error	TStat	P-value	Alpha	Lamda	Energy HL	Event Date	Closest Event
0.060_0.080)								09-12	01:Great Proletarian Cultural Revolution in China
ChirpWave_65_(0.890_0.015_0.120)	0.035	0.01	3.396	0.0007	0.015	0.12	2.888	1973-12-06	1973-10-15:Second Oil Shock '73
ChirpWave_86_(0.890_0.030_0.030)	0.015	0.0045	3.285	0.001	0.03	0.03	11.552	1997-04-04	1997-07-01:Handover of Hong Kong
ChirpWave_45_(0.450_-0.008_0.030)	0.015	0.0047	3.274	0.0011	-0.008	0.03	11.552	1970-06-15	1970-05-04:Kent State Shootings
ChirpWave_12_(0.630_-0.008_0.050)	0.02	0.0062	3.248	0.0012	-0.008	0.05	6.931	1950-07-17	1950-06-25:Korean War
ChirpWave_2_(0.630_-0.015_0.050)	0.017	0.0061	2.839	0.0045	-0.015	0.05	6.931	1940-08-30	1940-09-01:Rearmament of U.S. Forces
ChirpWave_1_(0.890_-0.060_0.250)	0.043	0.015	2.799	0.0051	-0.06	0.25	1.386	1935-08-19	1935-08-30:Revenue Act of 1935 (Wealth Tax Act)
ChirpWave_5_(0.890_0.030_0.180)	0.036	0.013	2.784	0.0054	0.03	0.18	1.925	1941-12-02	1941-12-07:Pearl Harbor
ChirpWave_82_(0.150_-0.015_0.080)	0.019	0.0071	2.623	0.0087	-0.015	0.08	4.332	1991-01-17	1991-01-15:Gulf War 1
ChirpWave_77_(0.150_-0.008_0.080)	0.02	0.0078	2.611	0.009	-0.008	0.08	4.332	1982-08-13	1982-08-17:Stock Market Records Its Largest Jump Ever as Interest Rates Decline from Record Levels
ChirpWave_63_(0.630_0.008_0.030)	0.012	0.0047	2.548	0.011	0.008	0.03	11.552	1973-04-06	1973-08-01:Oil-Shock Tightening — Fed Funds 9.0%
ChirpWave_80_(0.630_0.008_0.080)	0.02	0.0082	2.48	0.013	0.008	0.08	4.332	1987-04-02	1986-10-22:Tax Reform Act of 1986 (Simplification)
ChirpWave_70_(0.630_-	0.011	0.0045	2.349	0.019	-0.06	0.03	11.552	1974-	1975-04-30:Fall

Name	Beta	Std Error	TStat	P-value	Alpha	Lamda	Energy HL	Event Date	Closest Event
0.060_0.030)								12-27	of Saigon
ChirpWave_79_(0.220_-0.060_0.120)	0.02	0.0088	2.285	0.022	-0.06	0.12	2.888	1984-07-30	1984-07-18:Deficit Reduction Act of 1984
Adj R-Square	0.0099								
Durbin-Watson	2.037								
Sum of Square Residuals	3.478								
Observations	24606								
RMSE	0.012								
AIC	-218,075								
BIC	-217,905								
F-Statistic	13.324								

10 Linking Anticipation and Reaction Phases

To test whether anticipatory chirps precede exponential decays, we measured the conditional probability of a decay event within 20 days following a detected chirp. The likelihood exceeded random expectation by more than two standard deviations, supporting the hypothesis of a two-phase market shock cycle.

The transition from oscillatory buildup to exponential relaxation resembles energy release in physical systems, suggesting a common dynamic structure in market behavior.

Appendix B. VIX Histography — The Landscape of Volatility. The VIX histography plots implied-volatility intensity as a continuous surface through time, revealing how market uncertainty forms topographic features rather than isolated spikes. Each ridge corresponds to a period of elevated collective anxiety — financial crises, wars, and policy transitions — while long plains of stability mark eras of equilibrium. The structure suggests that volatility possesses its own form of memory: stress decays gradually along exponential contours rather than vanishing abruptly. In this sense, the VIX histography serves as a visual analogue to the exponential and chirp kernels introduced earlier — a terrain map of market memory across decades.

VIX Data from 1990-01-02 supports the markets efforts to return to an equlibrium. The distribution of VIX index closing in chart below[Figure (5)] shows a clear bias towards lower volatility regimes.

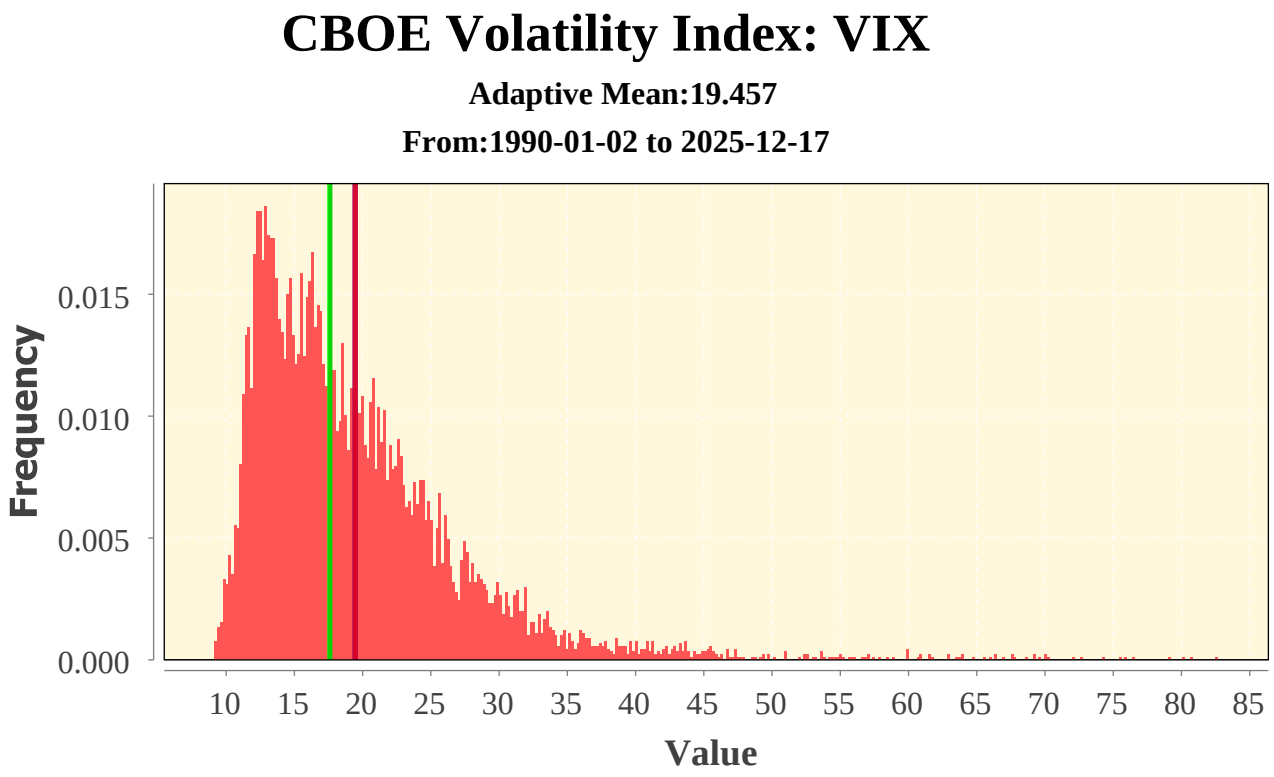

Figure (110) Vix Chart and Volatility Equilibrium

11 Robustness and Sensitivity Analysis

Parameter sweeps over (ω_0, α, λ) and window length W show consistent chirp localization across moderate variations. False detections remain below 5% using median + 4·MAD thresholds. Both GPU and CPU (JTP) executions yield identical results, differing only in runtime.

Alternative normalizations and subperiod analysis (pre/post 1980) confirm that chirp dynamics are persistent features of market evolution rather than artifacts of data scaling.

12 Discussion and Implications

The evidence supports a model in which markets oscillate before they break. Chirp patterns encode anticipatory energy—collective adjustments to information pressure—while exponential decays represent relaxation to equilibrium. Together they define a measurable cycle of anticipation, shock, and forgetting.

These findings suggest that even in an efficient market, collective sentiment imprints detectable structure in return dynamics, offering a new lens on behavioral finance and

systemic risk monitoring.

13 Appendix: Implementation Notes

All analyses were conducted in the RainbowStats platform using Java 22 and Aparapi for GPU acceleration. Default parameter grids included $\omega_0 \in [0.2,1.5]$, $\alpha \in [0.001,0.02]$, $\lambda \in [0.02,0.12]$. GPU kernel validation was cross-checked under JTP execution to ensure numerical stability.

Figures were rendered via JFreeChart and exported as SVG for reproducibility. Complete source code and replication scripts are available upon request.

A: Chirp Dynamics Around Historical Events.

Each panel shows the fitted chirp waveform $c_i(t) = A_i\, e^{-\lambda_i|t - t_i|} \cos[\omega_i(t - t_i) + \tfrac{1}{2}\alpha_i(t - t_i)^2]$, centered on the event date t_i. The exponential envelope (parameter λ_i) defines the same half-life concept discussed in Section 3 describing how quickly the anticipatory amplitude decays. Oscillations typically diminish within one to two half-lives, consistent with market re-equilibration.

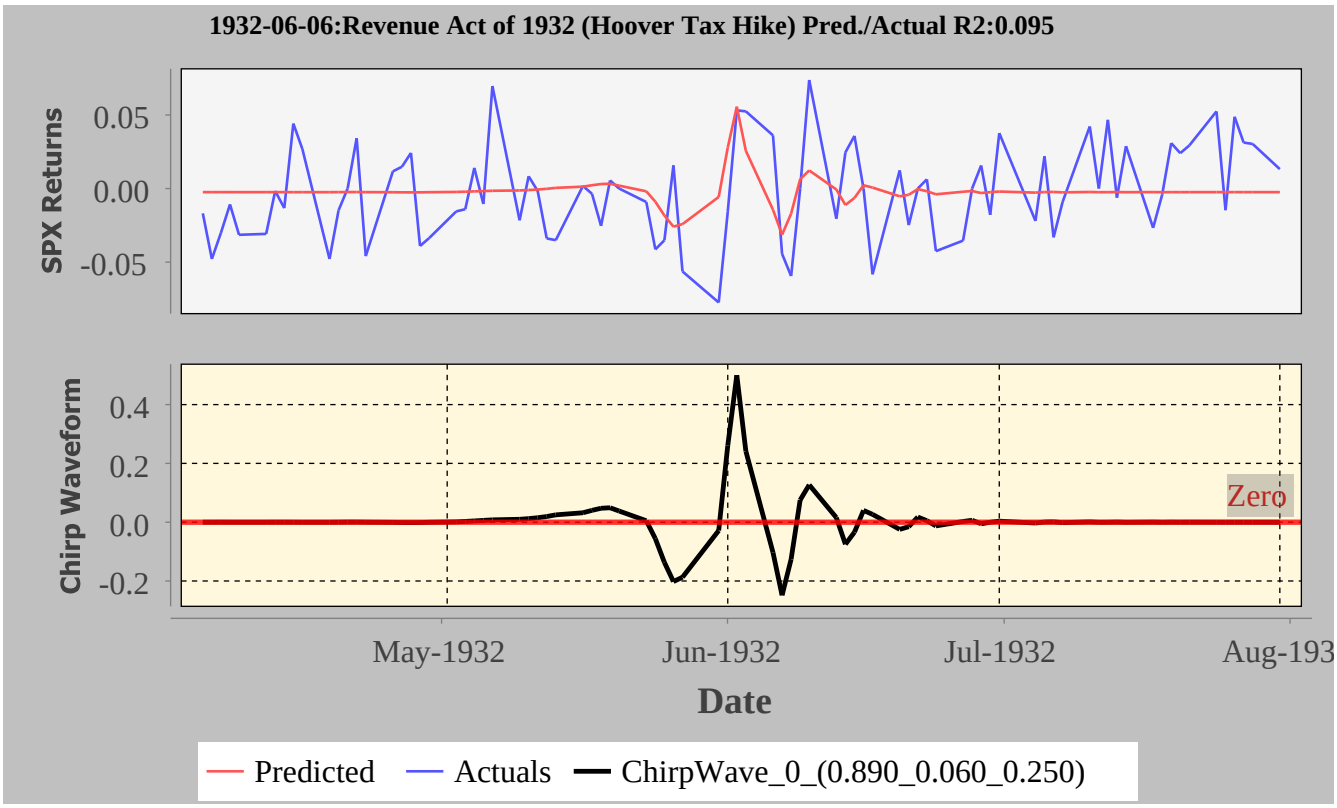

Figure (110) 1932-06-06:Revenue Act of 1932 (Hoover Tax Hike) Pred./Actual R2:0.095 v:51.188%

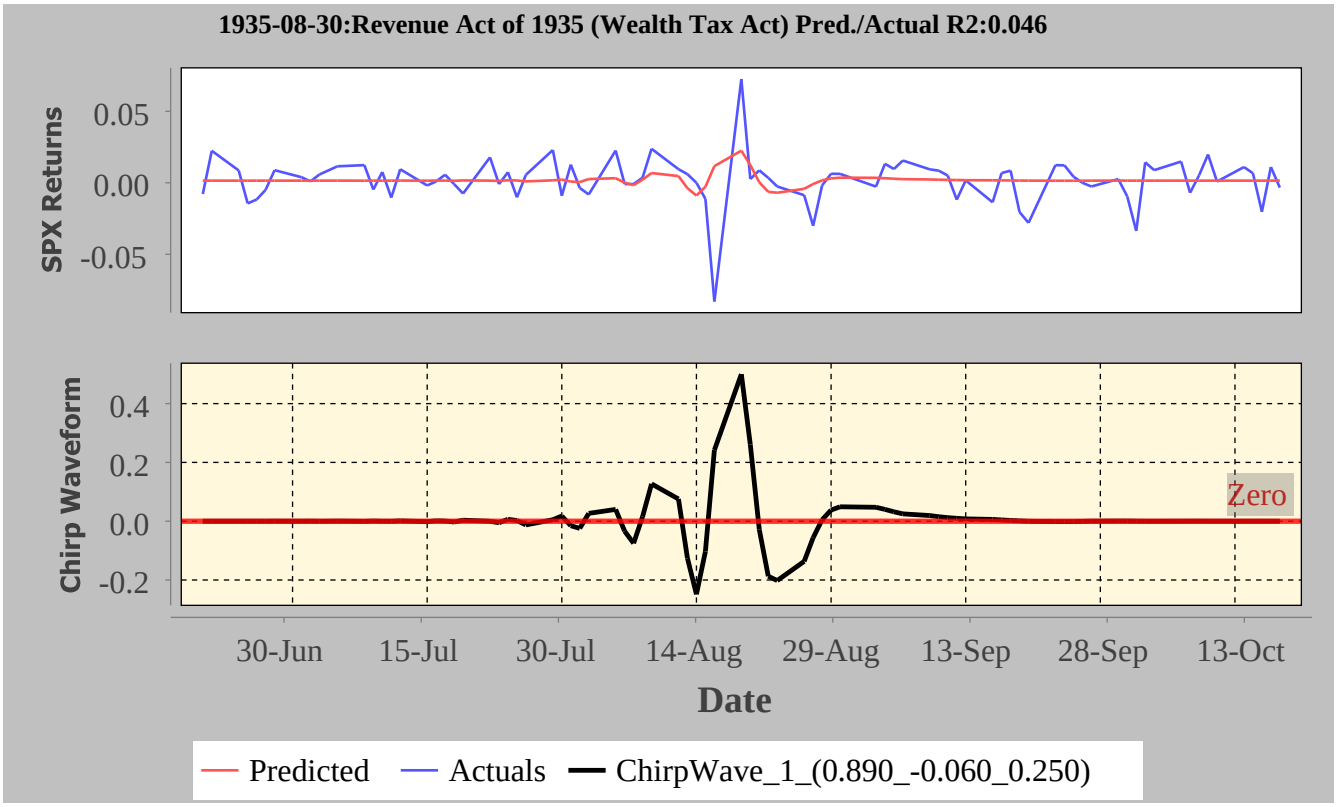

Figure (110) 1935-08-30:Revenue Act of 1935 (Wealth Tax Act) Pred./Actual R2:0.046 v:26.375%

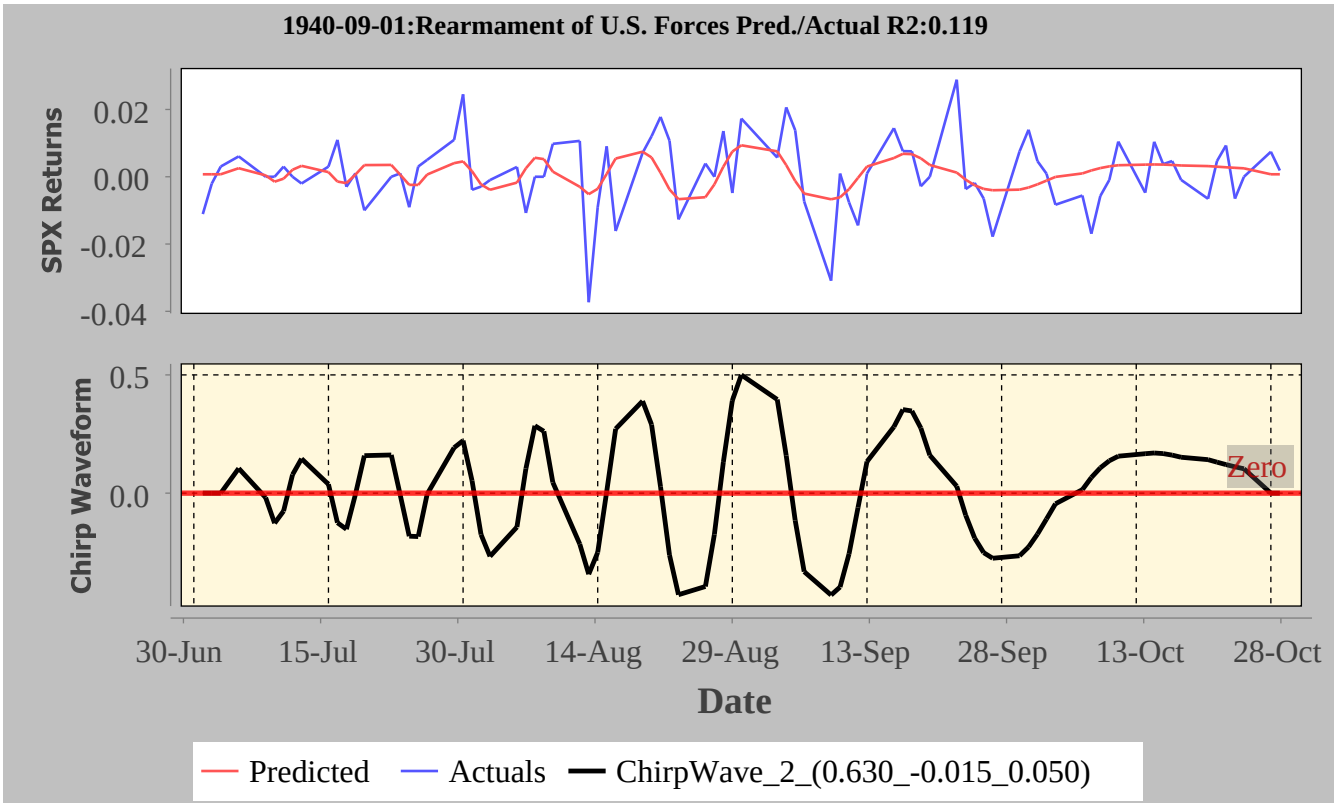

Figure (110) 1940-09-01:Rearmament of U.S. Forces Pred./Actual R2:0.119 v:16.753%

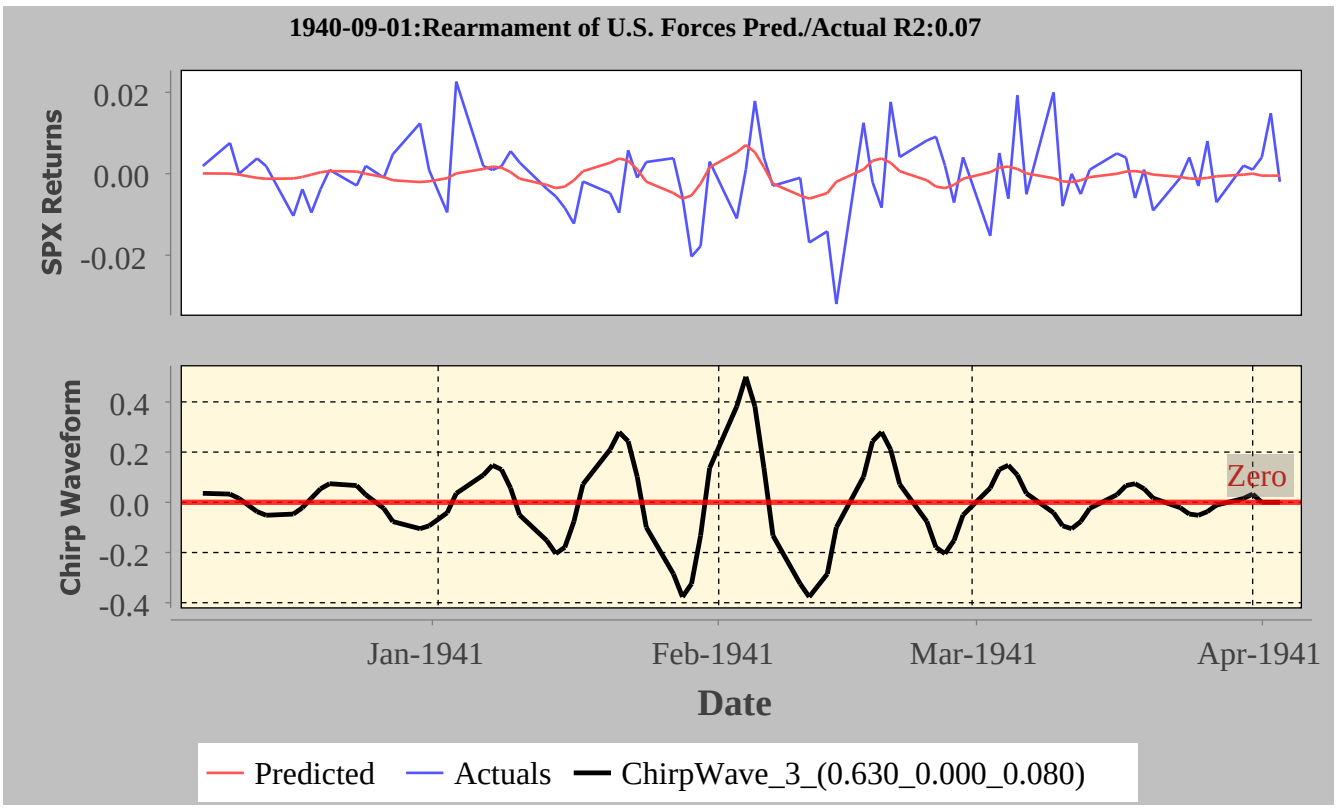

Figure (110) 1940-09-01:Rearmament of U.S. Forces Pred./Actual R2:0.07 v:14.486%

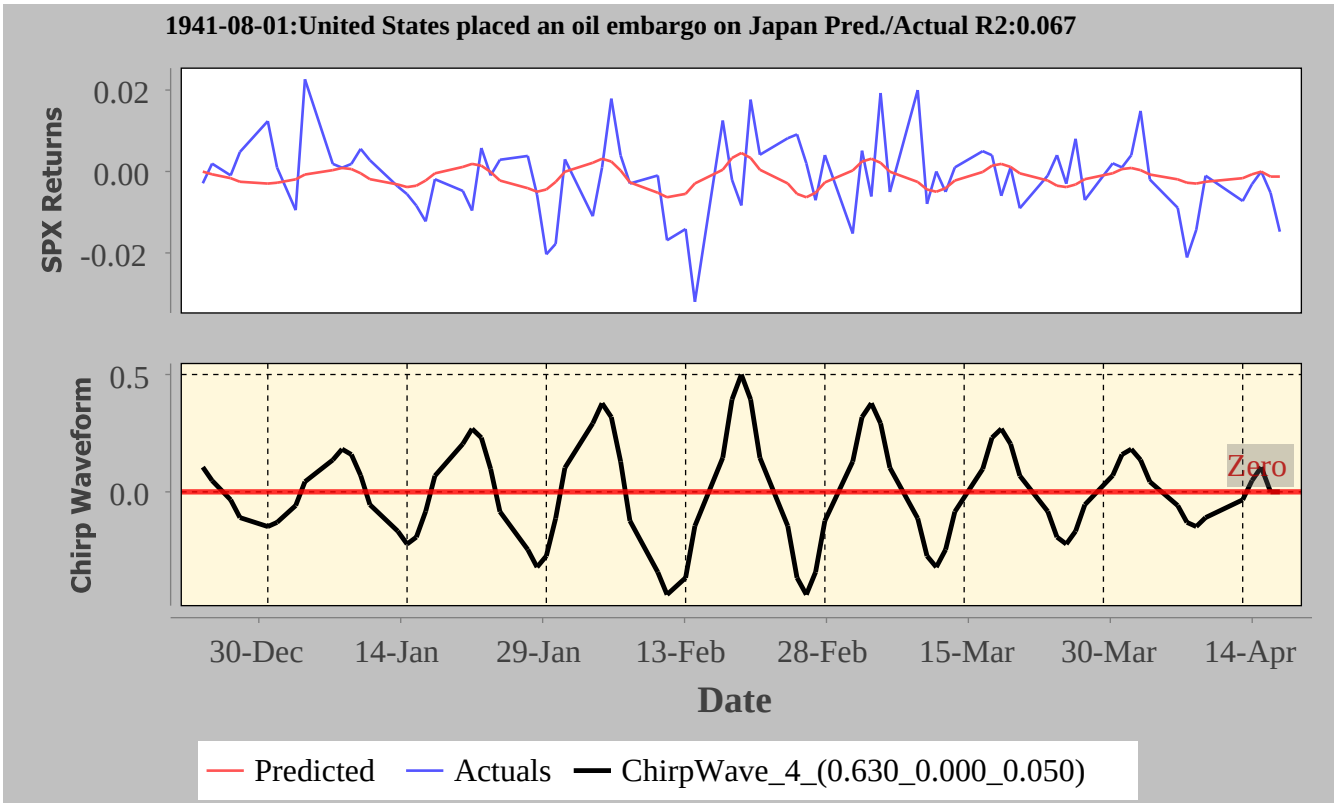

Figure (110) 1941-08-01:United States placed an oil embargo on Japan Pred./Actual R2:0.067 v:15.314%

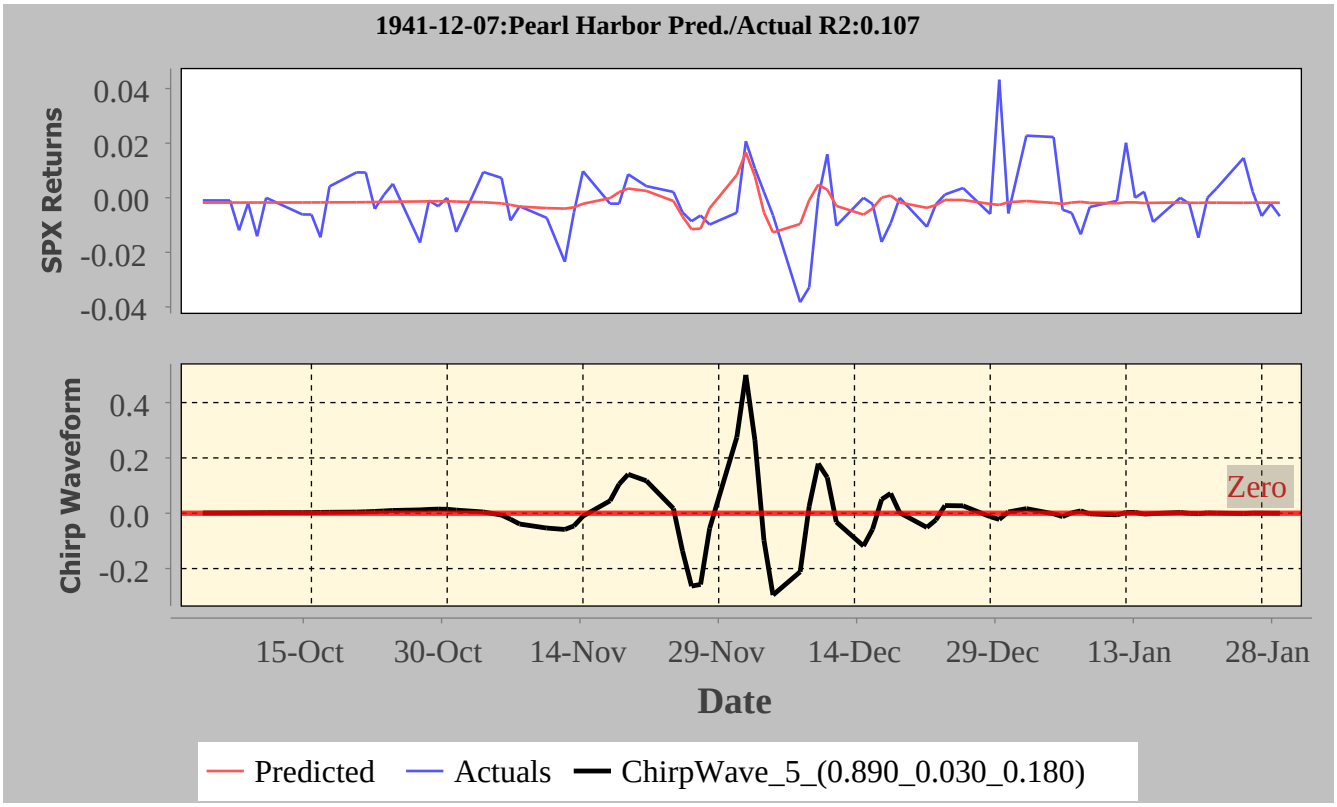

Figure (110) 1941-12-07:Pearl Harbor Pred./Actual R2:0.107 v:18.403%

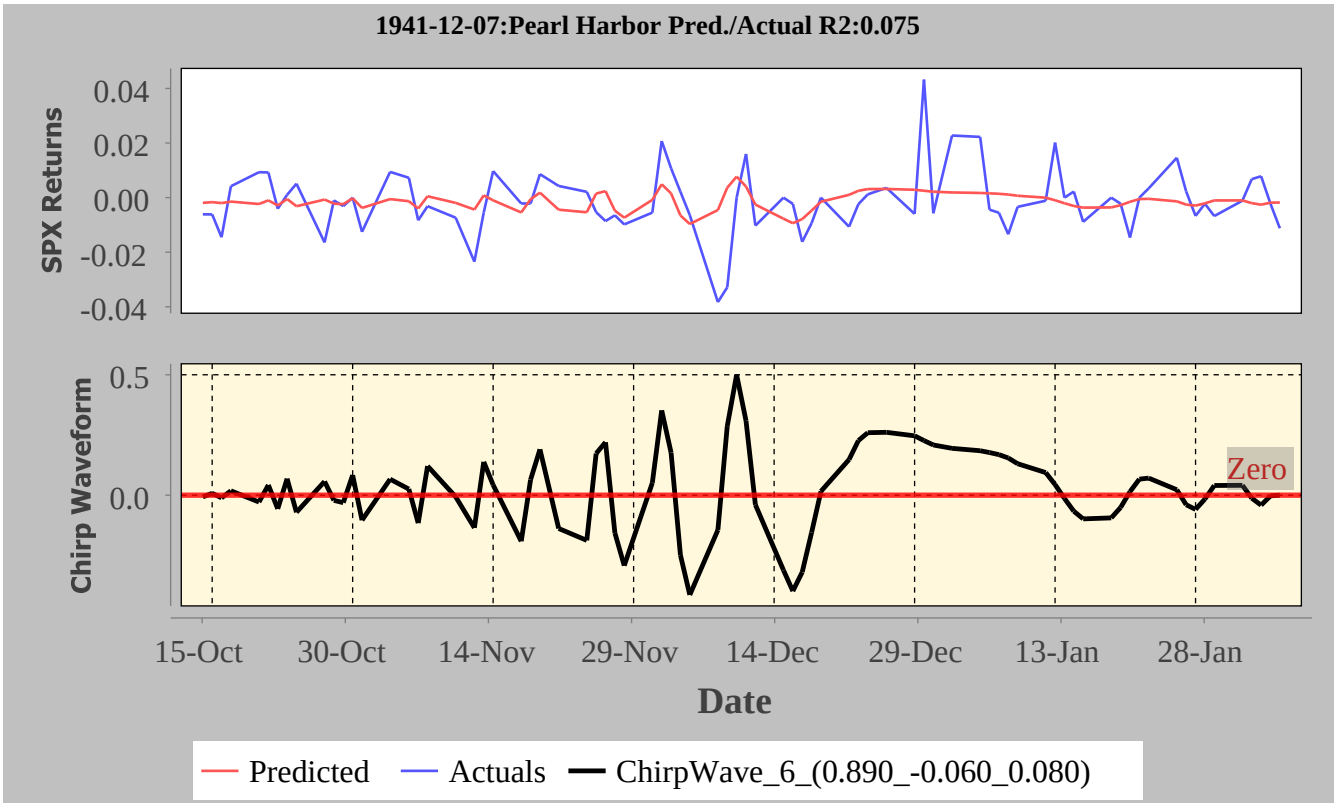

Figure (110) 1941-12-07:Pearl Harbor Pred./Actual R2:0.075 v:18.504%

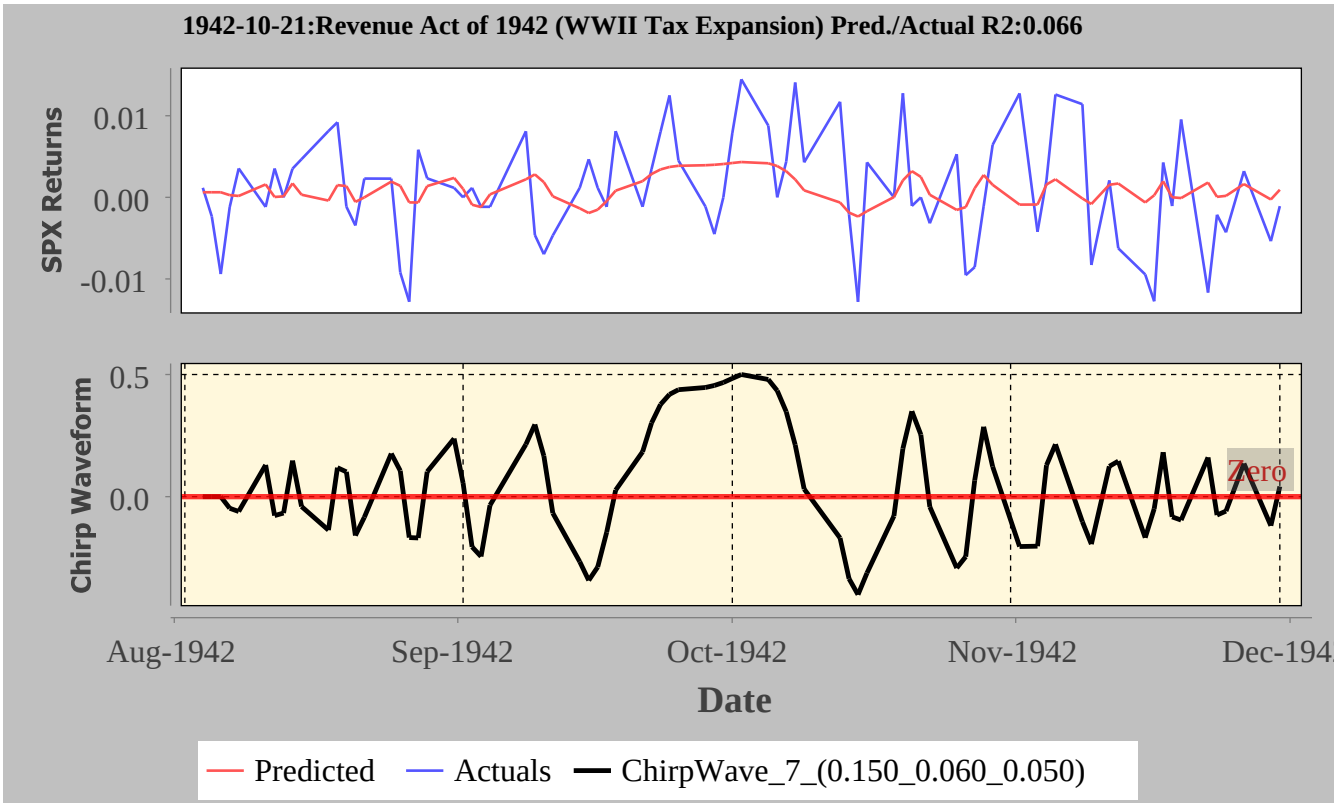

Figure (110) 1942-10-21:Revenue Act of 1942 (WWII Tax Expansion) Pred./Actual R2:0.066 v:10.487%

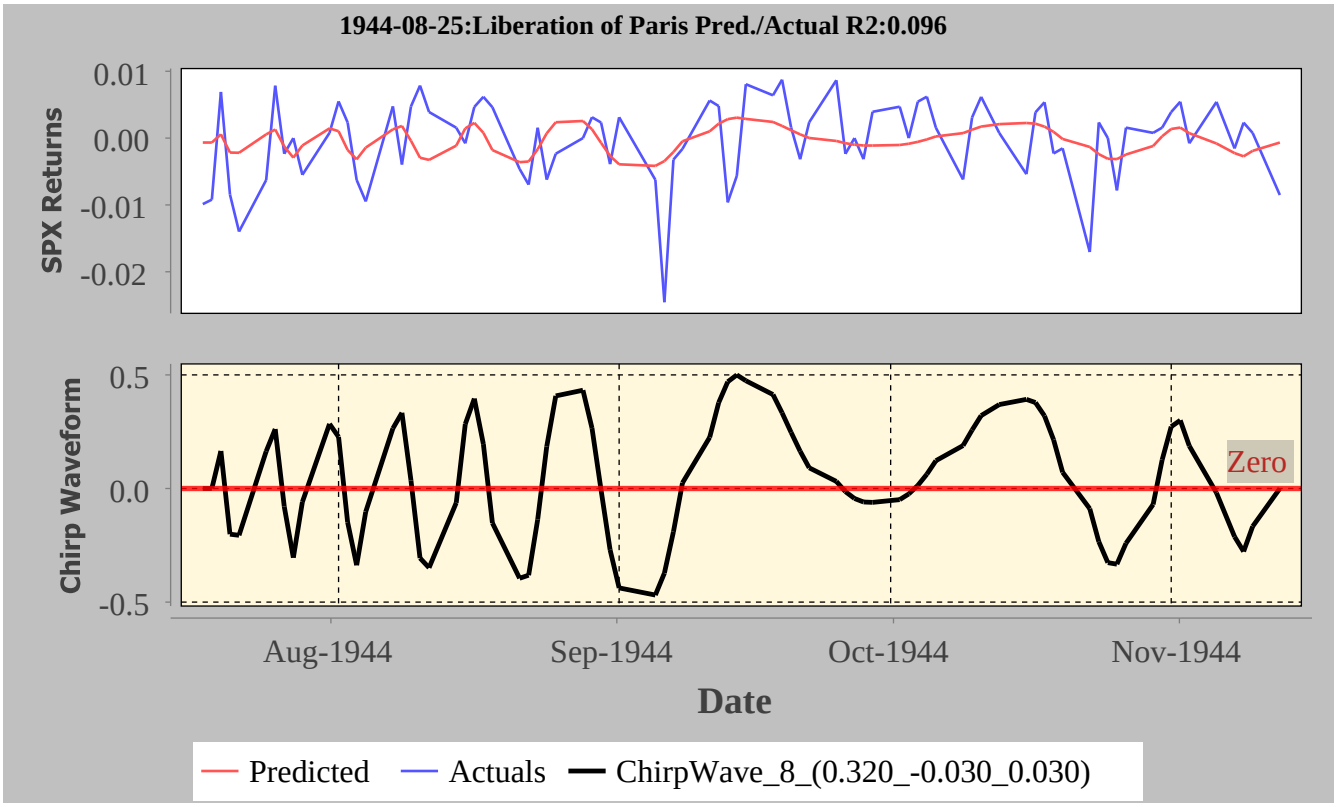

Figure (110) 1944-08-25:Liberation of Paris Pred./Actual R2:0.096 v:9.738%

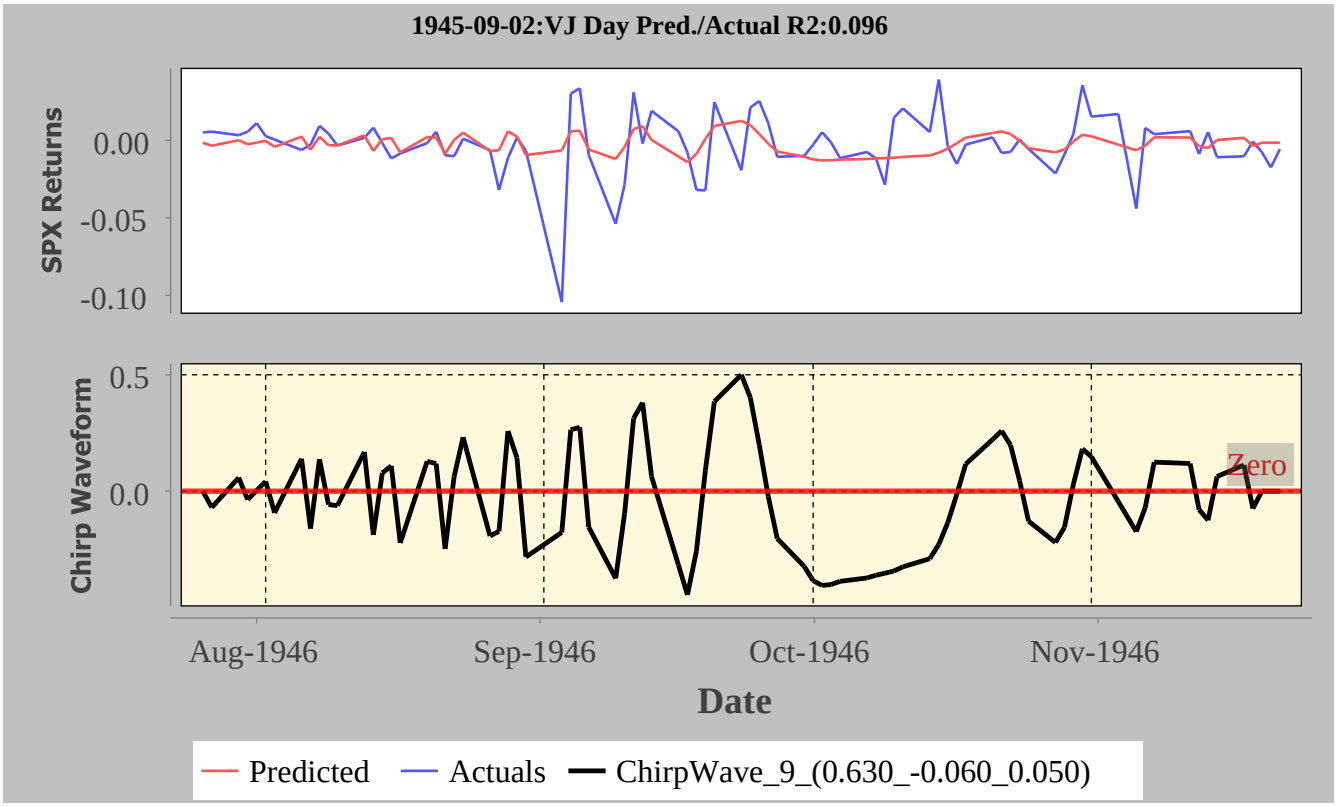

Figure (110) 1945-09-02:VJ Day Pred./Actual R2:0.096 v:31.756%

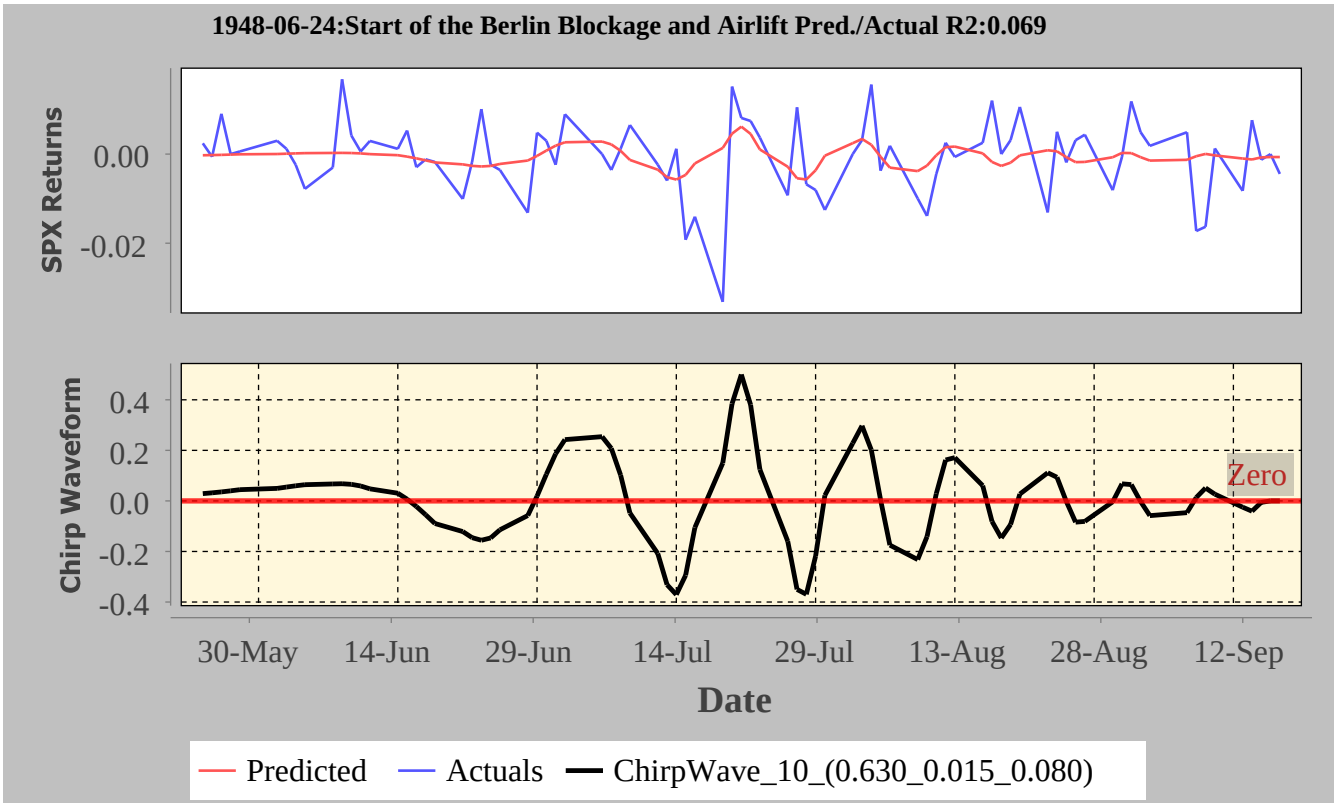

Figure (110) 1948-06-24:Start of the Berlin Blockage and Airlift Pred./Actual R2:0.069 v:13.28%

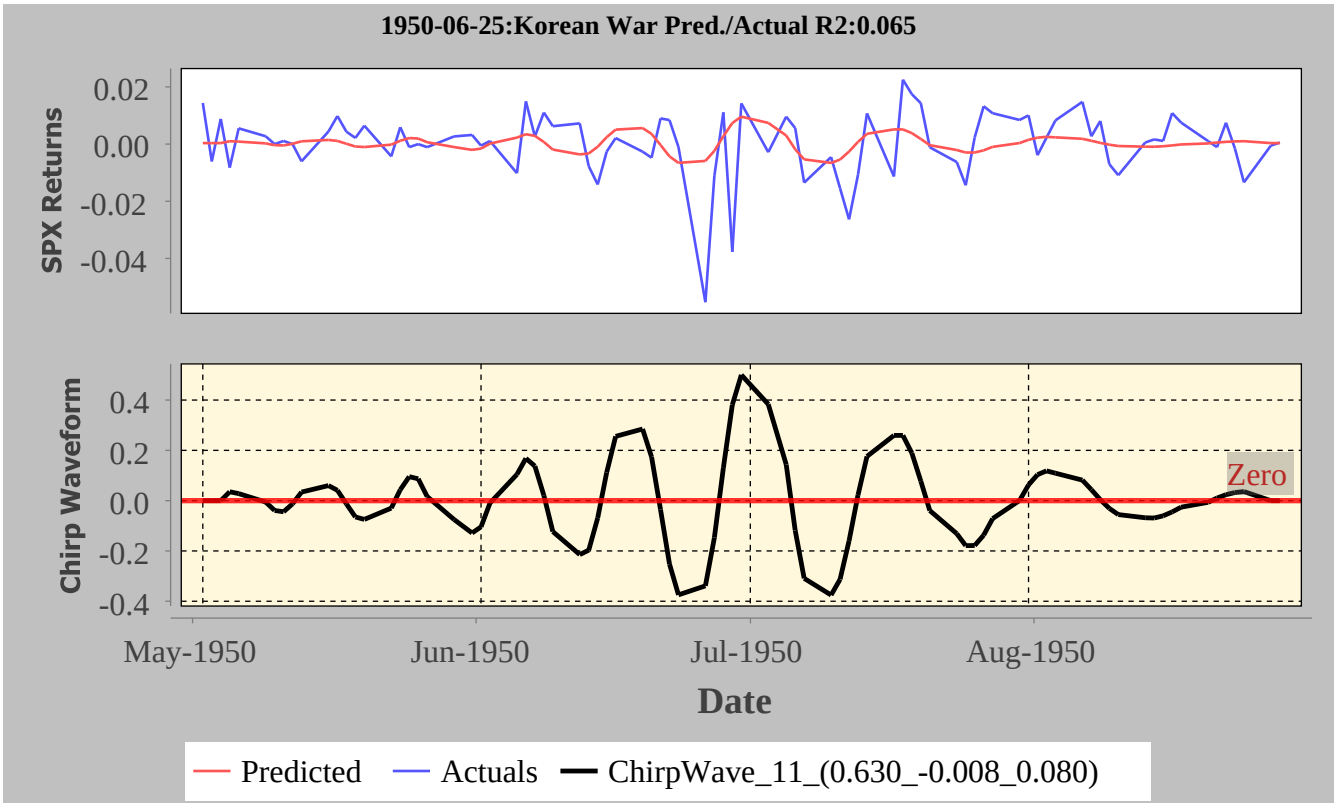

Figure (110) 1950-06-25:Korean War Pred./Actual R2:0.065 v:18.134%

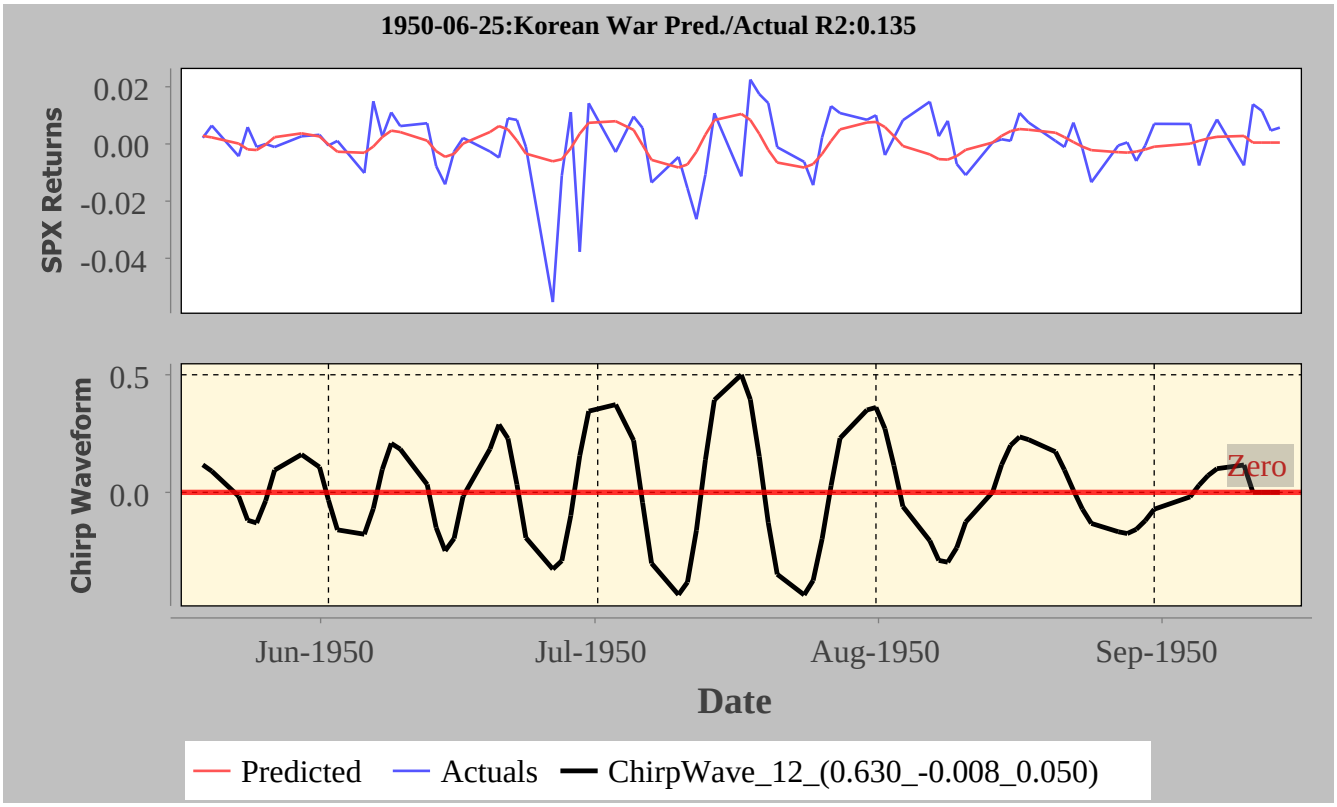

Figure (110) 1950-06-25:Korean War Pred./Actual R2:0.135 v:18.328%

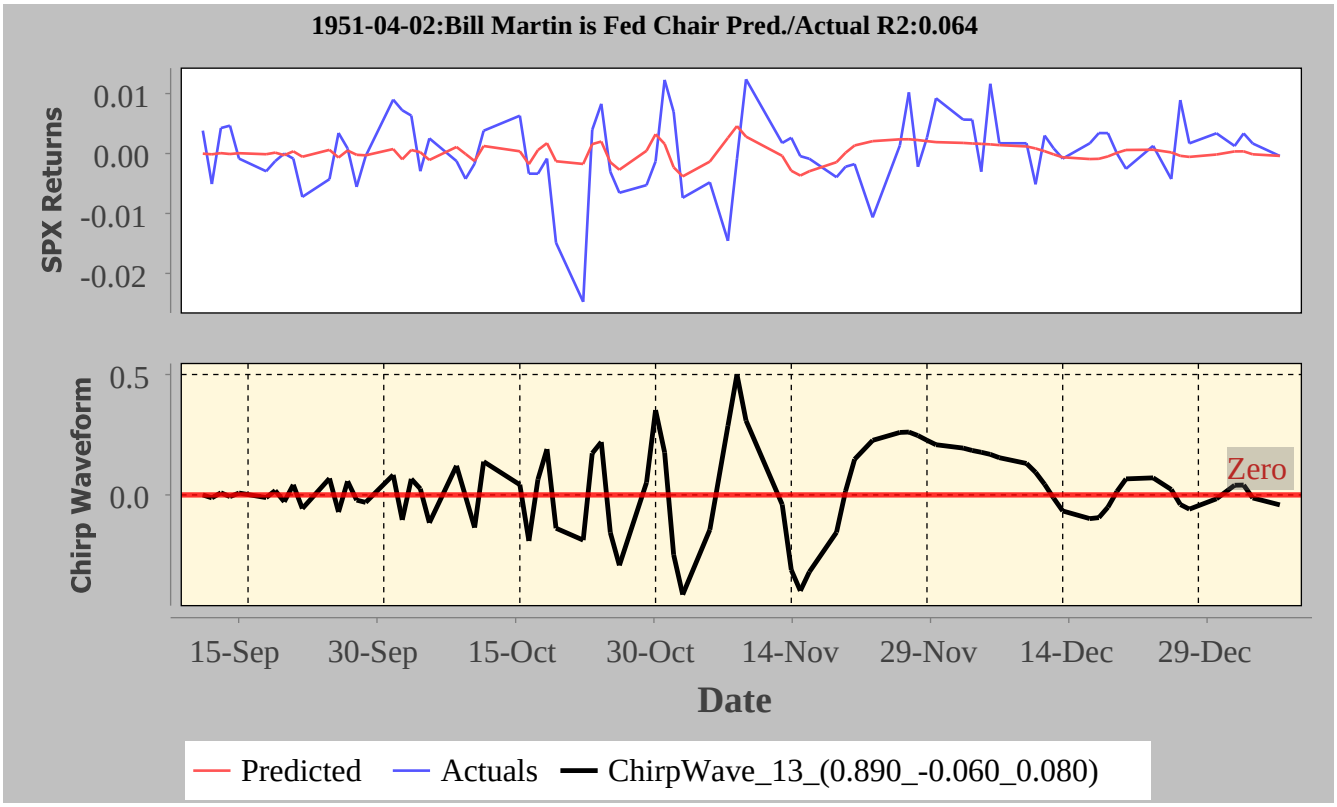

Figure (110) 1951-04-02:Bill Martin is Fed Chair Pred./Actual R2:0.064 v:9.616%

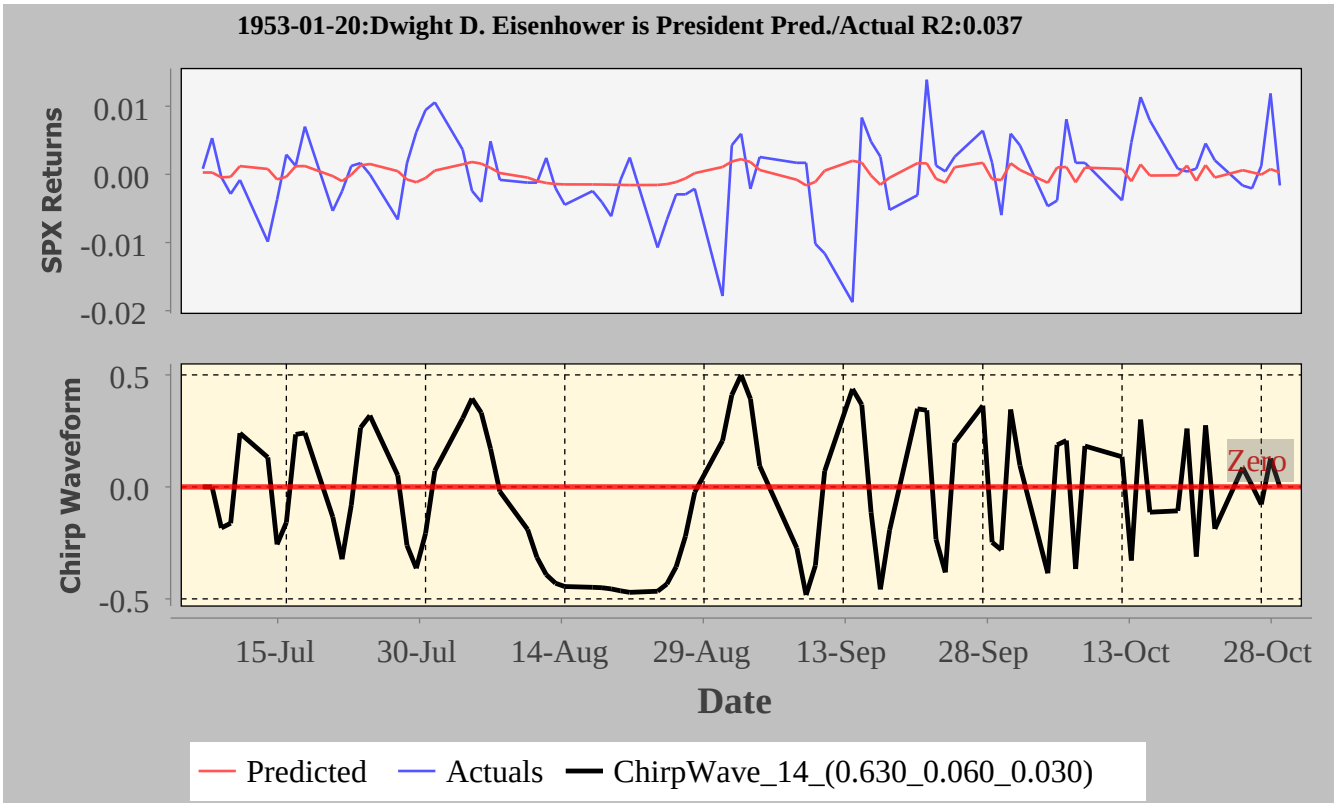

Figure (110) 1953-01-20:Dwight D. Eisenhower is President Pred./Actual R2:0.037 v:9.338%

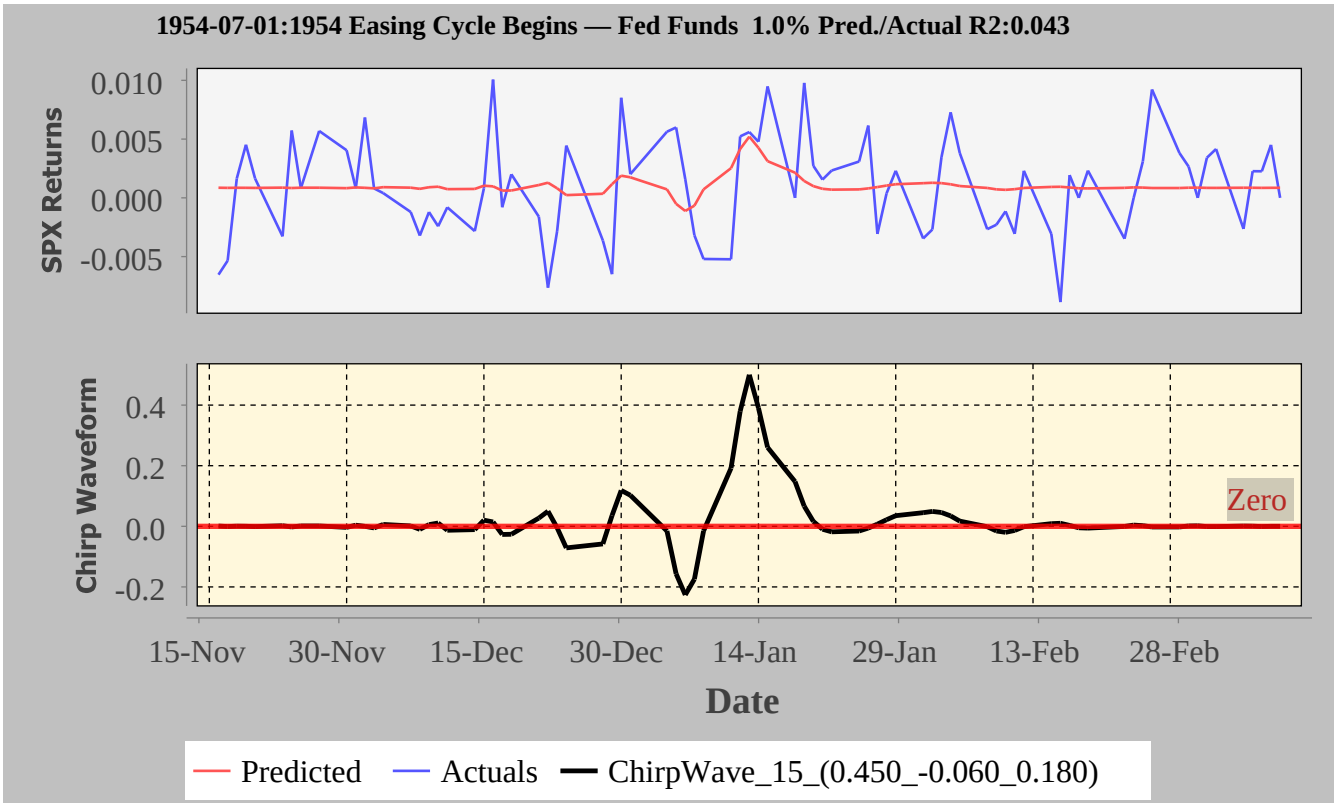

Figure (110) 1954-07-01:1954 Easing Cycle Begins — Fed Funds 1.0% Pred./Actual R2:0.043 v:6.652%

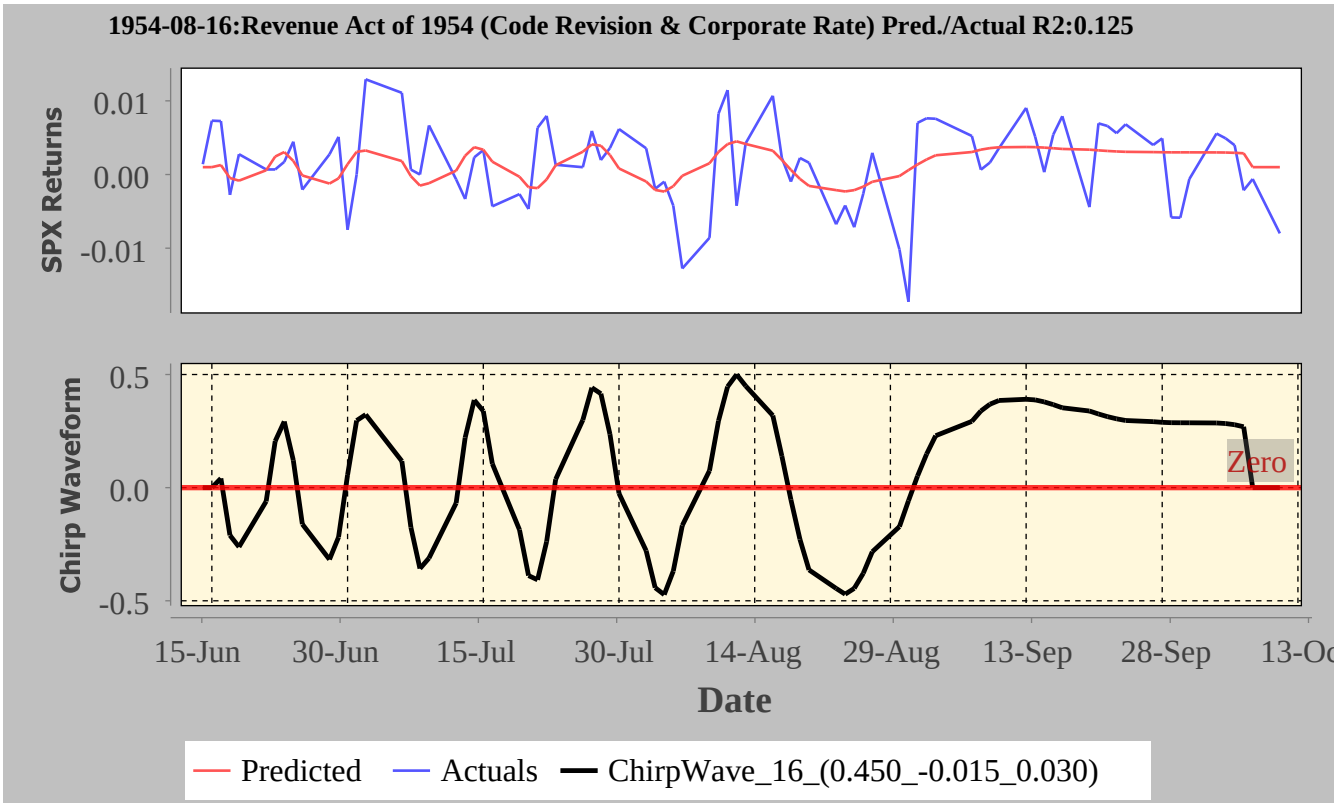

Figure (110) 1954-08-16:Revenue Act of 1954 (Code Revision & Corporate Rate) Pred./Actual R2:0.125 v:9.007%

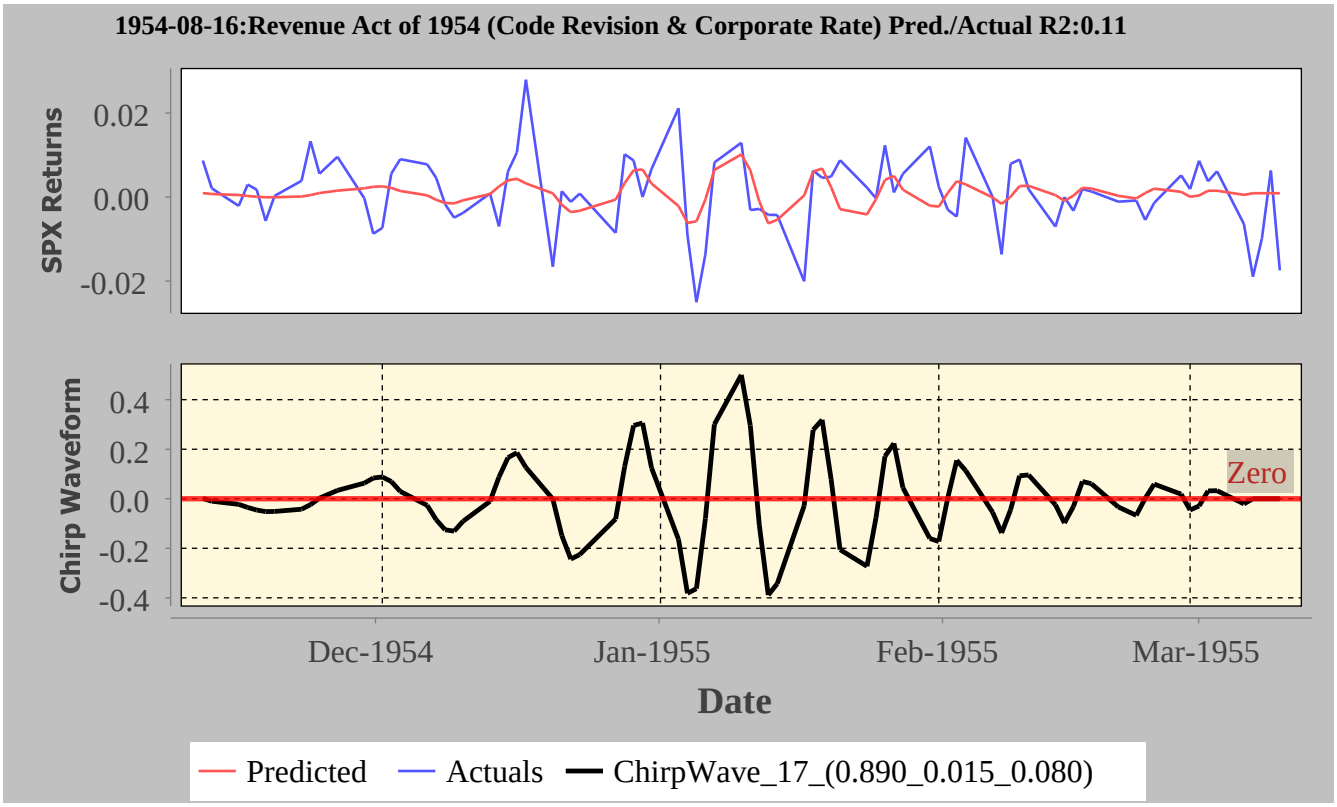

Figure (110) 1954-08-16:Revenue Act of 1954 (Code Revision & Corporate Rate) Pred./Actual R2:0.11 v:14.039%

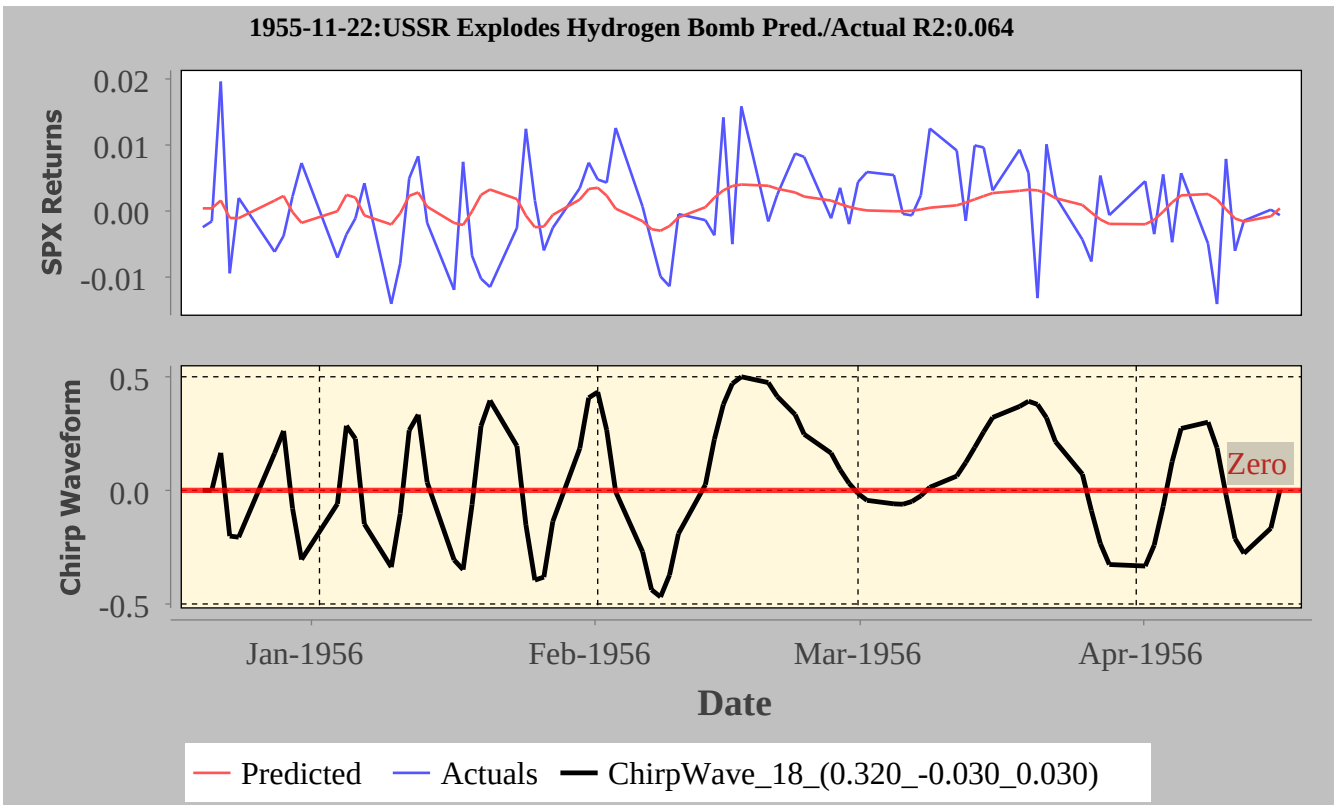

Figure (110) 1955-11-22:USSR Explodes Hydrogen Bomb Pred./Actual R2:0.064 v:11.547%

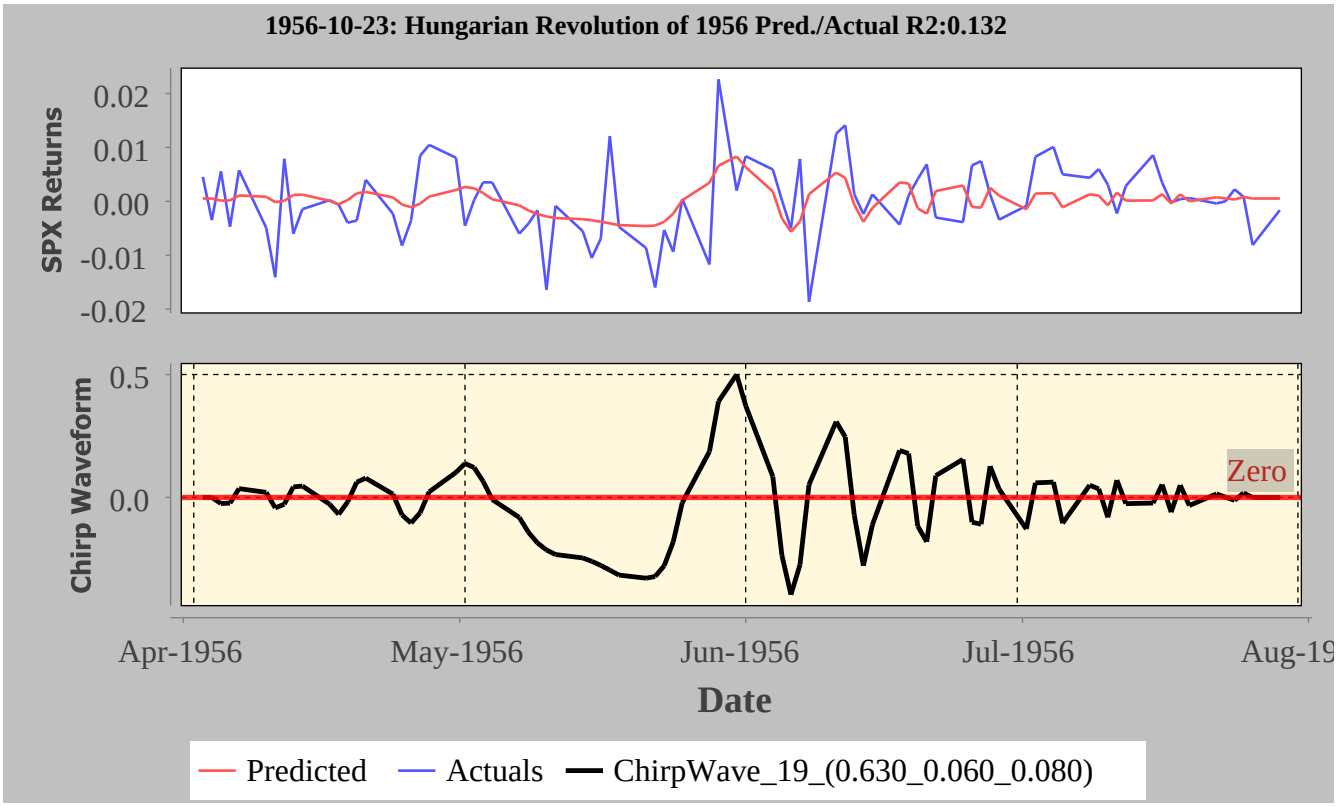

Figure (110) 1956-10-23: Hungarian Revolution of 1956 Pred./Actual R2:0.132 v:11.306%

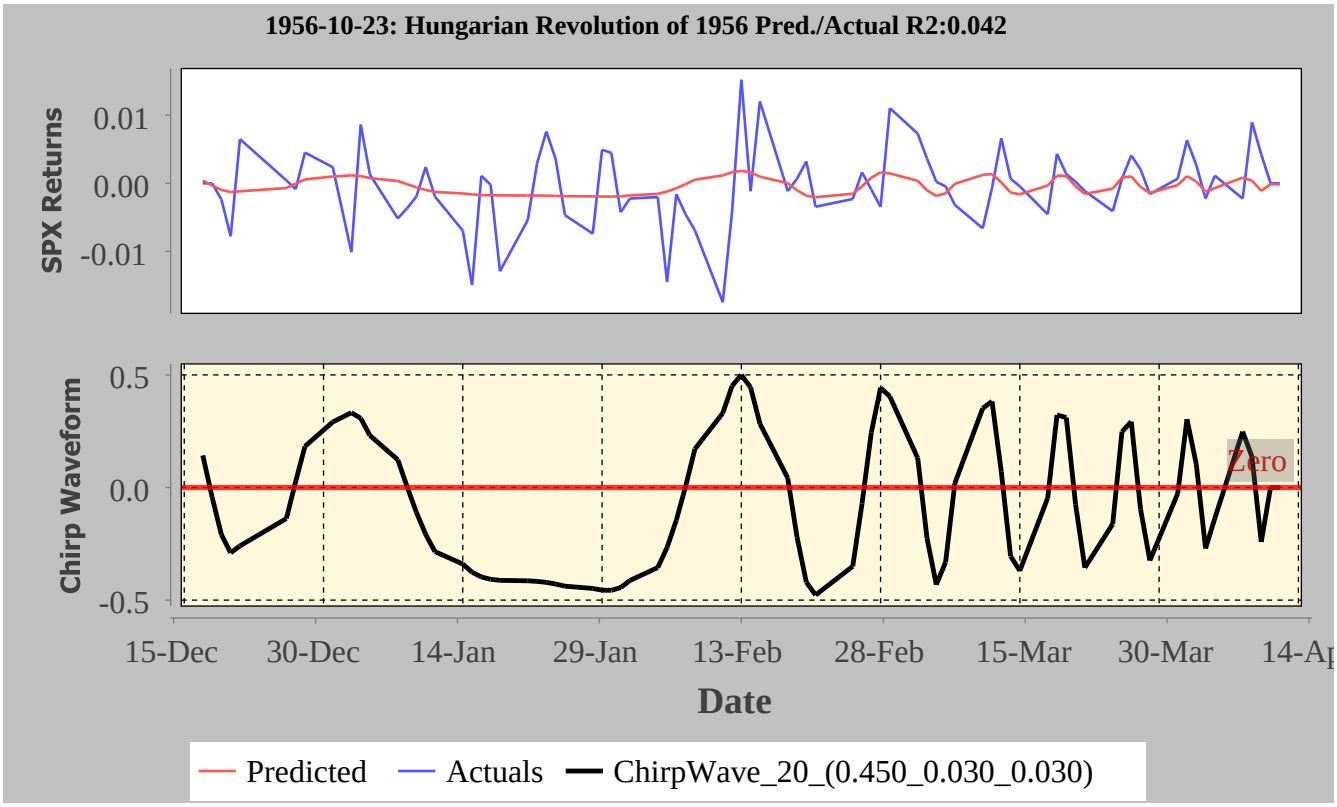

Figure (110) 1956-10-23: Hungarian Revolution of 1956 Pred./Actual R2:0.042 v:9.052%

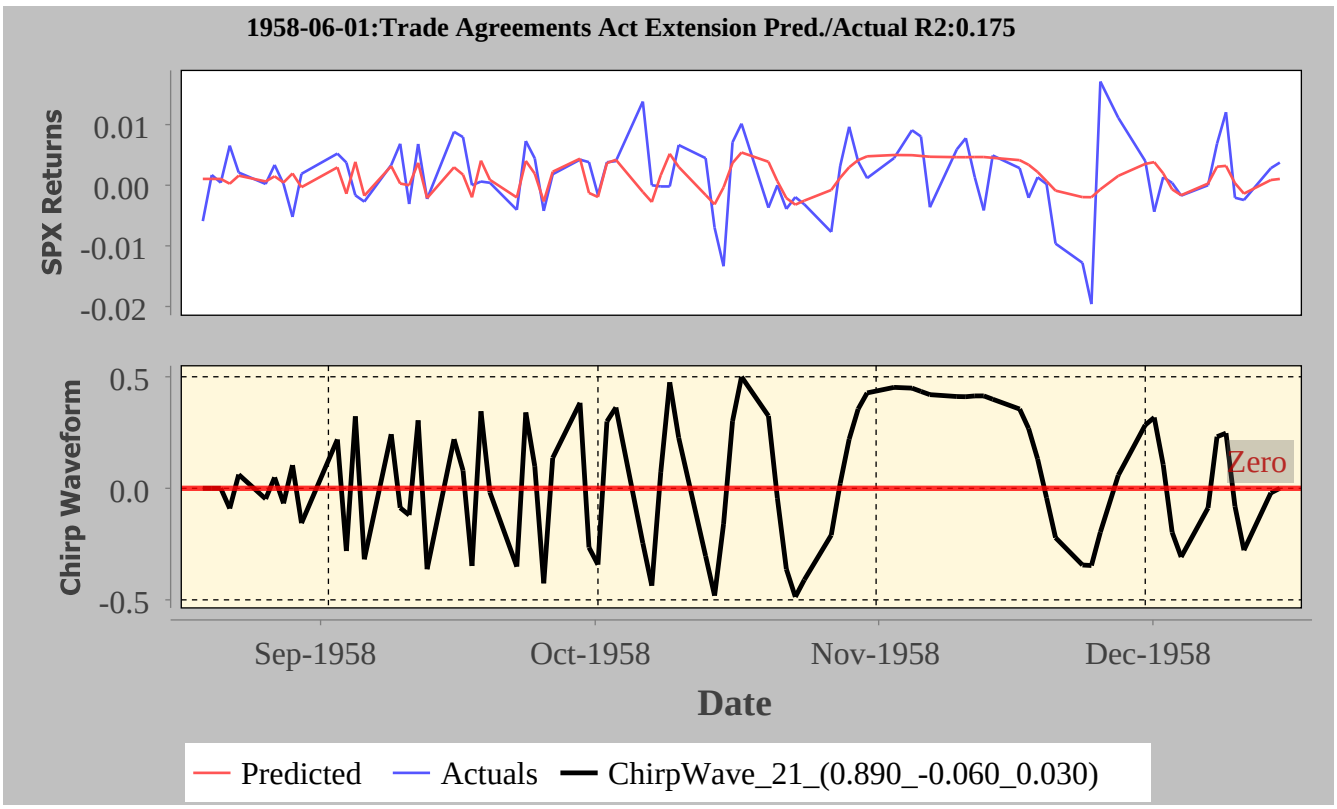

Figure (110) 1958-06-01:Trade Agreements Act Extension Pred./Actual R2:0.175 v:9.468%

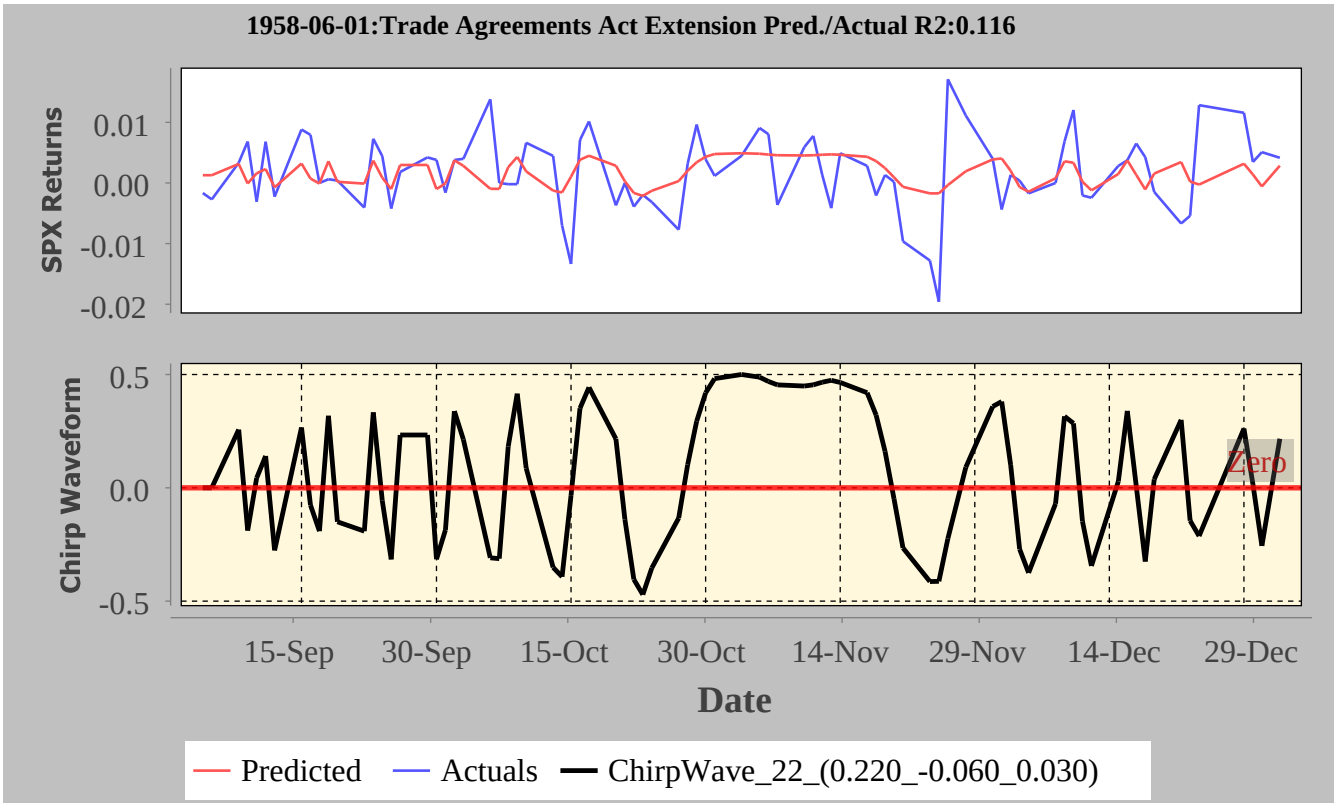

Figure (110) 1958-06-01:Trade Agreements Act Extension Pred./Actual R2:0.116 v:9.987%

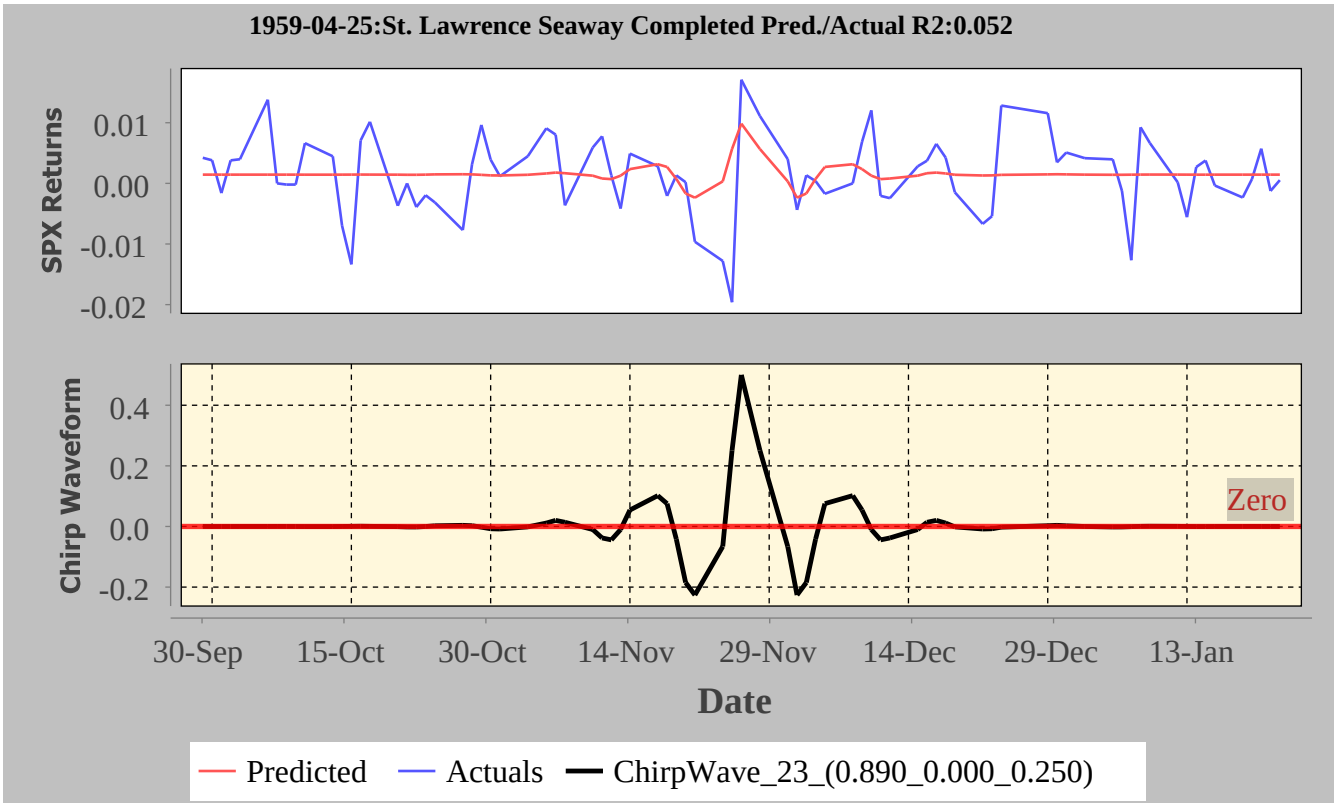

Figure (110) 1959-04-25:St. Lawrence Seaway Completed Pred./Actual R2:0.052 v:10.239%

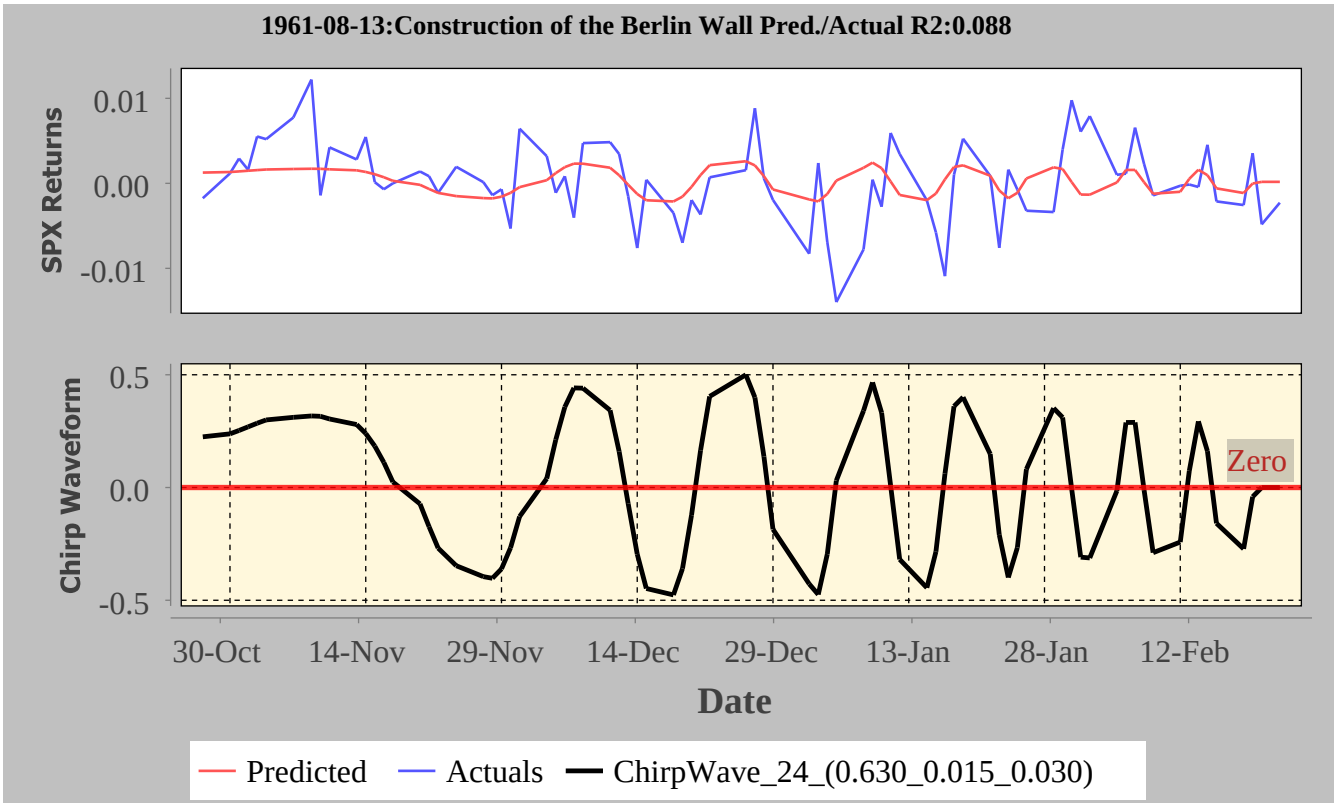

Figure (110) 1961-08-13:Construction of the Berlin Wall Pred./Actual R2:0.088 v:7.445%

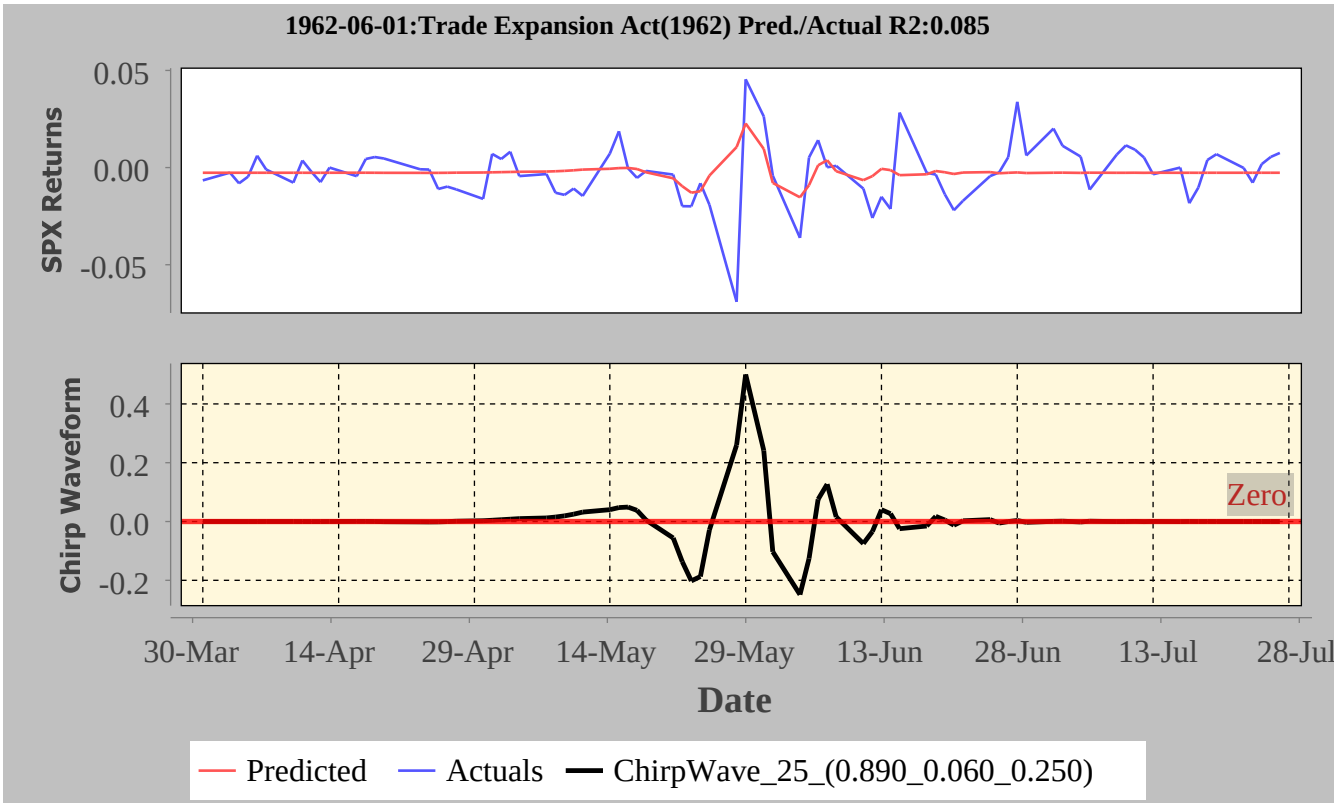

Figure (110) 1962-06-01:Trade Expansion Act(1962) Pred./Actual R2:0.085 v:23.692%

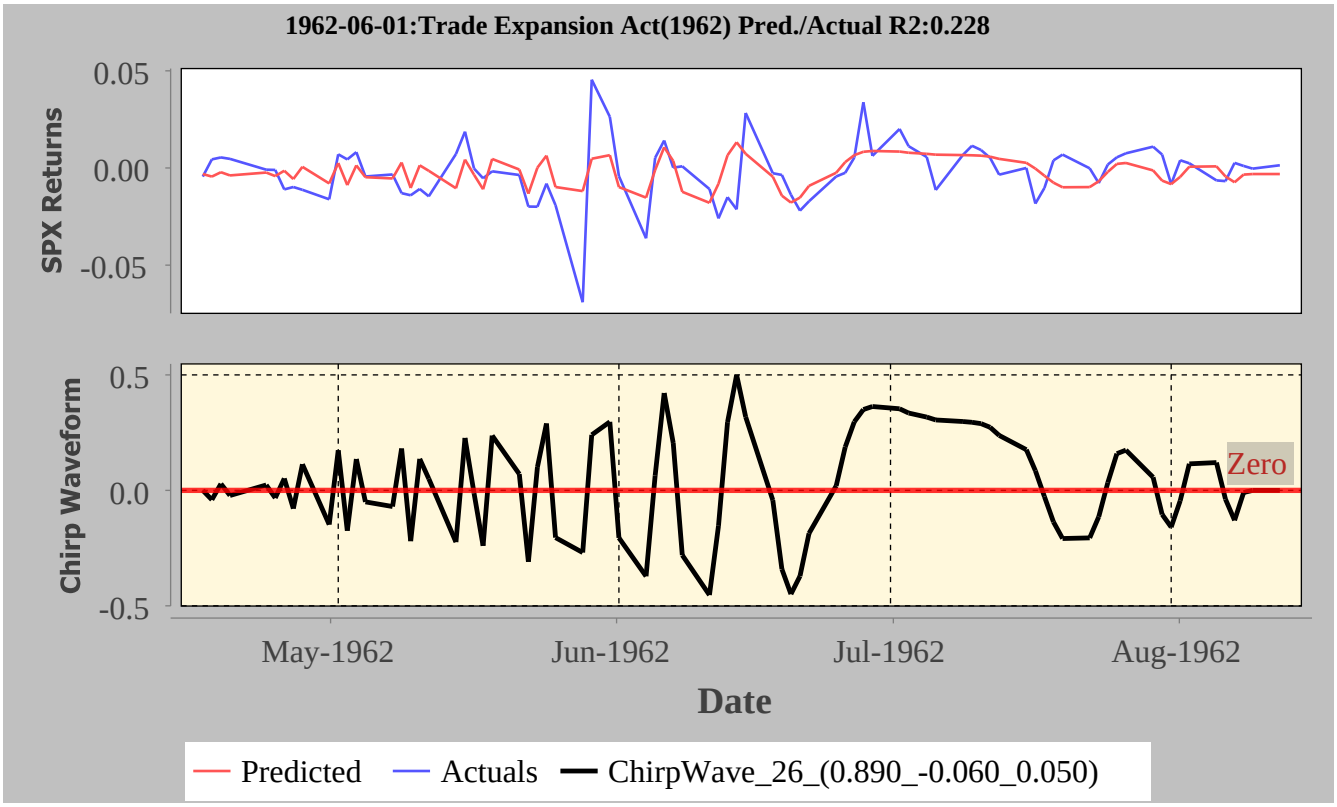

Figure (110) 1962-06-01:Trade Expansion Act(1962) Pred./Actual R2:0.228 v:23.829%

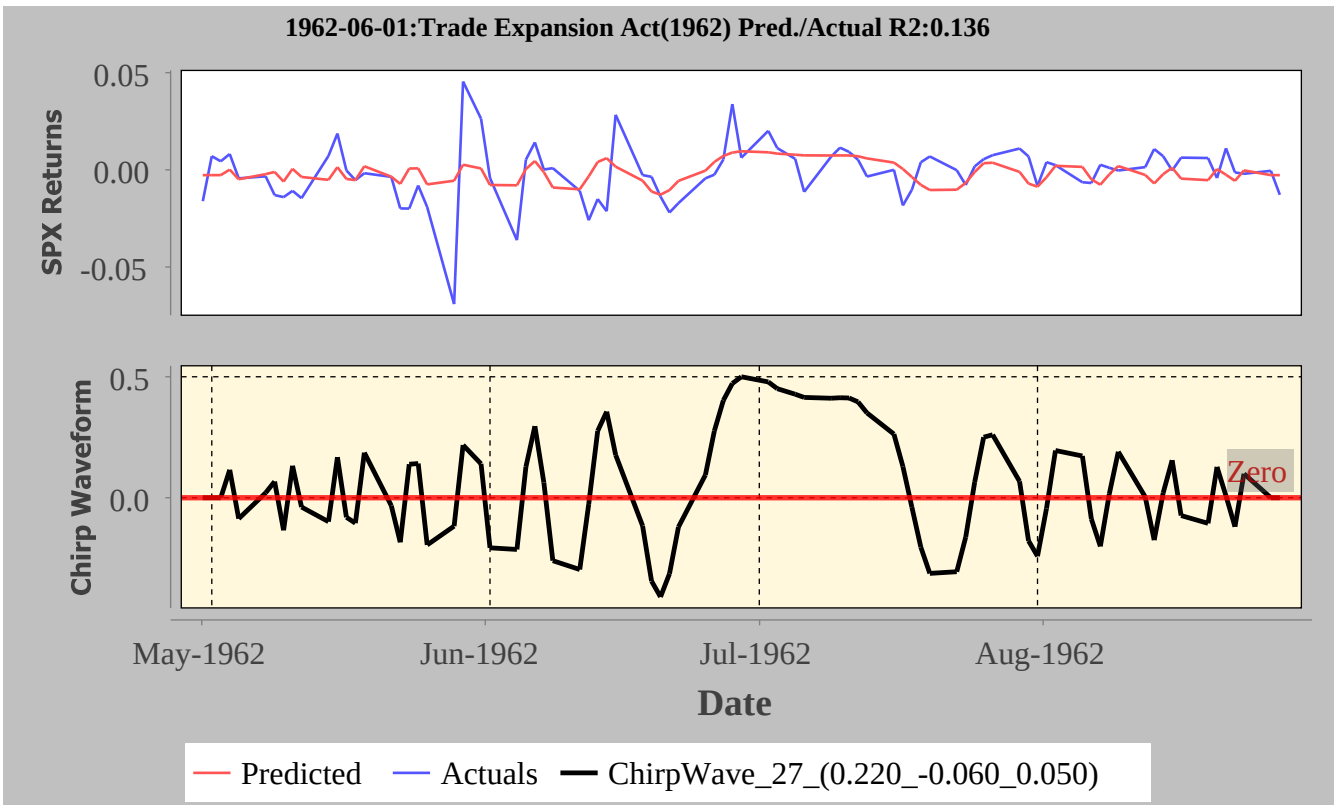

Figure (110) 1962-06-01:Trade Expansion Act(1962) Pred./Actual R2:0.136 v:23.715%

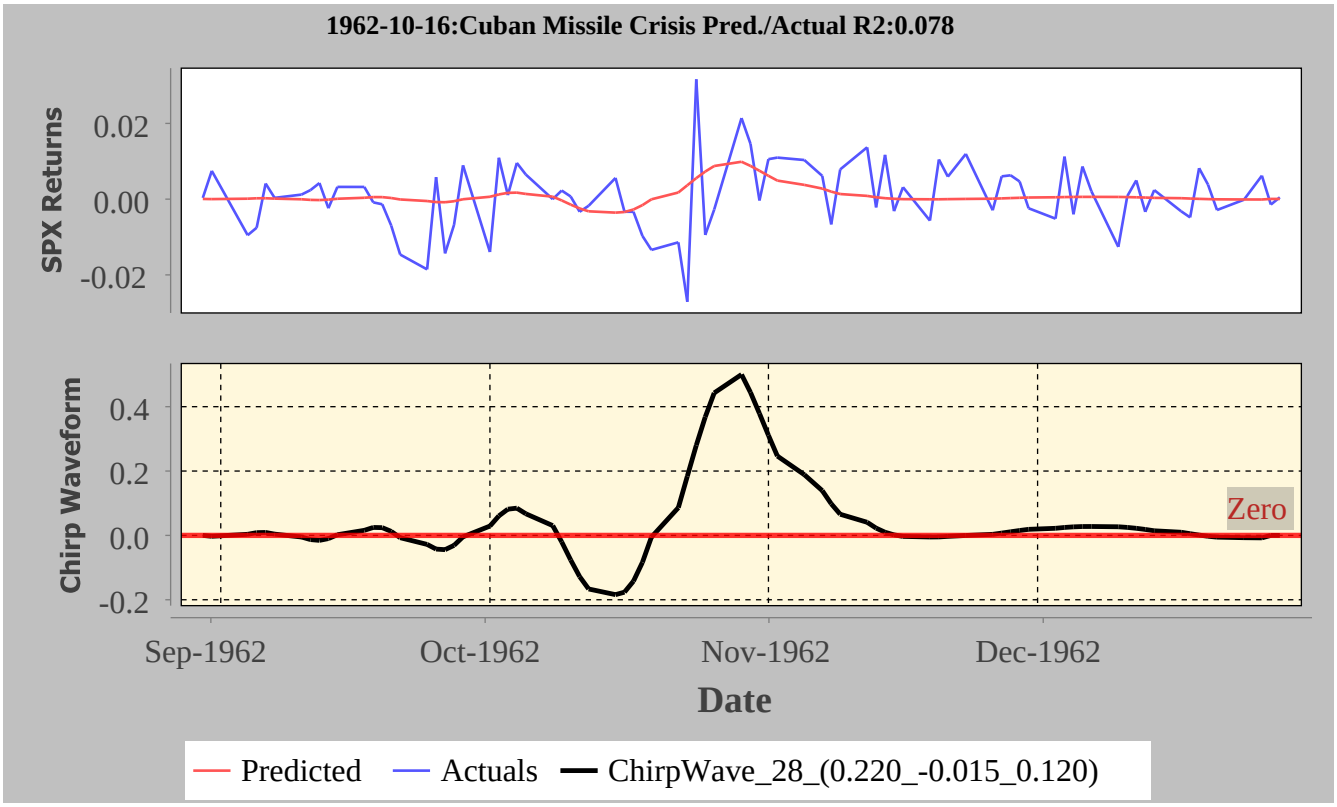

Figure (110) 1962-10-16:Cuban Missile Crisis Pred./Actual R2:0.078 v:14.127%

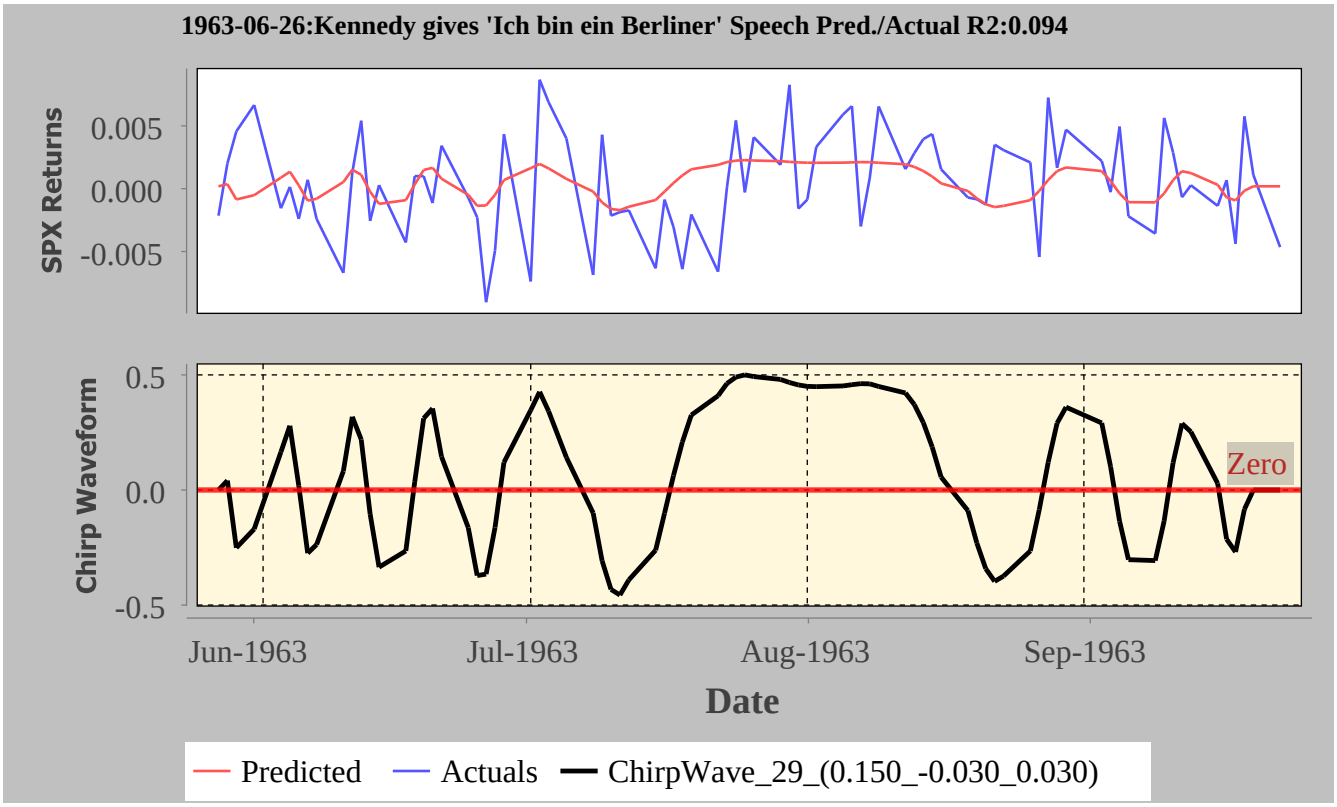

Figure (110) 1963-06-26:Kennedy gives 'Ich bin ein Berliner' Speech Pred./Actual R2:0.094 v:6.403%

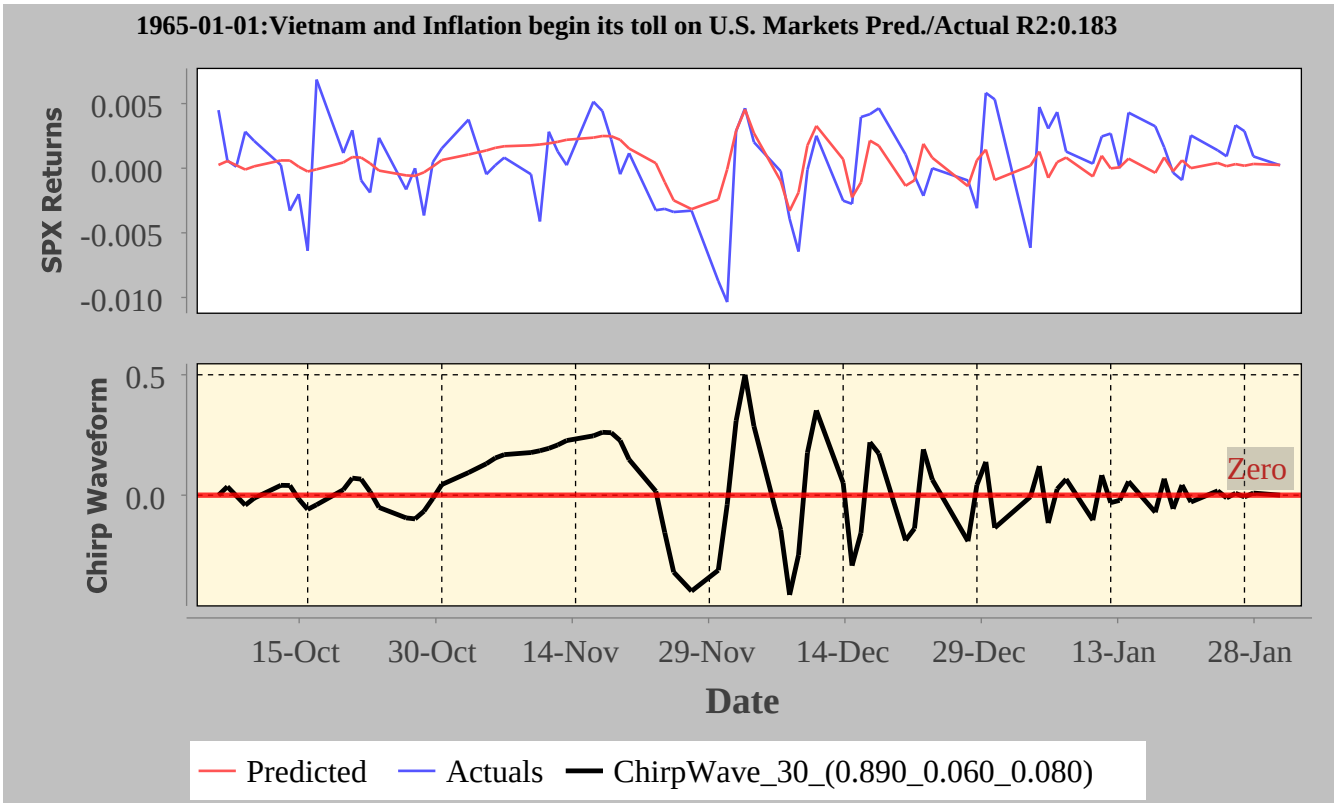

Figure (110) 1965-01-01:Vietnam and Inflation begin its toll on U.S. Markets Pred./Actual R2:0.183 v:5.257%

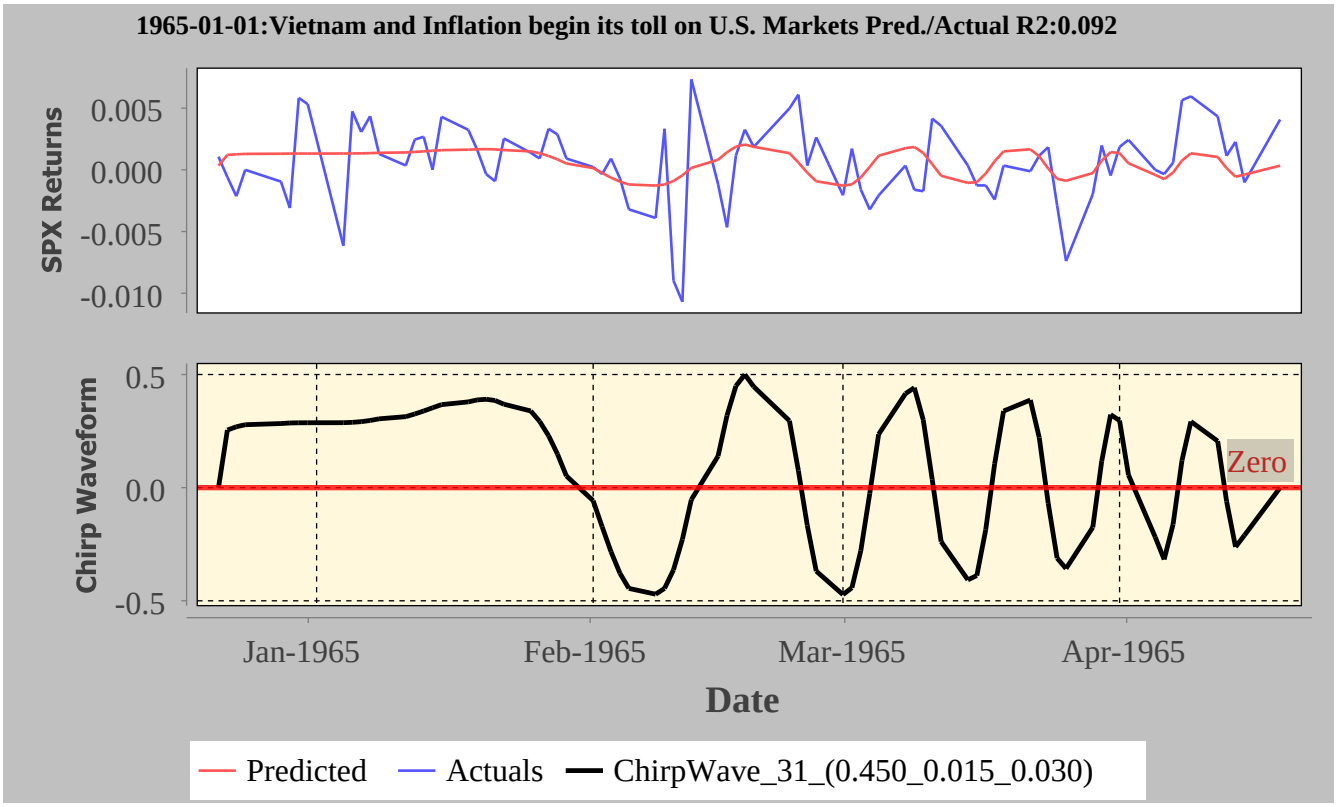

Figure (110) 1965-01-01:Vietnam and Inflation begin its toll on U.S. Markets Pred./Actual R2:0.092 v:5.217%

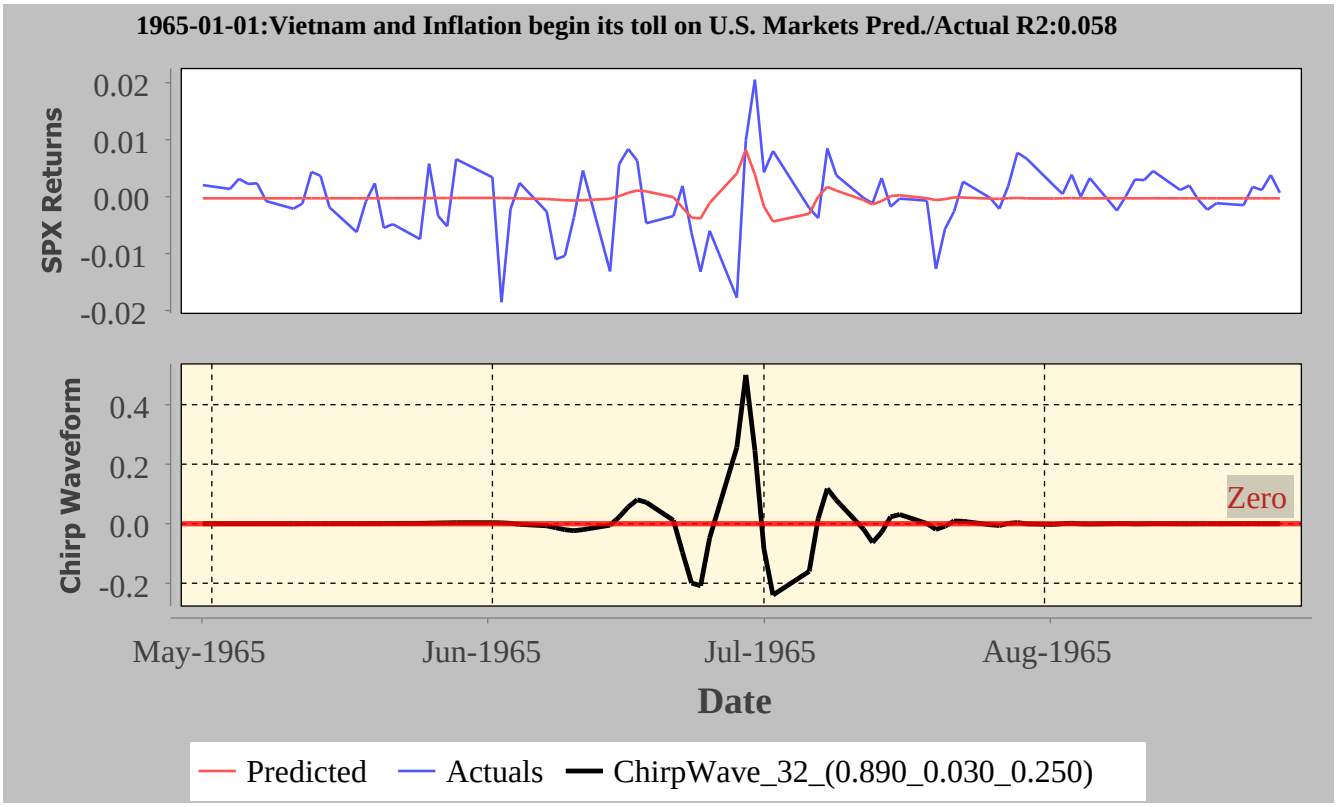

Figure (110) 1965-01-01:Vietnam and Inflation begin its toll on U.S. Markets Pred./Actual R2:0.058 v:9.6%

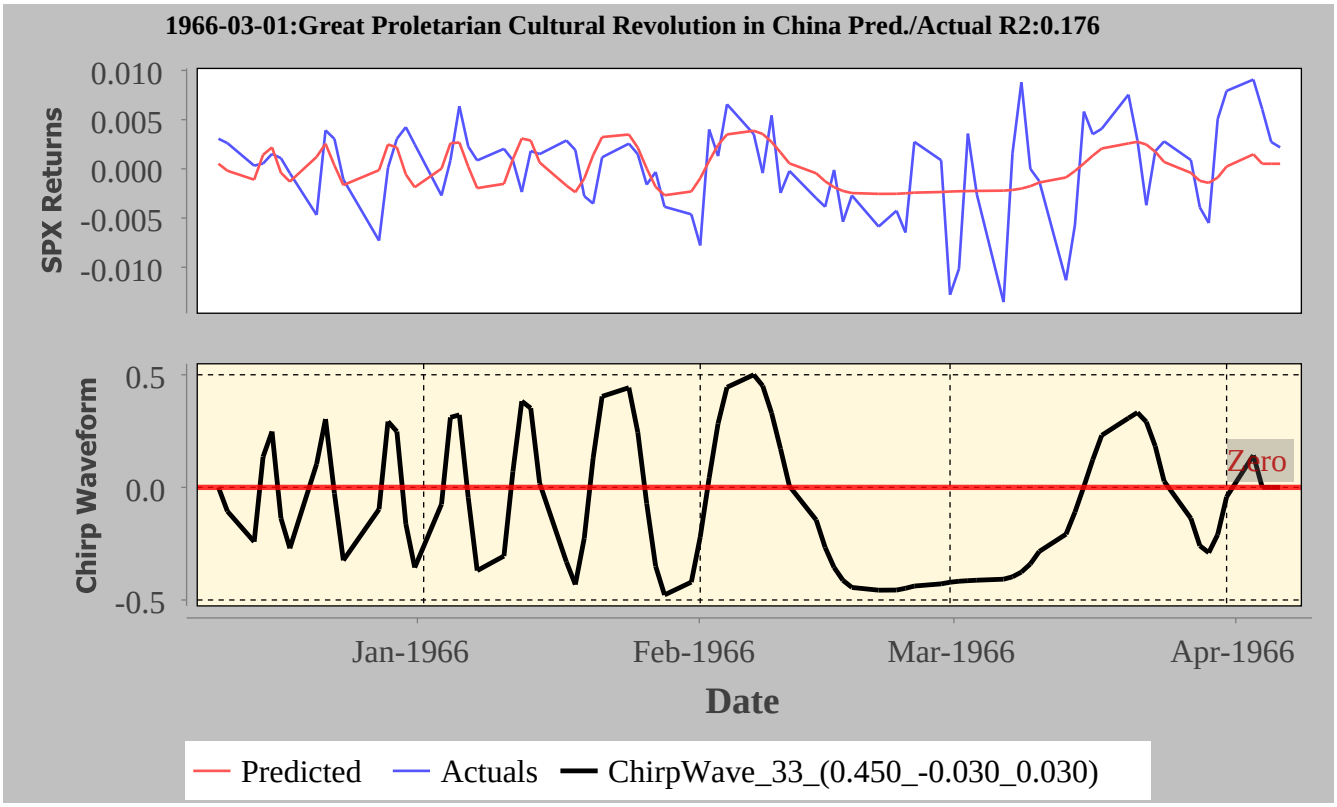

Figure (110) 1966-03-01:Great Proletarian Cultural Revolution in China Pred./Actual R2:0.176 v:7.329%

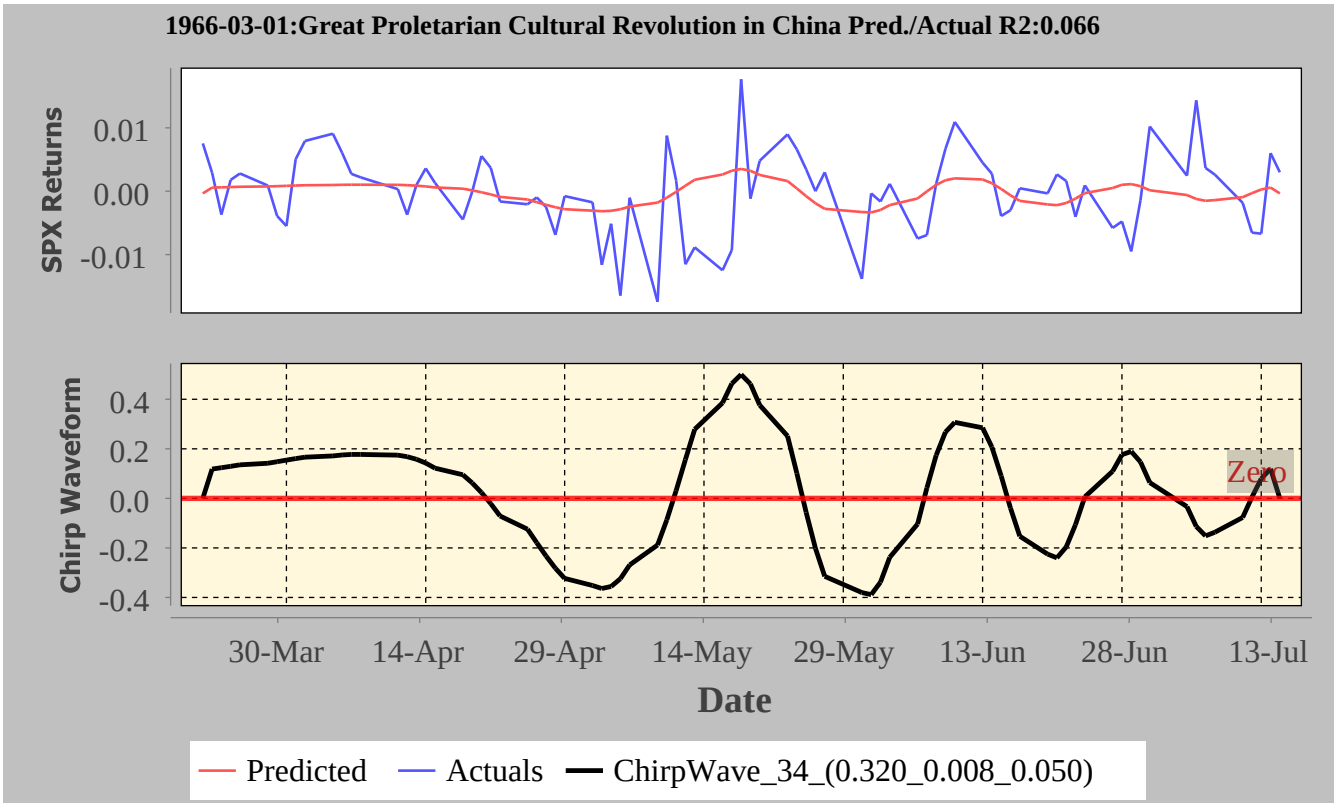

Figure (110) 1966-03-01:Great Proletarian Cultural Revolution in China Pred./Actual R2:0.066 v:10.33%

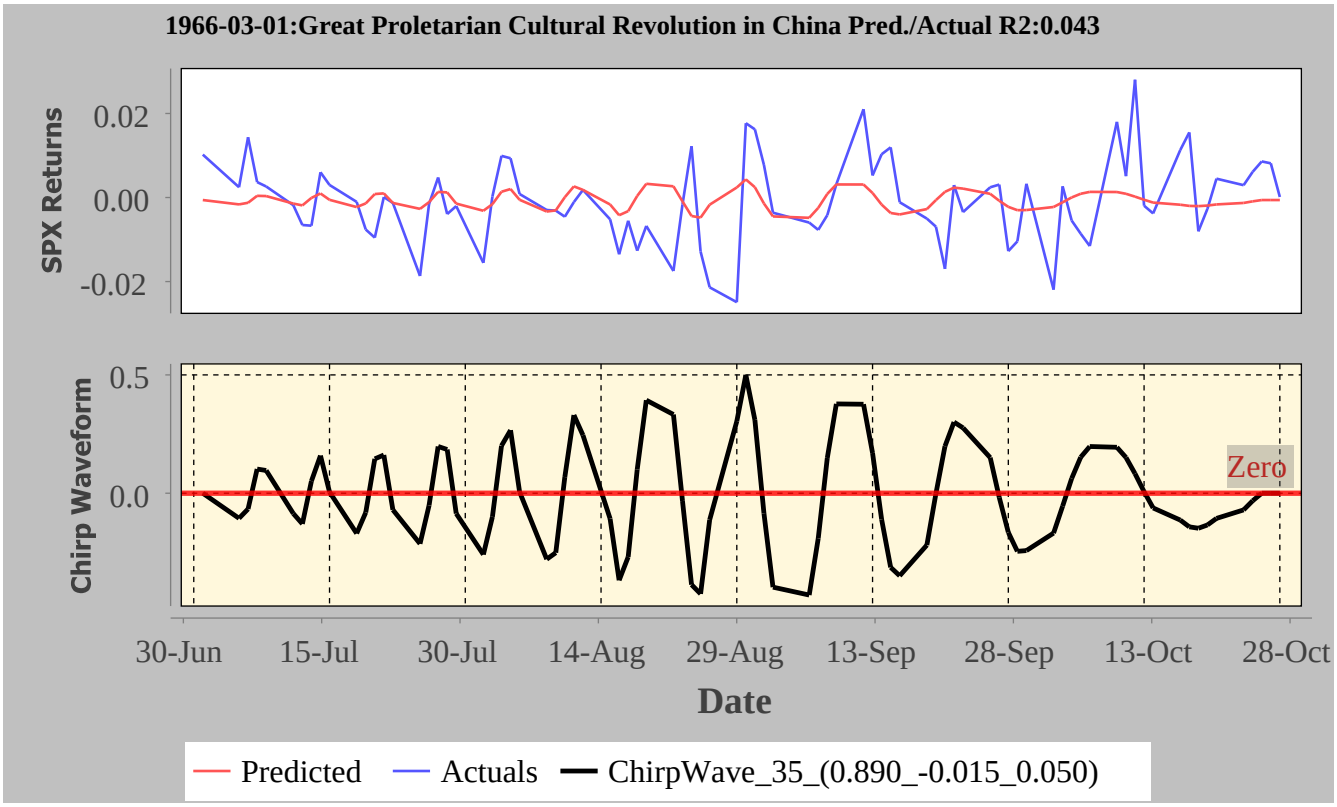

Figure (110) 1966-03-01:Great Proletarian Cultural Revolution in China Pred./Actual R2:0.043 v:15.868%

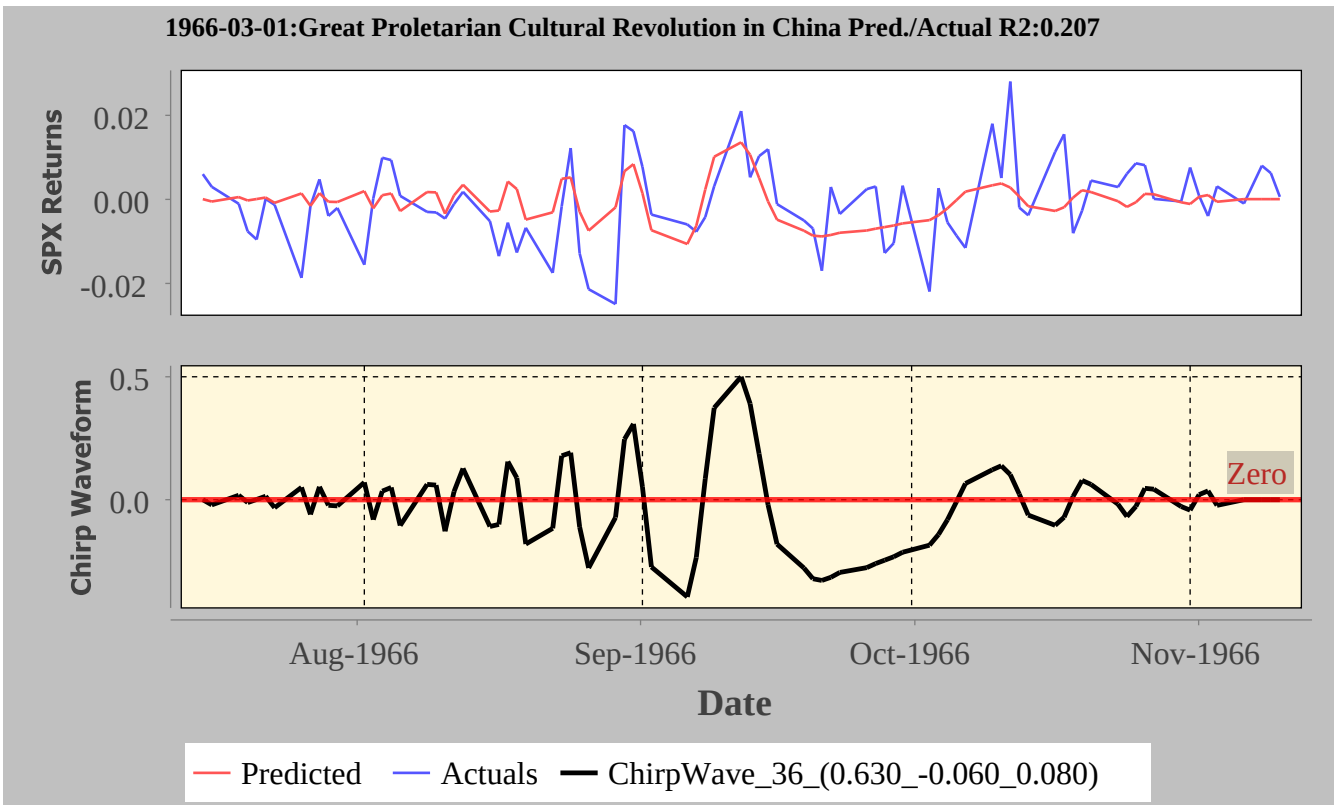

Figure (110) 1966-03-01:Great Proletarian Cultural Revolution in China Pred./Actual R2:0.207 v:15.548%

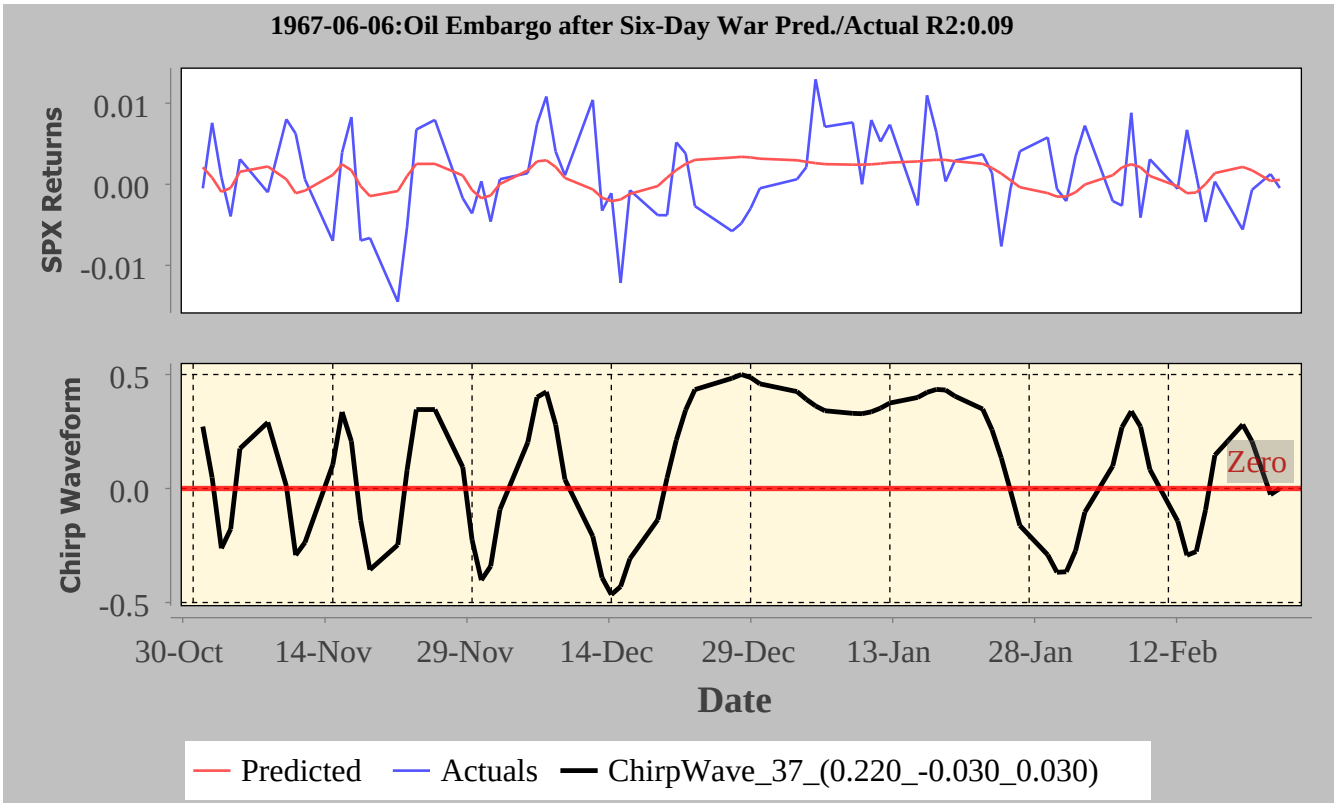

Figure (110) 1967-06-06:Oil Embargo after Six-Day War Pred./Actual R2:0.09 v:8.612%

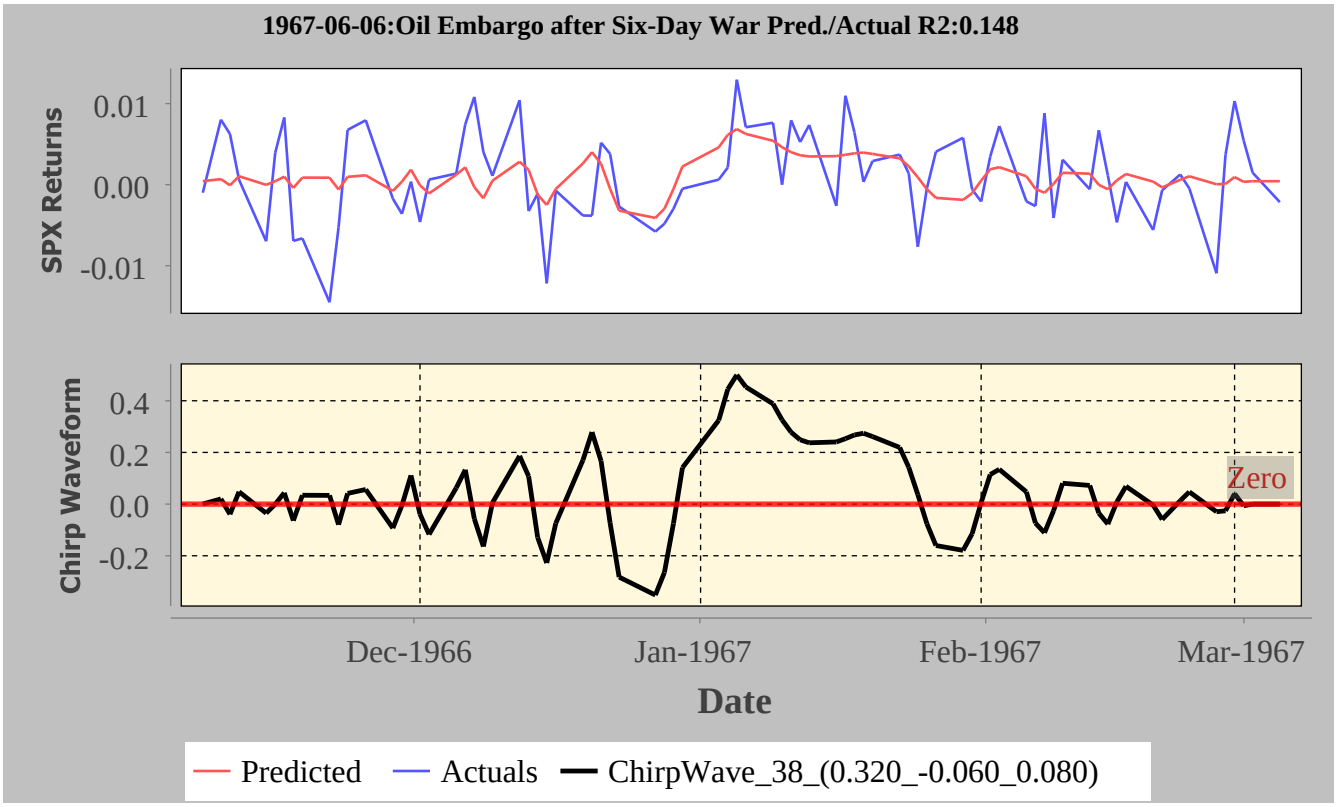

Figure (110) 1967-06-06:Oil Embargo after Six-Day War Pred./Actual R2:0.148 v:8.904%

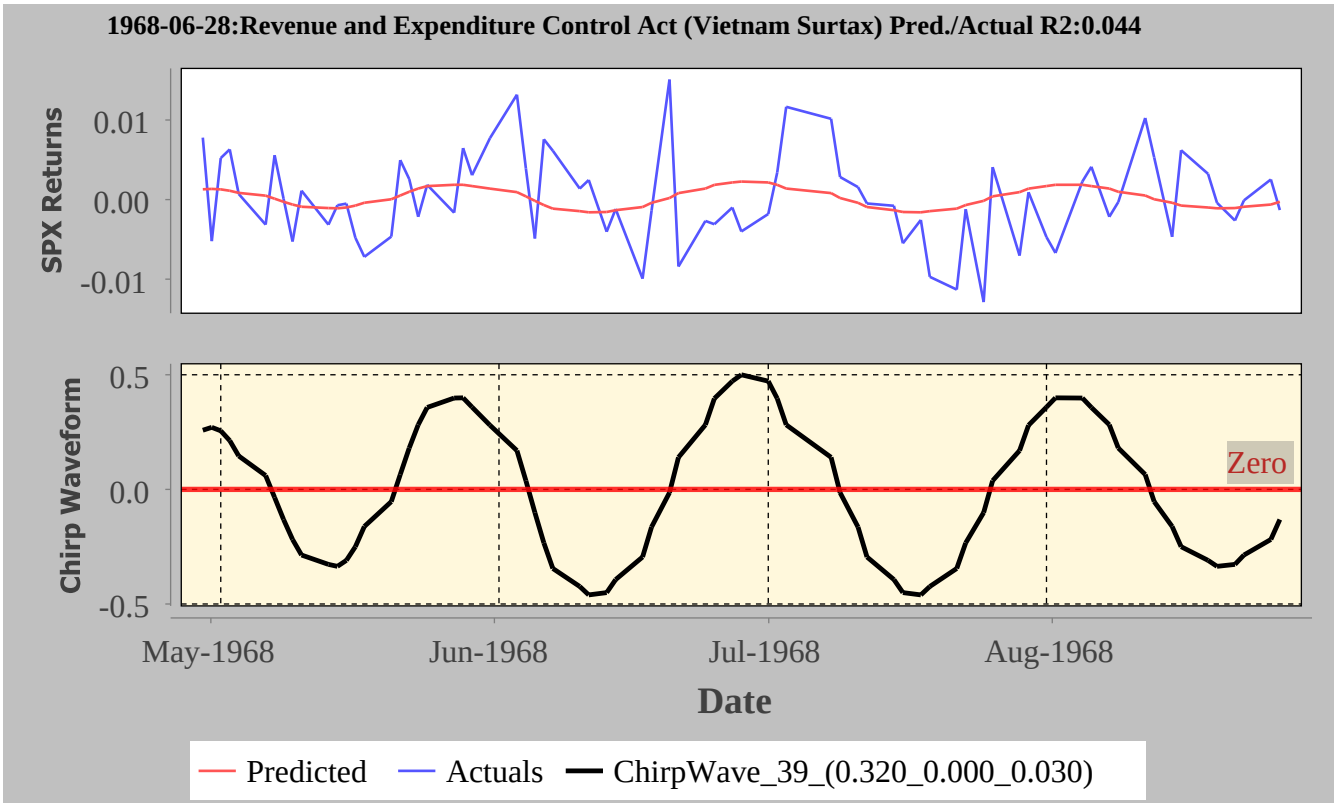

Figure (110) 1968-06-28:Revenue and Expenditure Control Act (Vietnam Surtax) Pred./Actual R2:0.044 v:8.952%

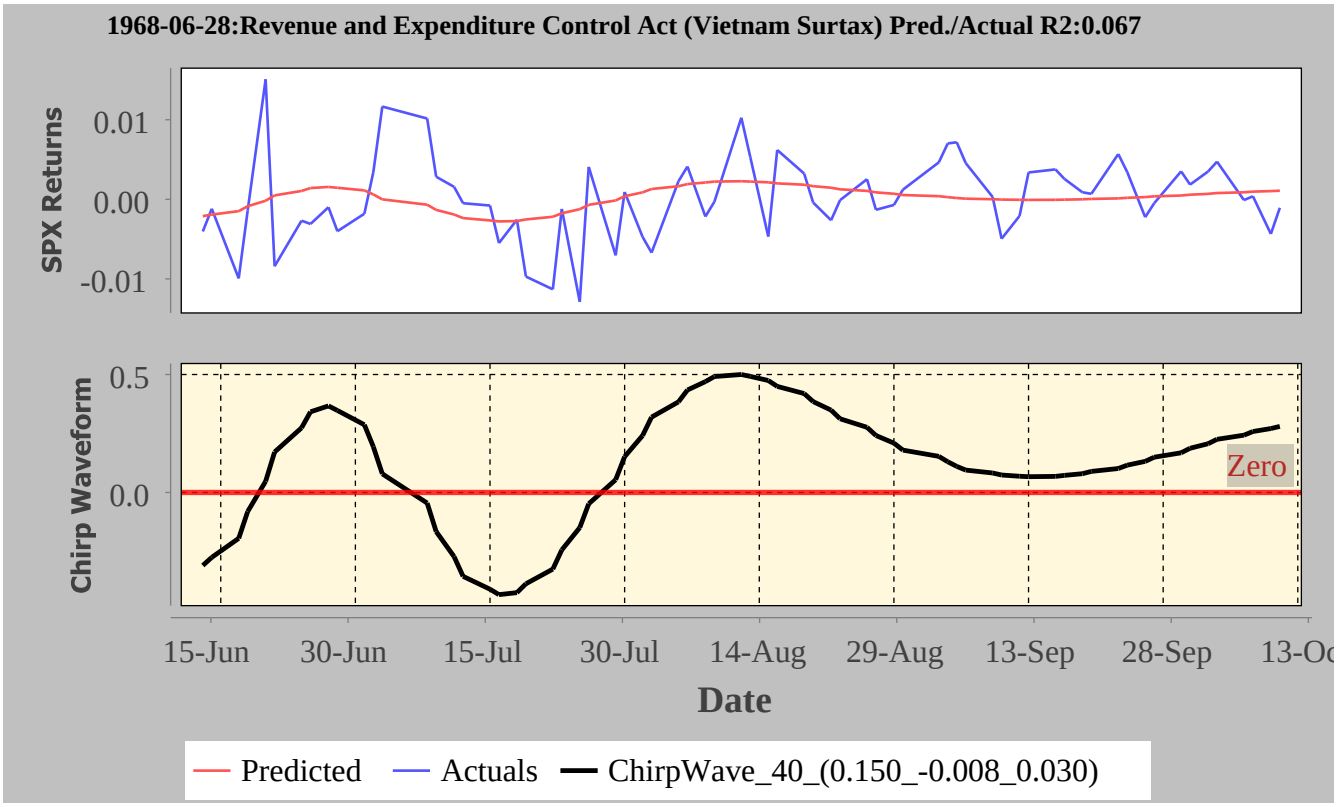

Figure (110) 1968-06-28:Revenue and Expenditure Control Act (Vietnam Surtax) Pred./Actual R2:0.067 v:8.273%

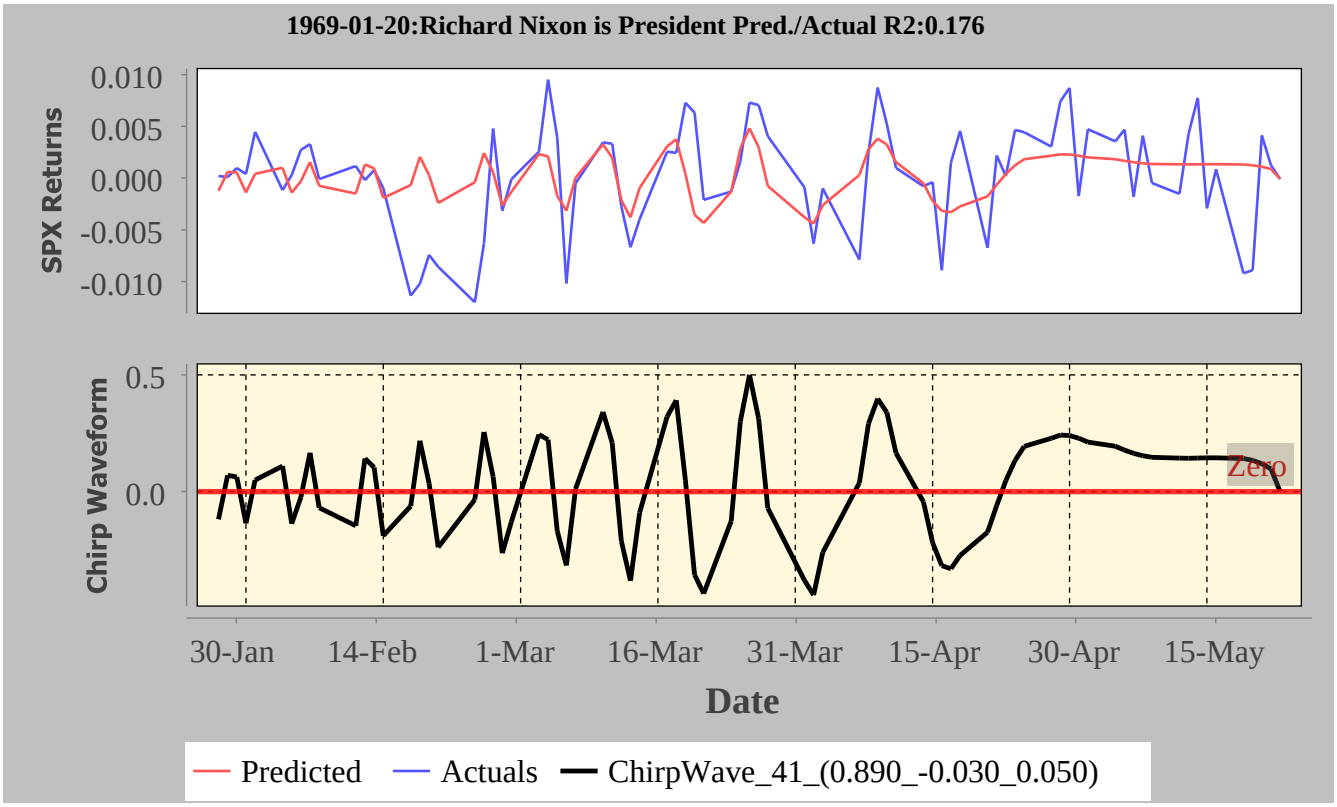

Figure (110) 1969-01-20:Richard Nixon is President Pred./Actual R2:0.176 v:8.055%

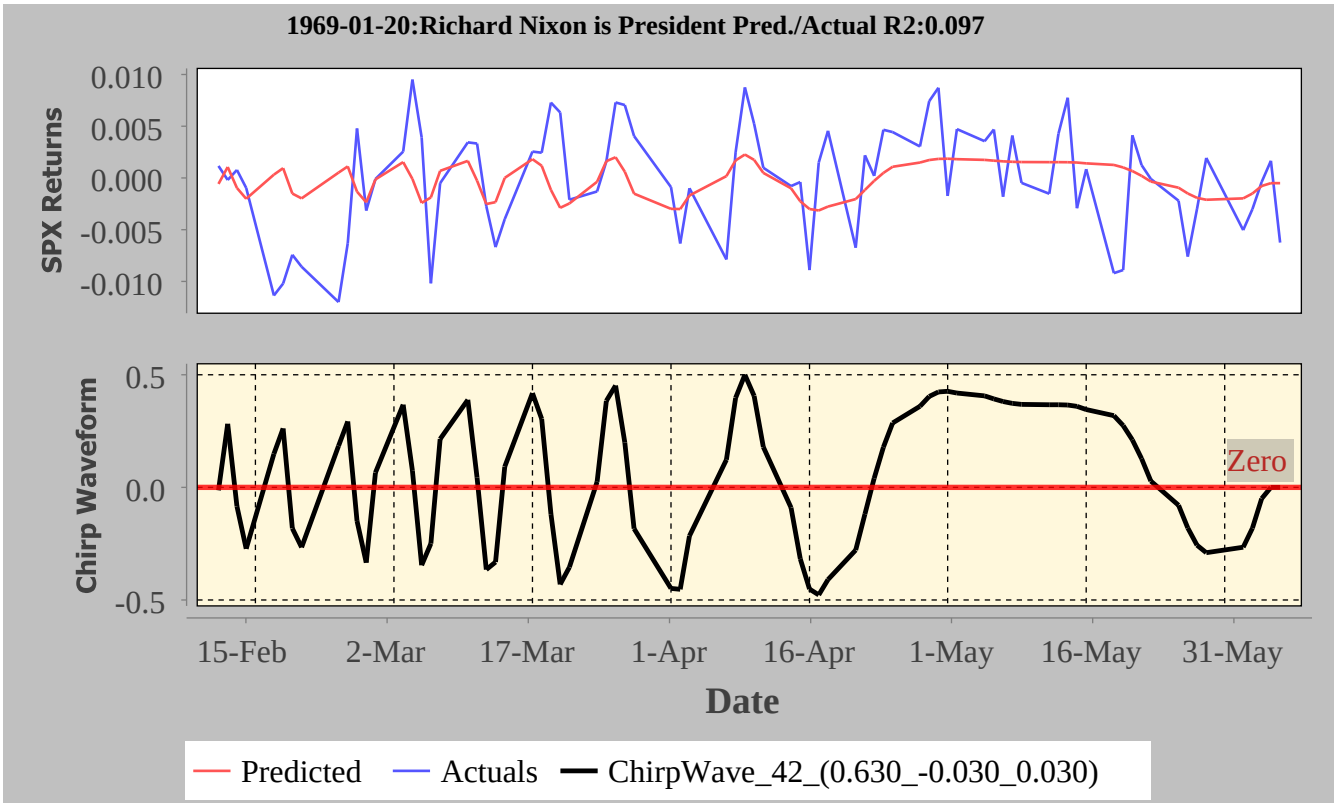

Figure (110) 1969-01-20:Richard Nixon is President Pred./Actual R2:0.097 v:8.327%

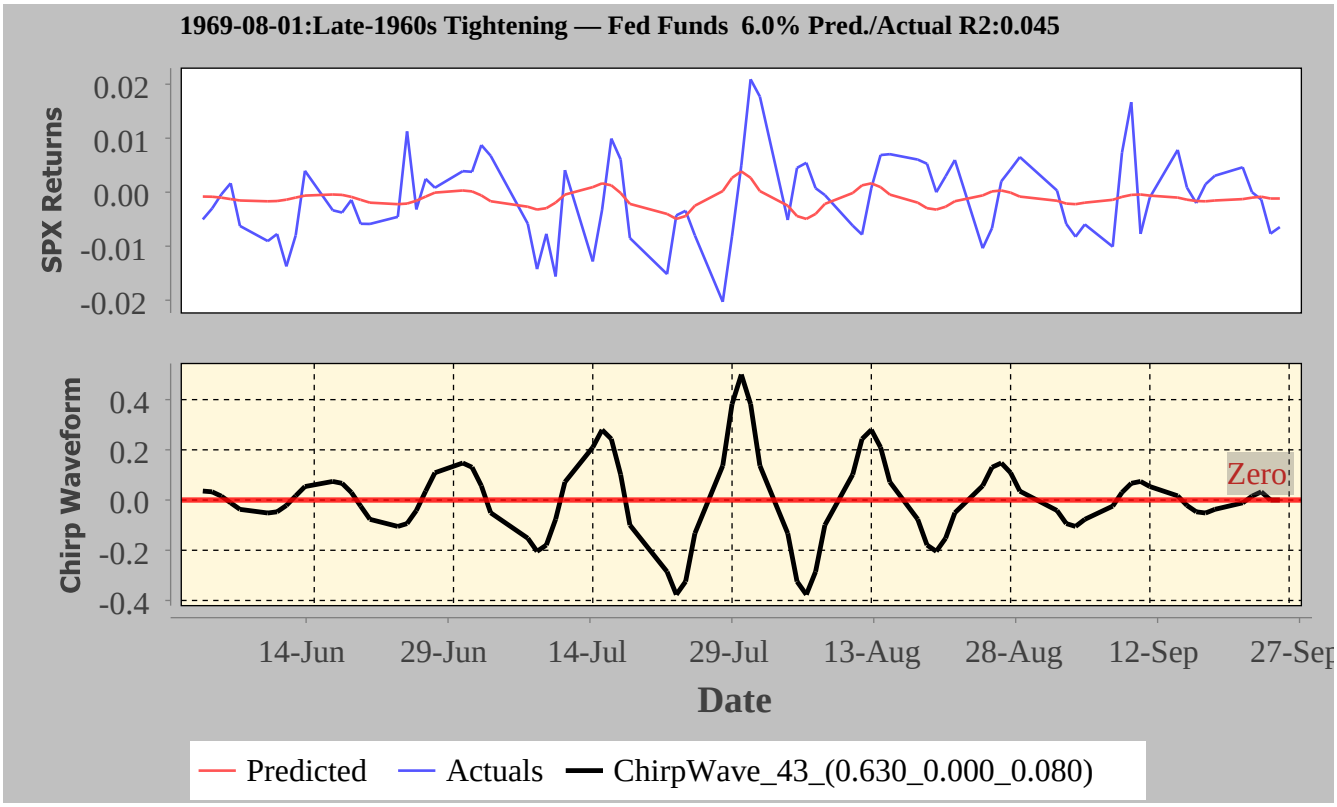

Figure (110) 1969-08-01:Late-1960s Tightening — Fed Funds 6.0% Pred./Actual R2:0.045 v:12.145%

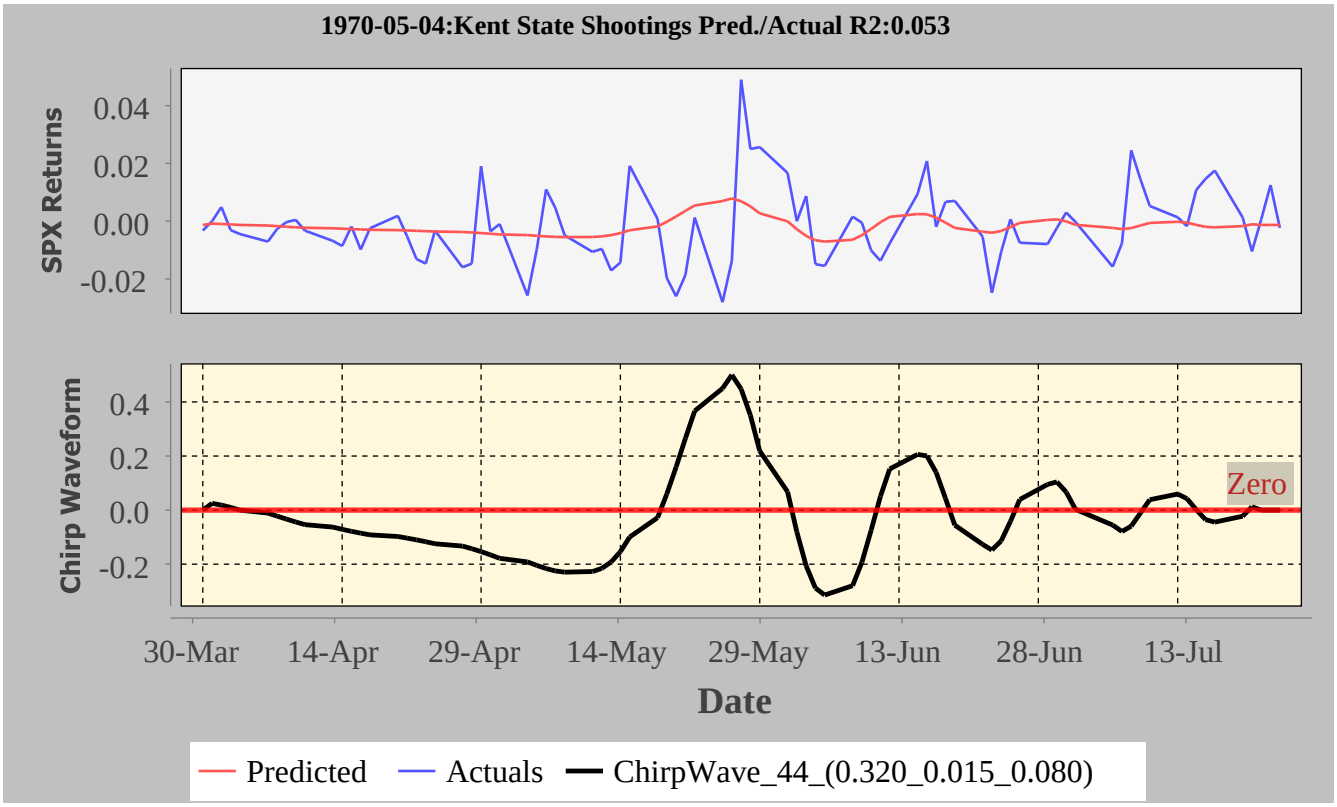

Figure (110) 1970-05-04:Kent State Shootings Pred./Actual R2:0.053 v:20.766%

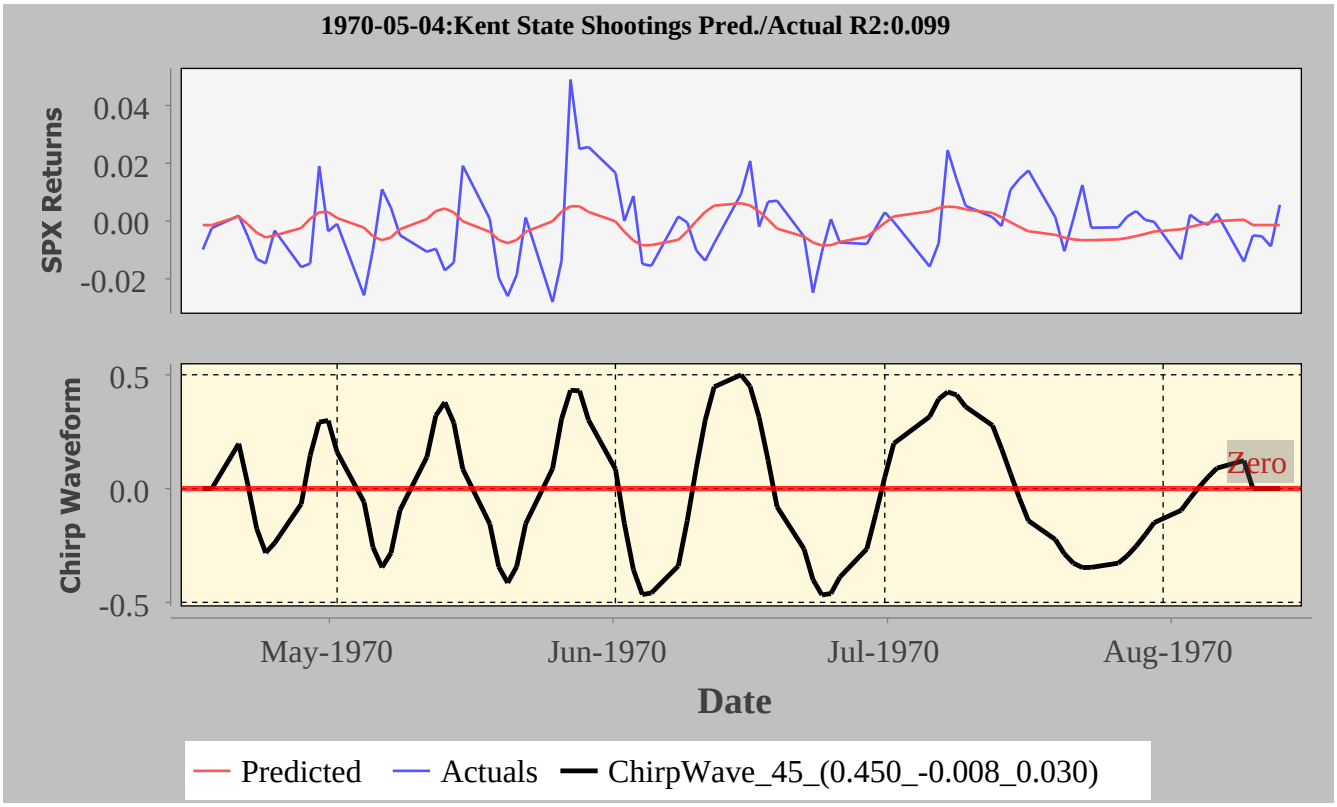

Figure (110) 1970-05-04:Kent State Shootings Pred./Actual R2:0.099 v:20.753%

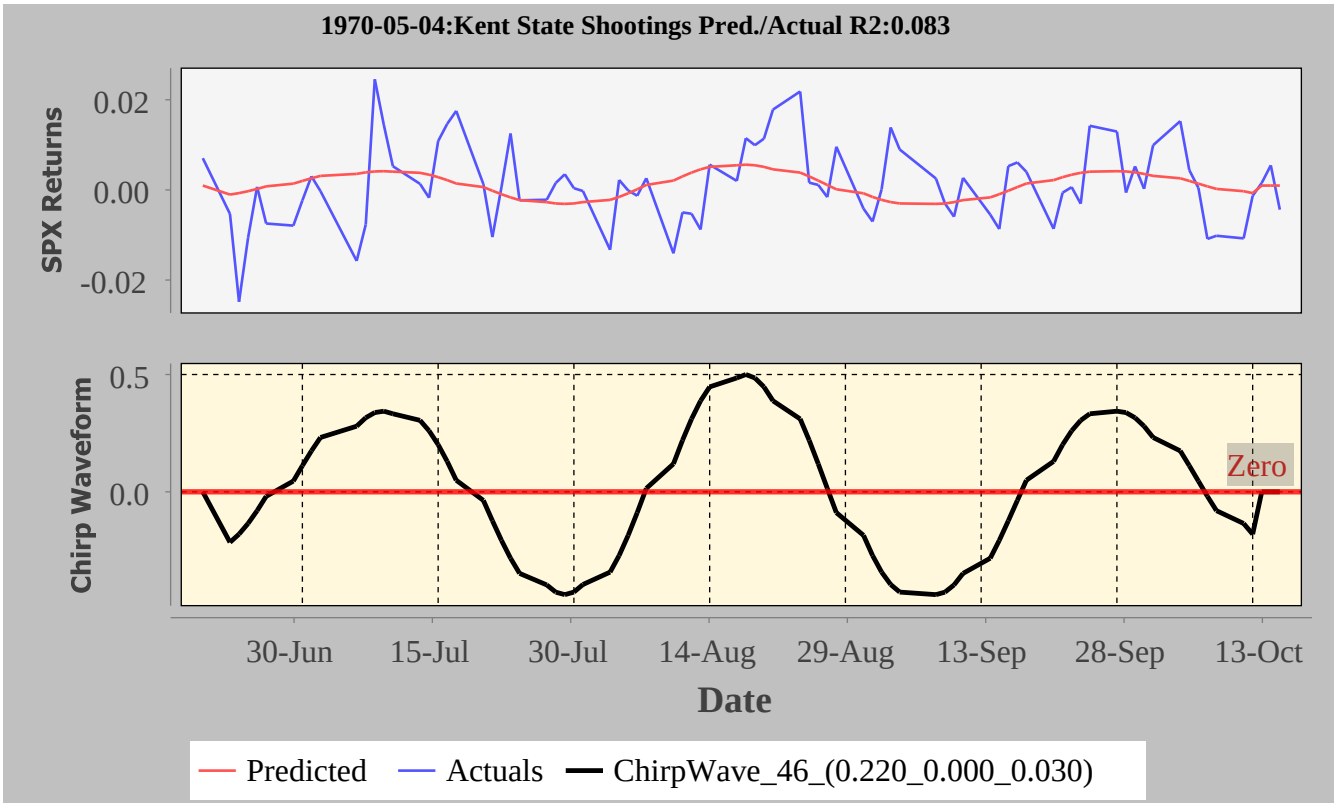

Figure (110) 1970-05-04:Kent State Shootings Pred./Actual R2:0.083 v:14.075%

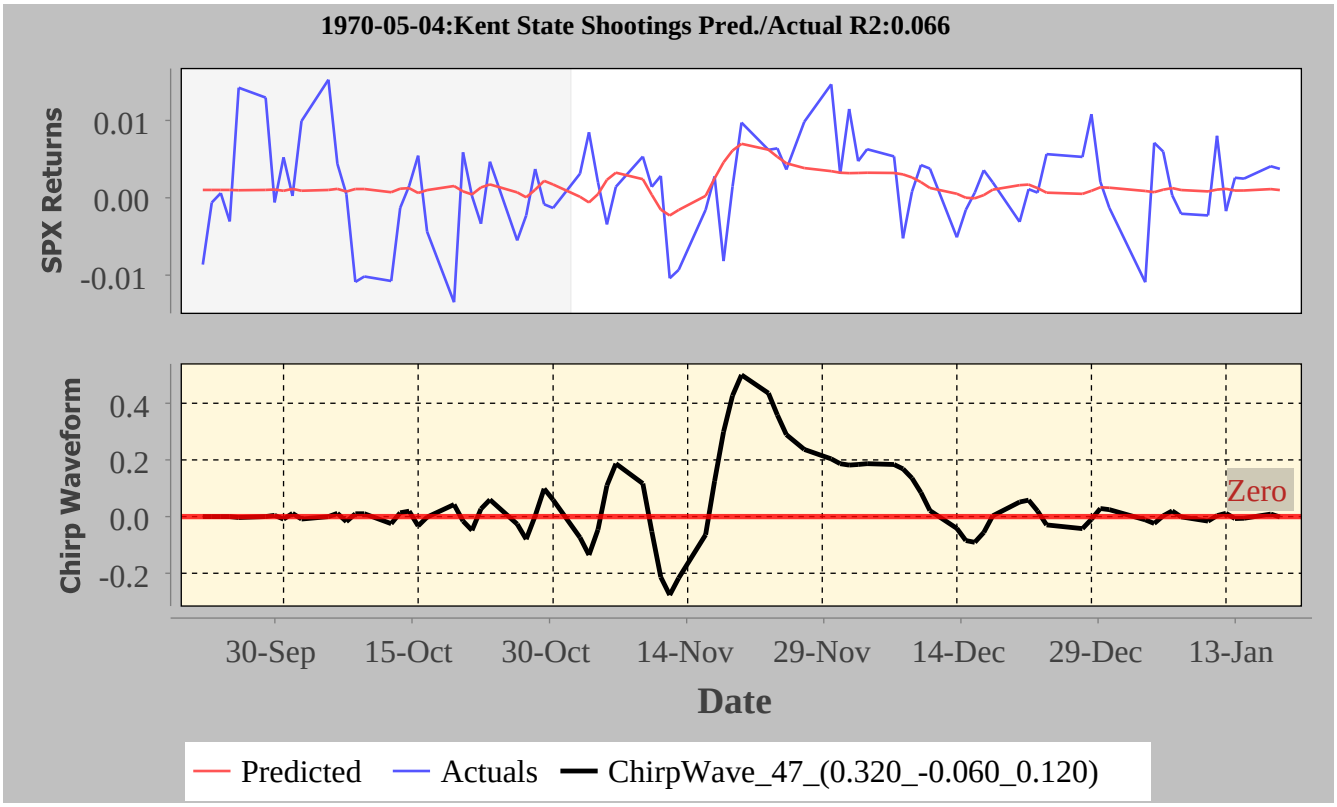

Figure (110) 1970-05-04:Kent State Shootings Pred./Actual R2:0.066 v:9.705%

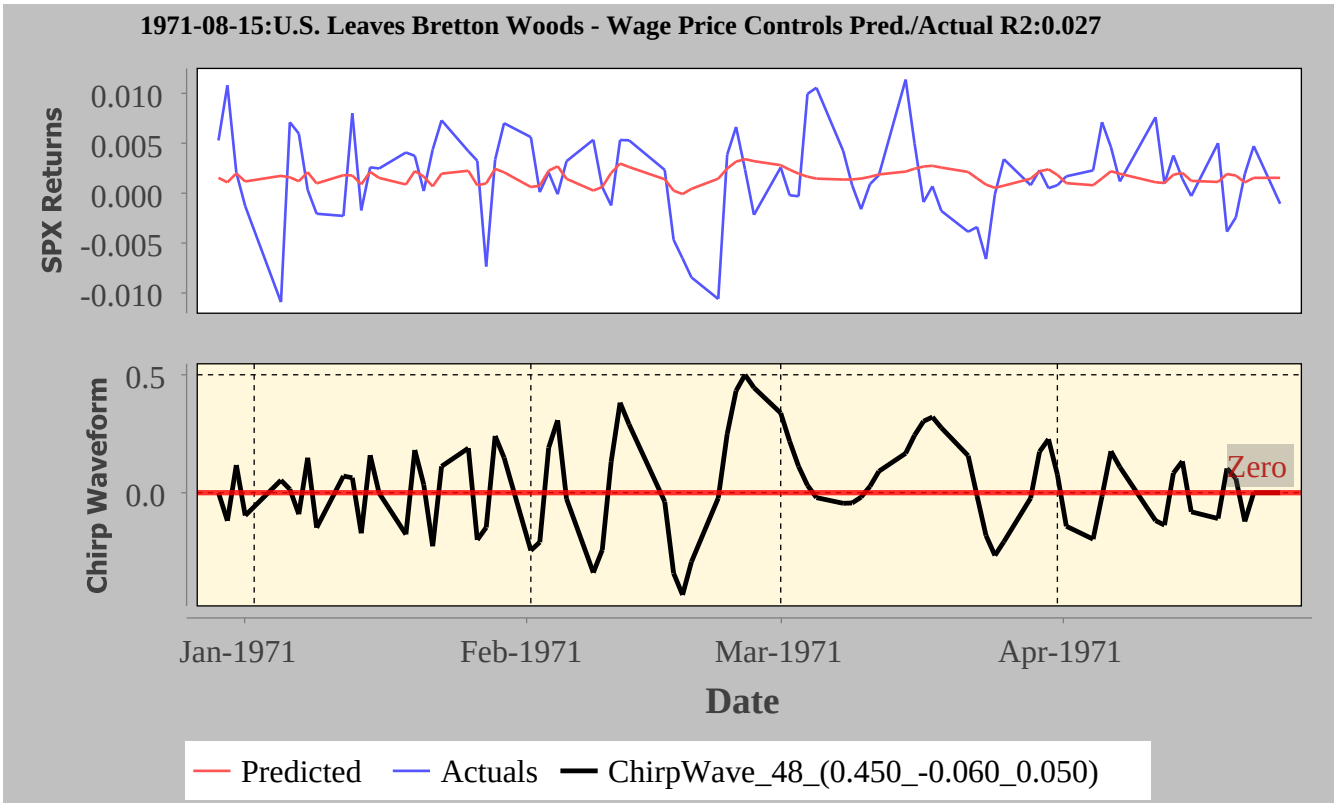

Figure (110) 1971-08-15:U.S. Leaves Bretton Woods - Wage Price Controls Pred./Actual R2:0.027 v:7.099%

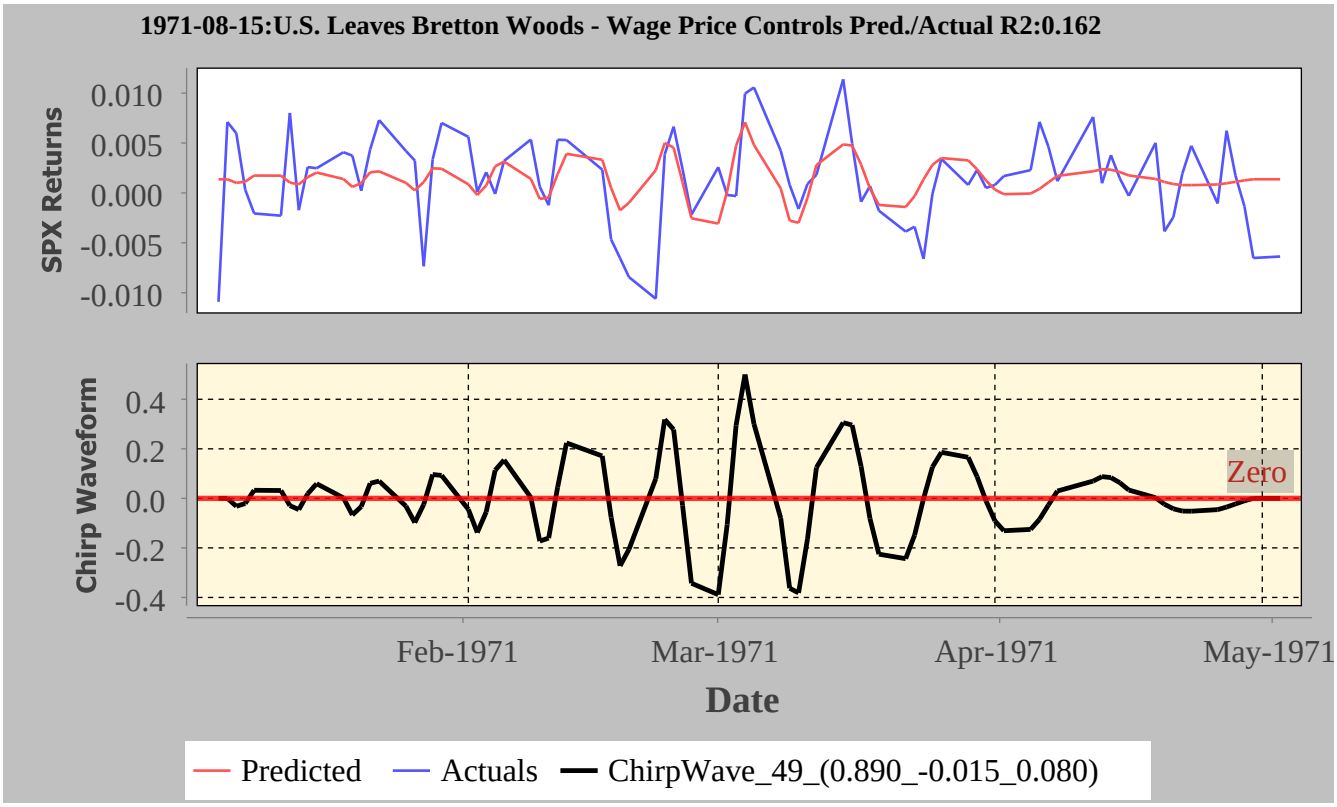

Figure (110) 1971-08-15:U.S. Leaves Bretton Woods - Wage Price Controls Pred./Actual R2:0.162 v:7.158%

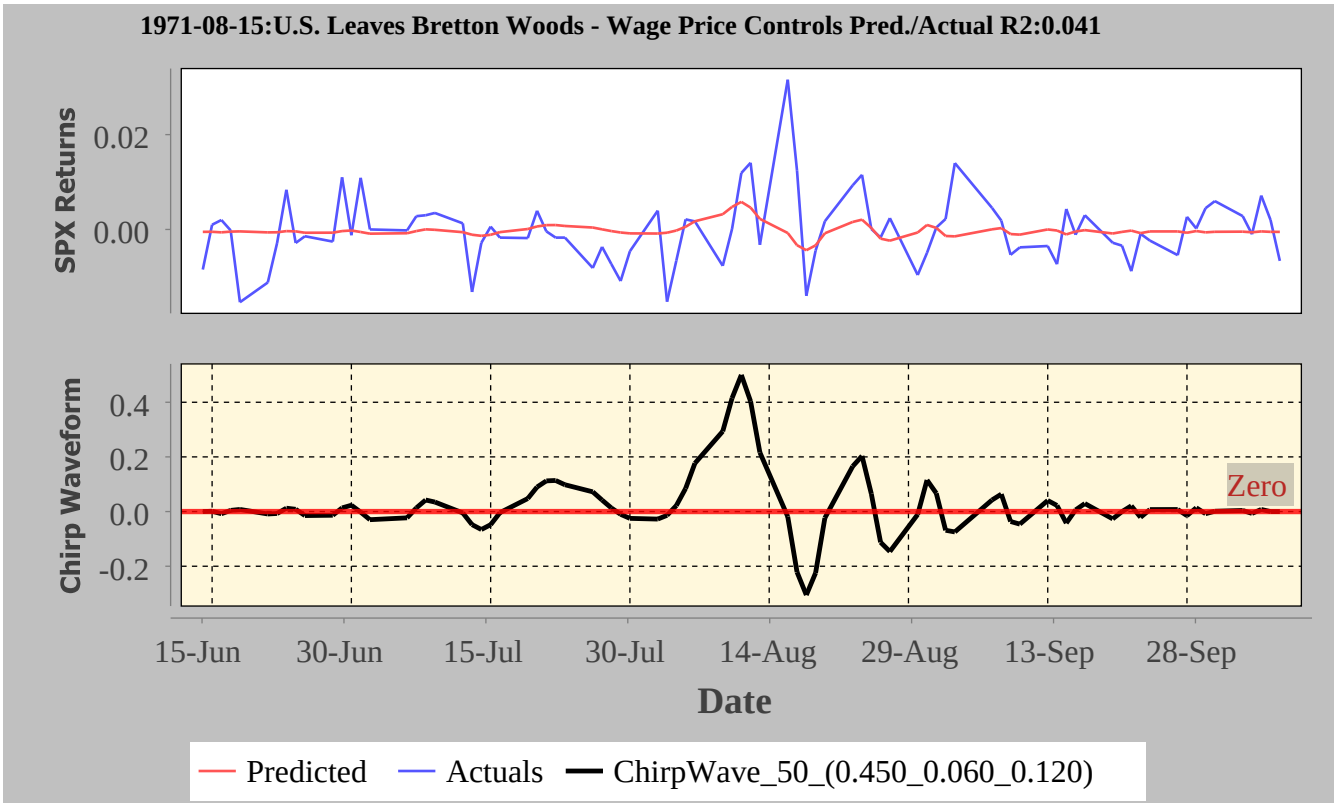

Figure (110) 1971-08-15:U.S. Leaves Bretton Woods - Wage Price Controls Pred./Actual R2:0.041 v:11.586%

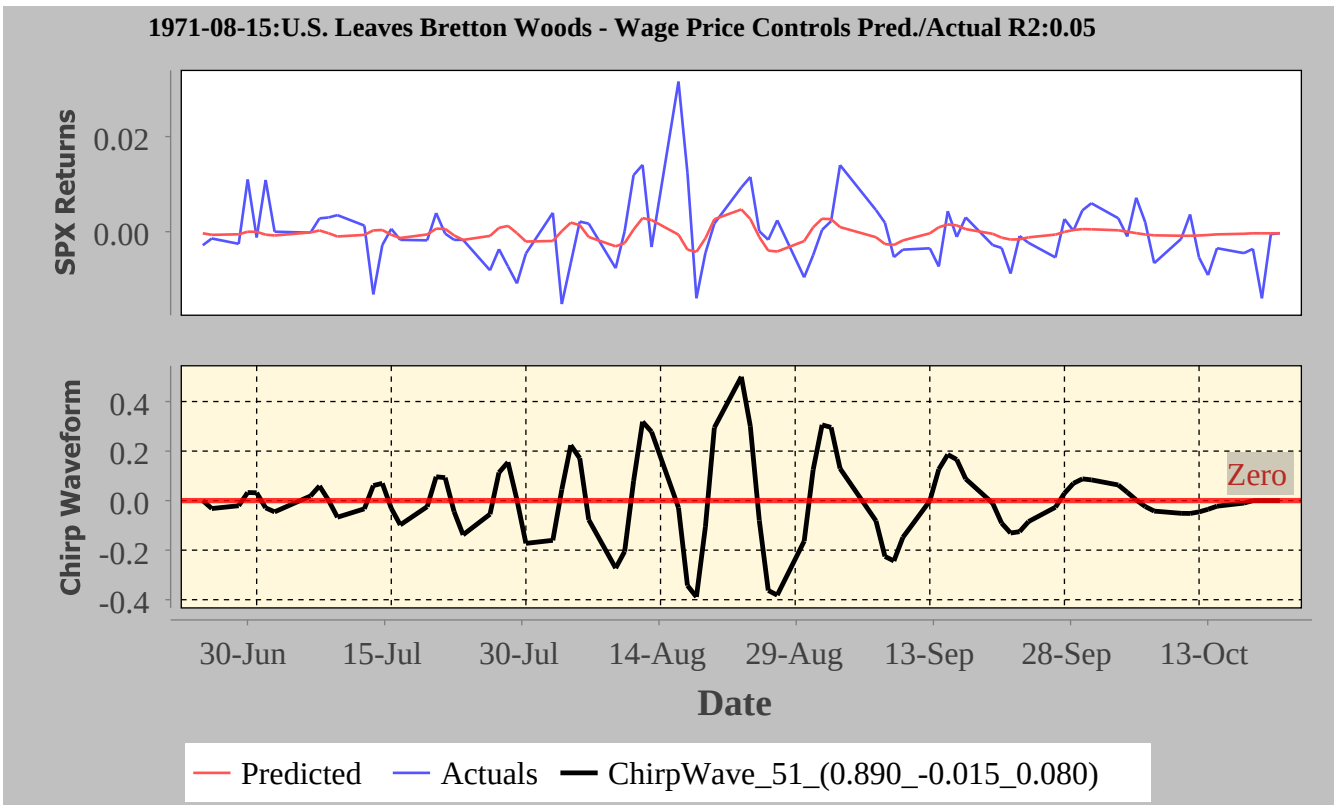

Figure (110) 1971-08-15:U.S. Leaves Bretton Woods - Wage Price Controls Pred./Actual R2:0.05 v:11.248%

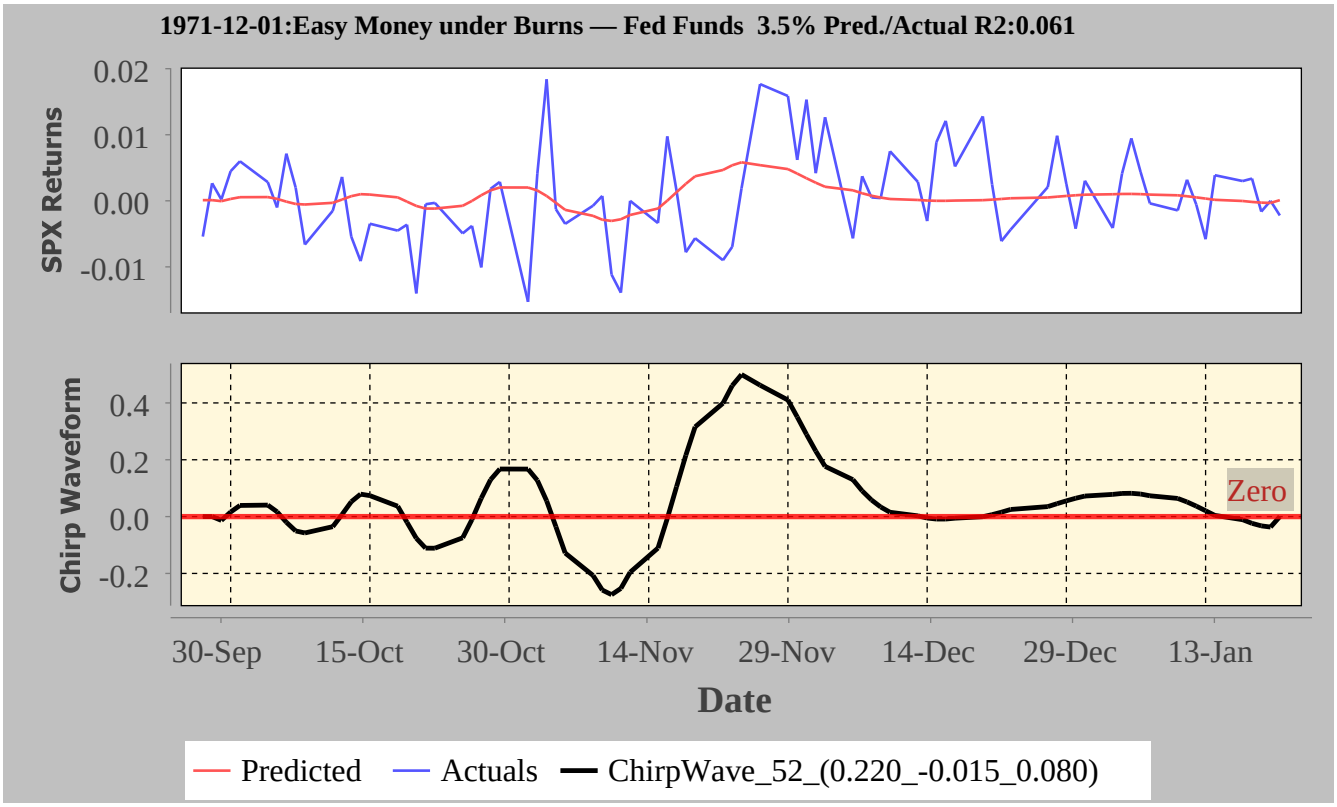

Figure (110) 1971-12-01:Easy Money under Burns — Fed Funds 3.5% Pred./Actual R2:0.061 v:10.979%

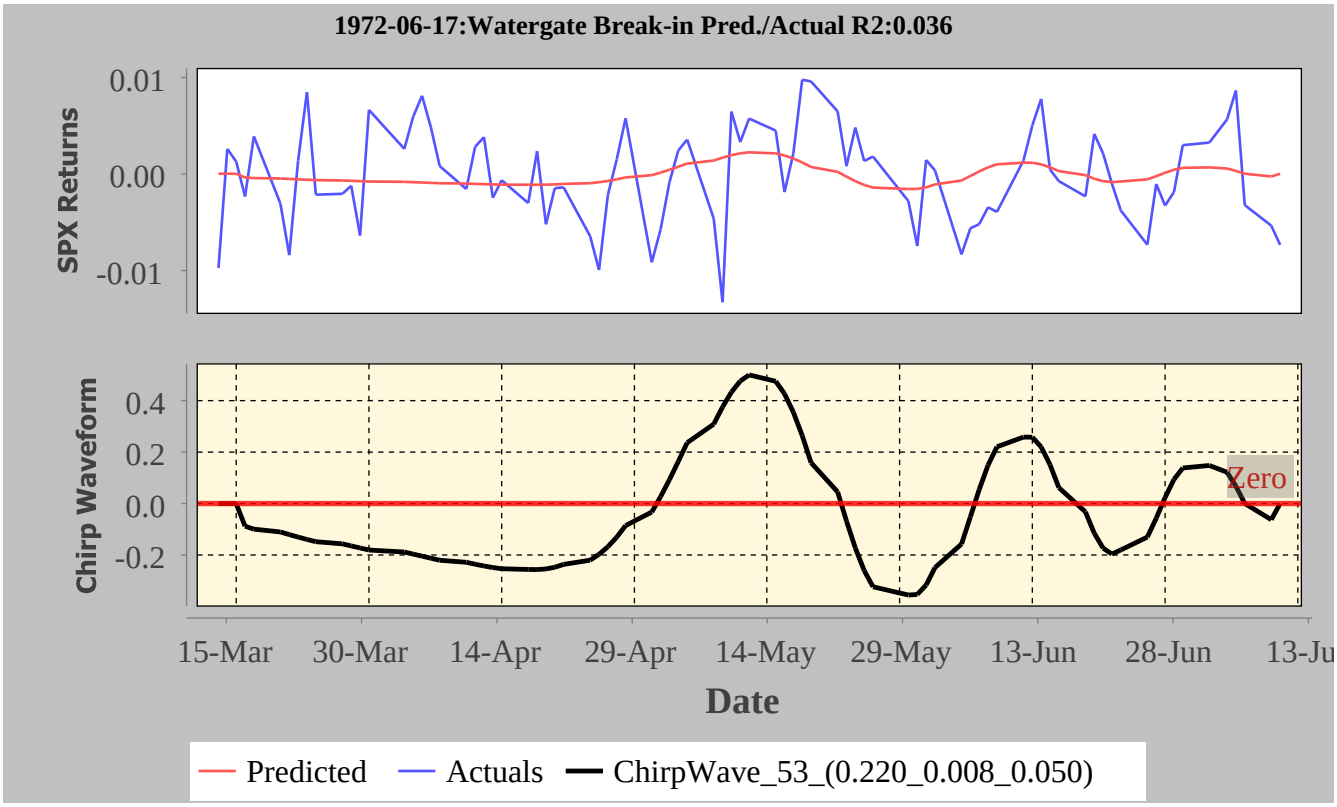

Figure (110) 1972-06-17:Watergate Break-in Pred./Actual R2:0.036 v:8%

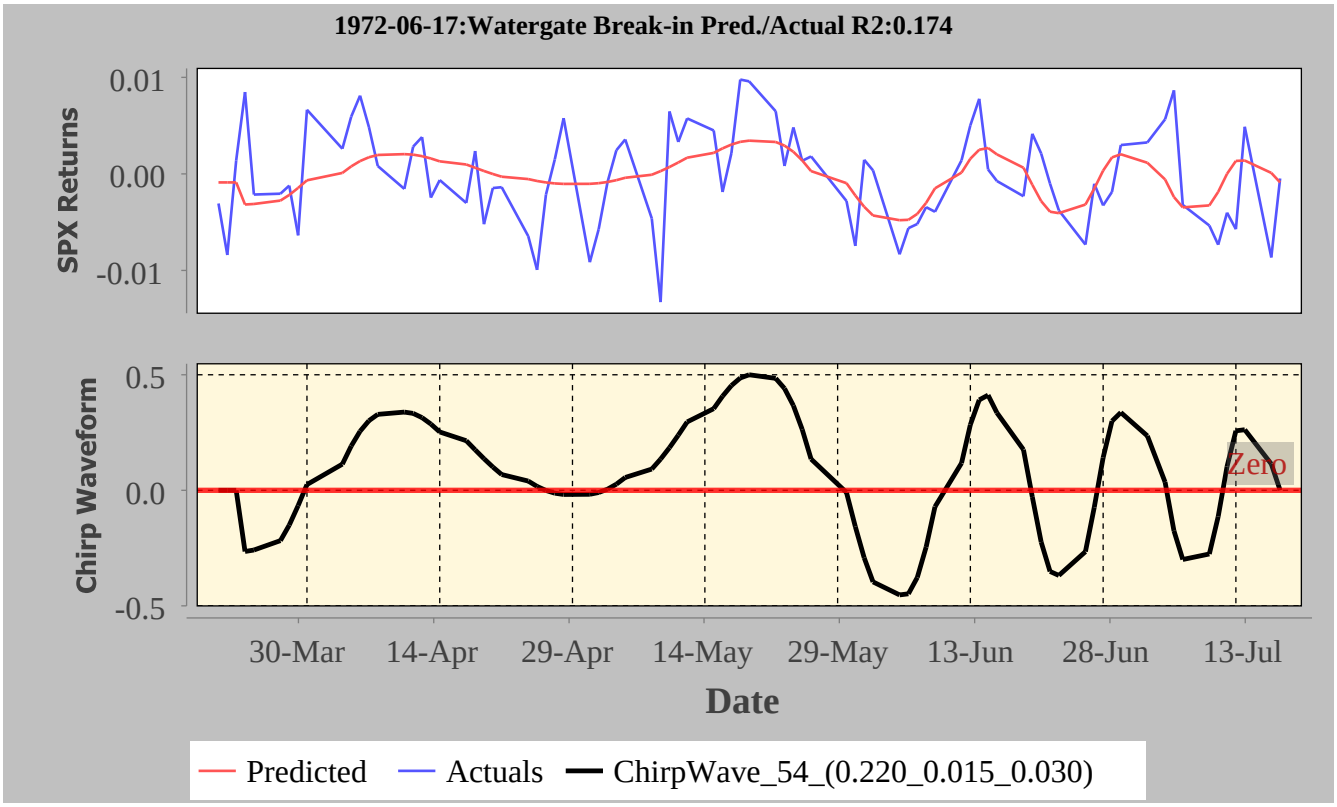

Figure (110) 1972-06-17:Watergate Break-in Pred./Actual R2:0.174 v:8.038%

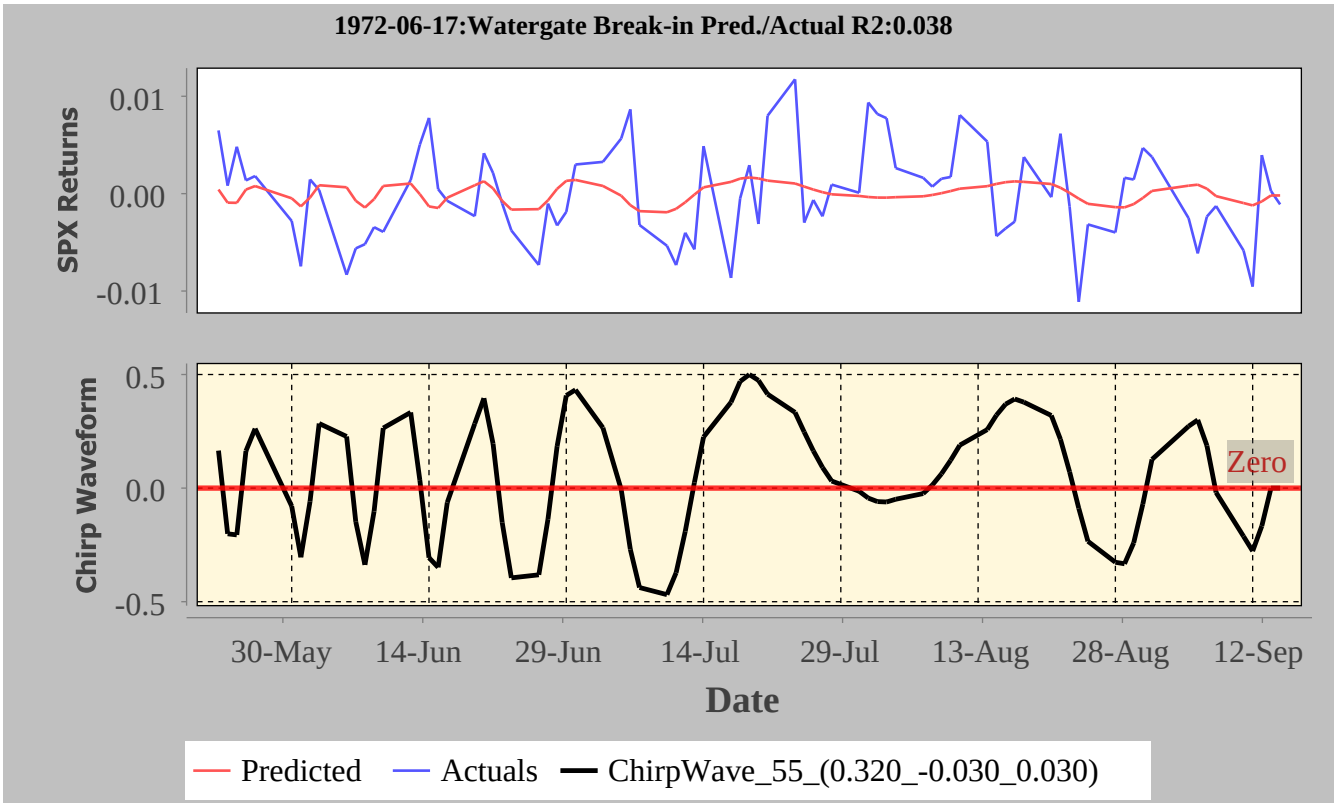

Figure (110) 1972-06-17:Watergate Break-in Pred./Actual R2:0.038 v:7.679%

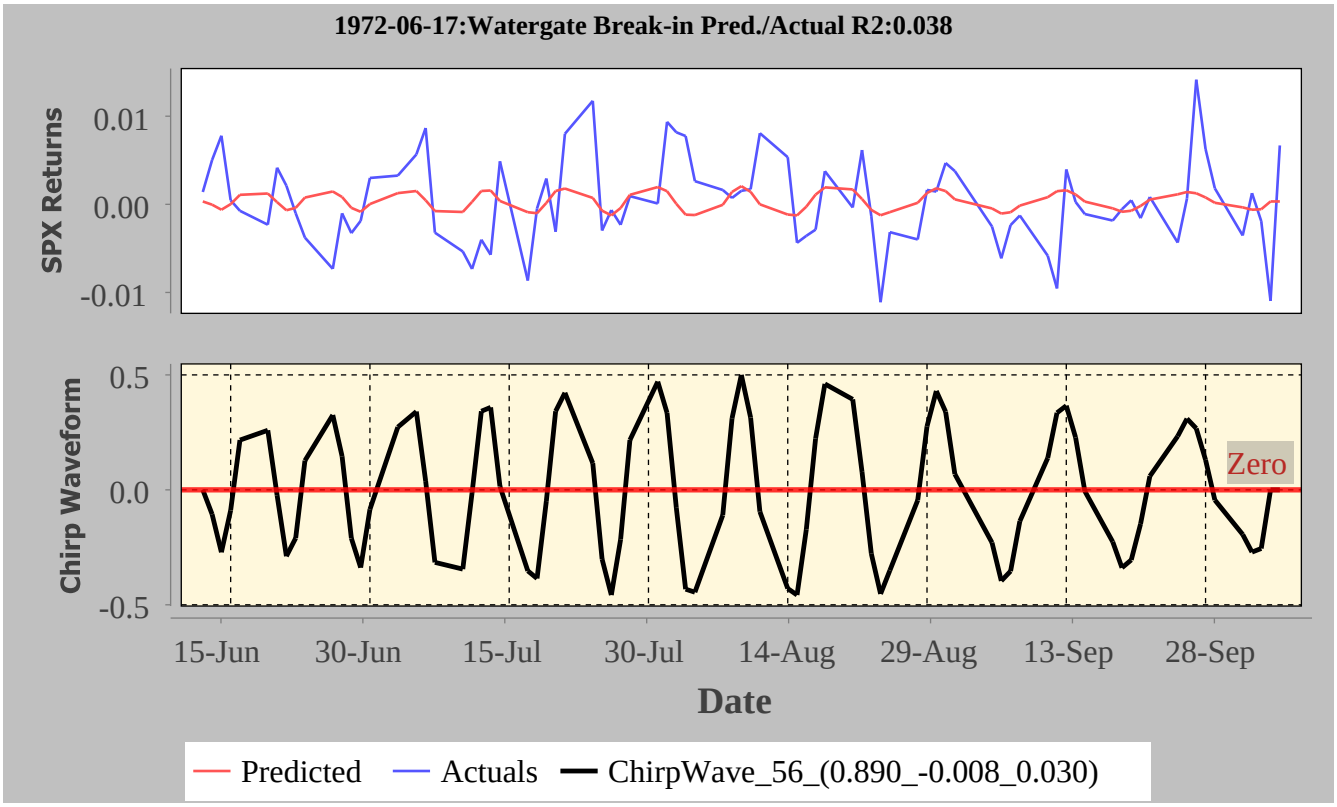

Figure (110) 1972-06-17:Watergate Break-in Pred./Actual R2:0.038 v:7.932%

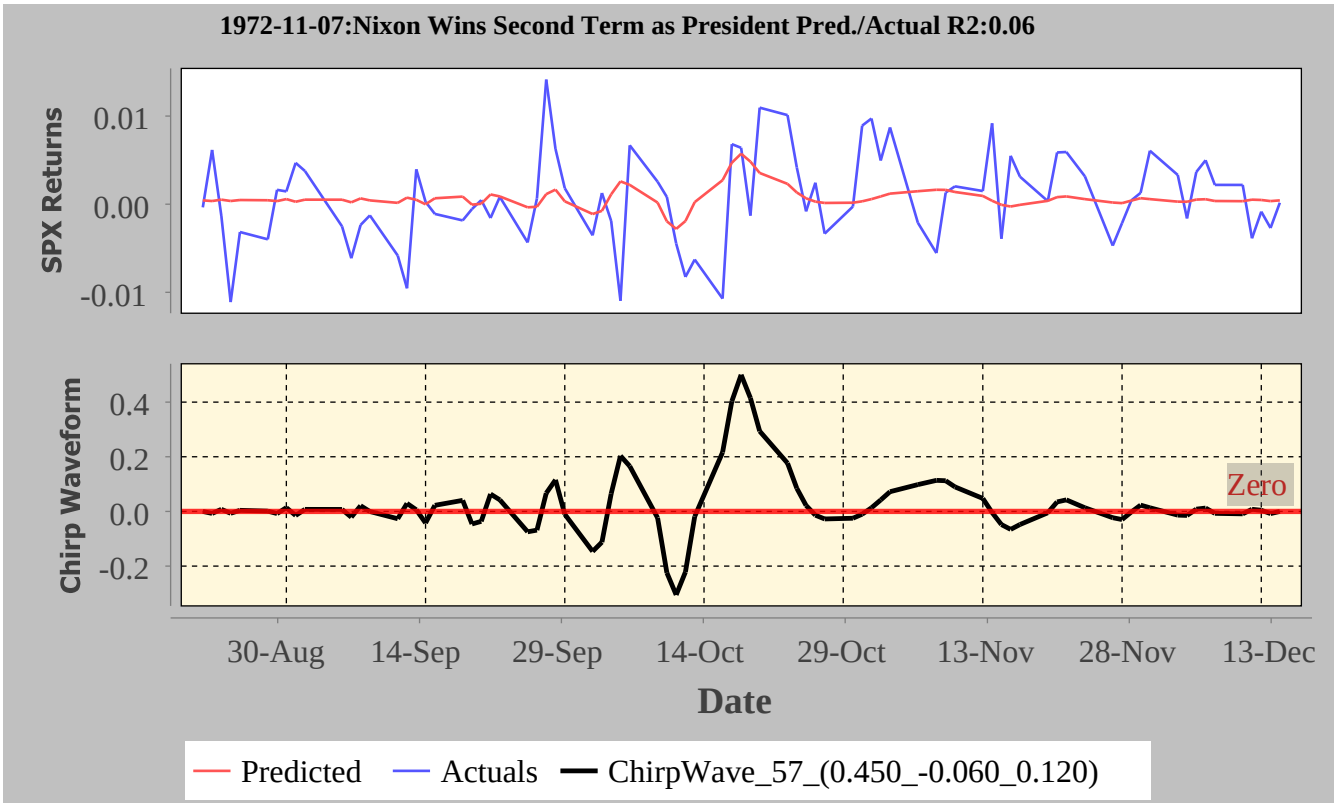

Figure (110) 1972-11-07:Nixon Wins Second Term as President Pred./Actual R2:0.06 v:8.117%

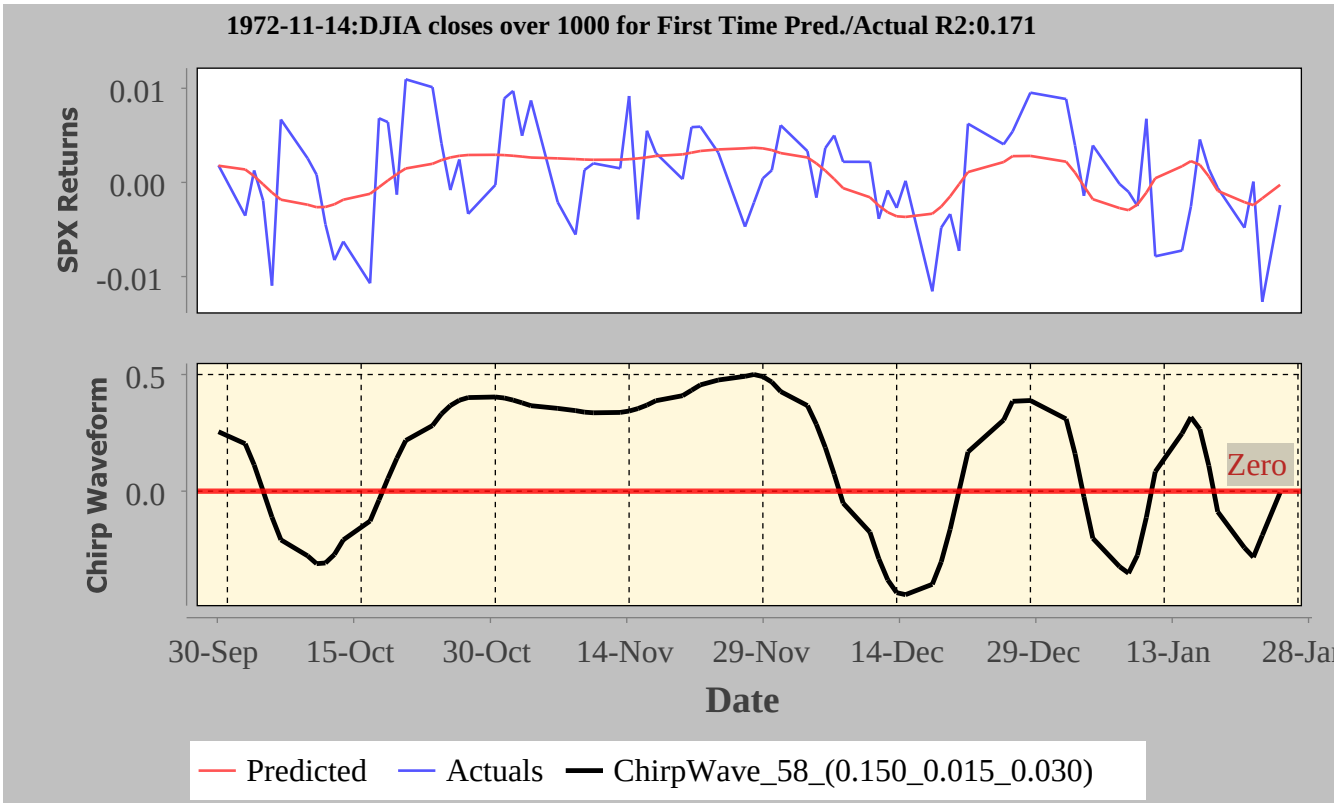

Figure (110) 1972-11-14:DJIA closes over 1000 for First Time Pred./Actual R2:0.171 v:8.613%

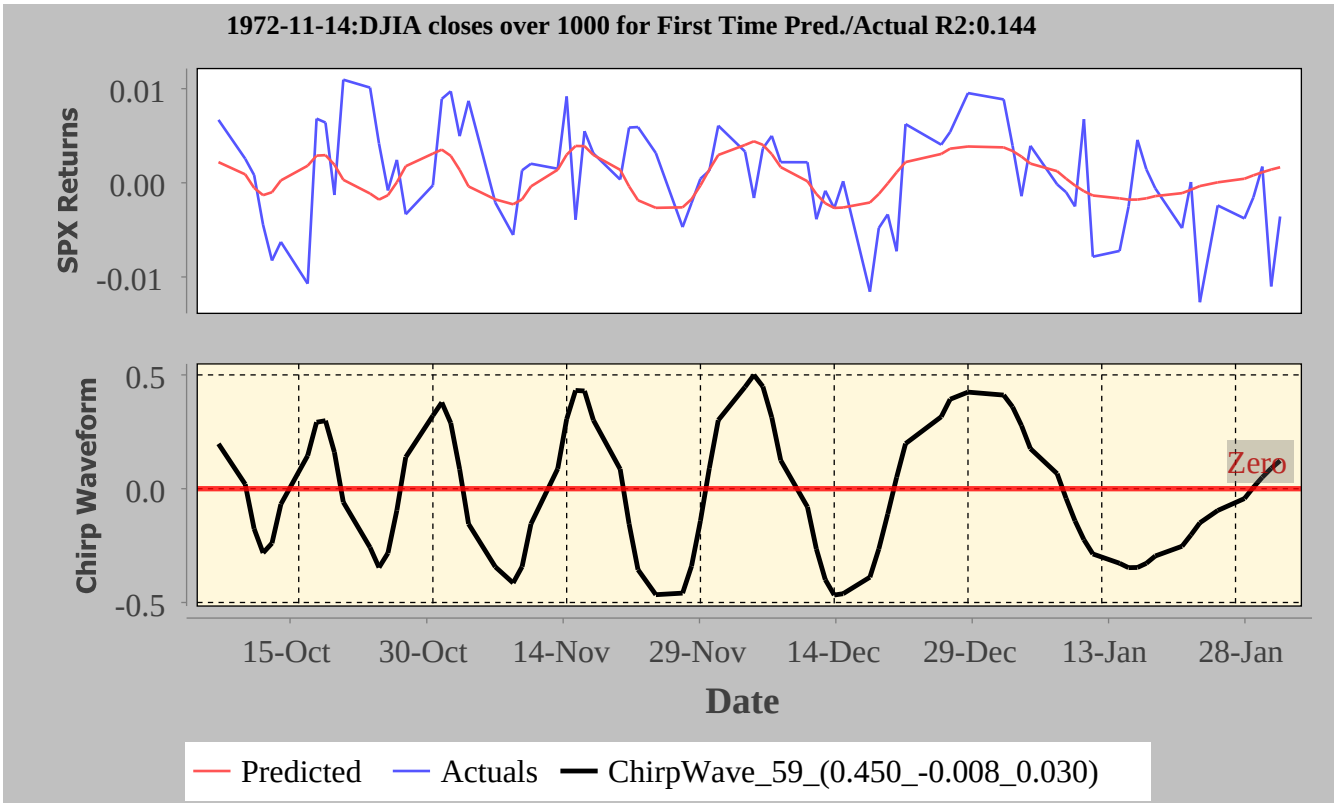

Figure (110) 1972-11-14:DJIA closes over 1000 for First Time Pred./Actual R2:0.144 v:8.648%

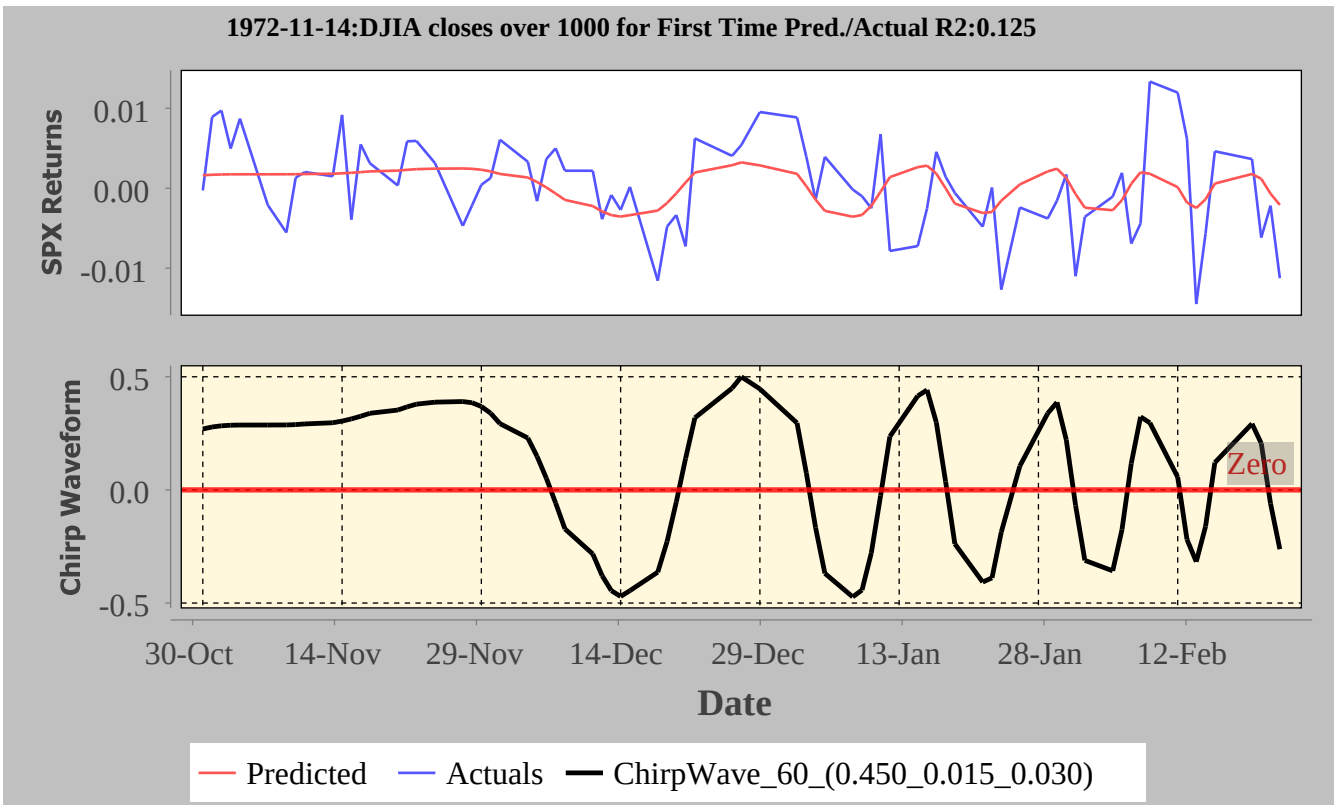

Figure (110) 1972-11-14:DJIA closes over 1000 for First Time Pred./Actual R2:0.125 v:9.234%

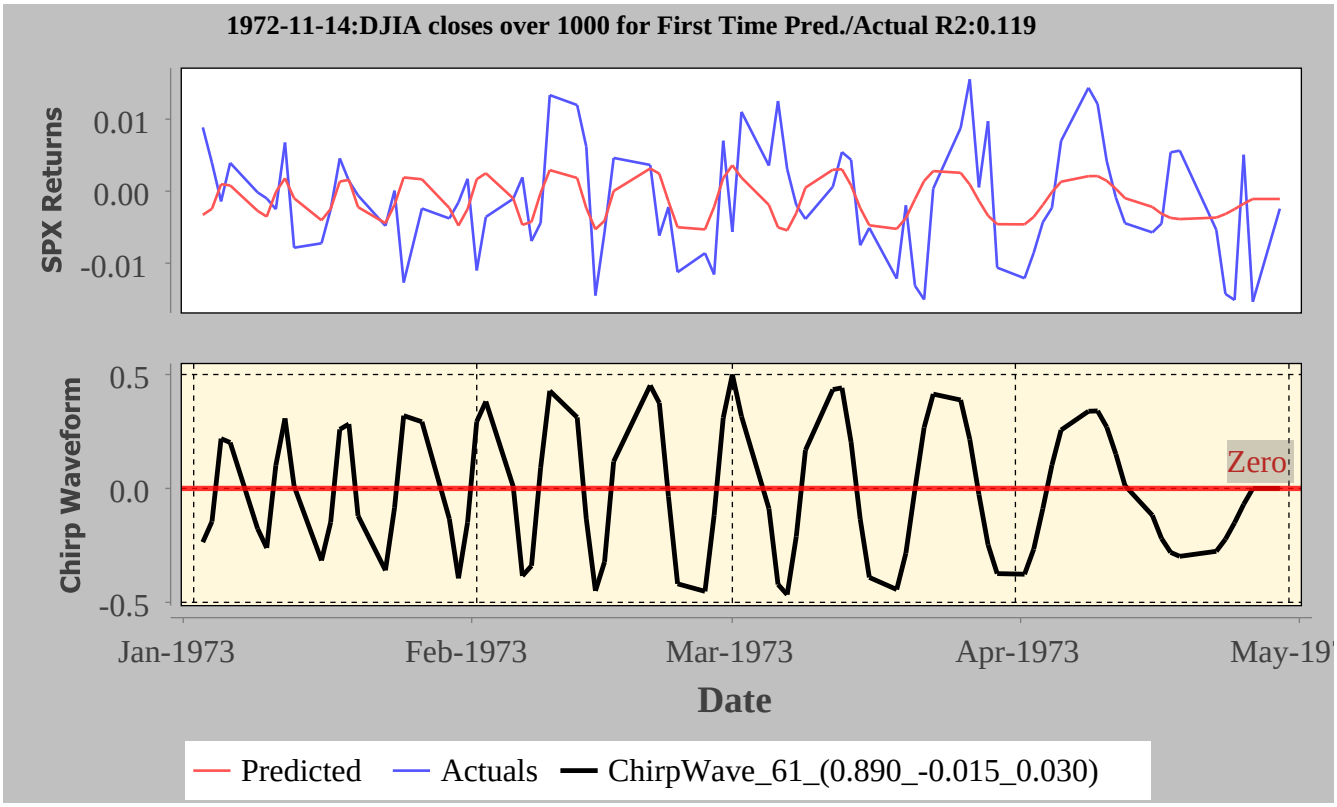

Figure (110) 1972-11-14:DJIA closes over 1000 for First Time Pred./Actual R2:0.119 v:12.157%

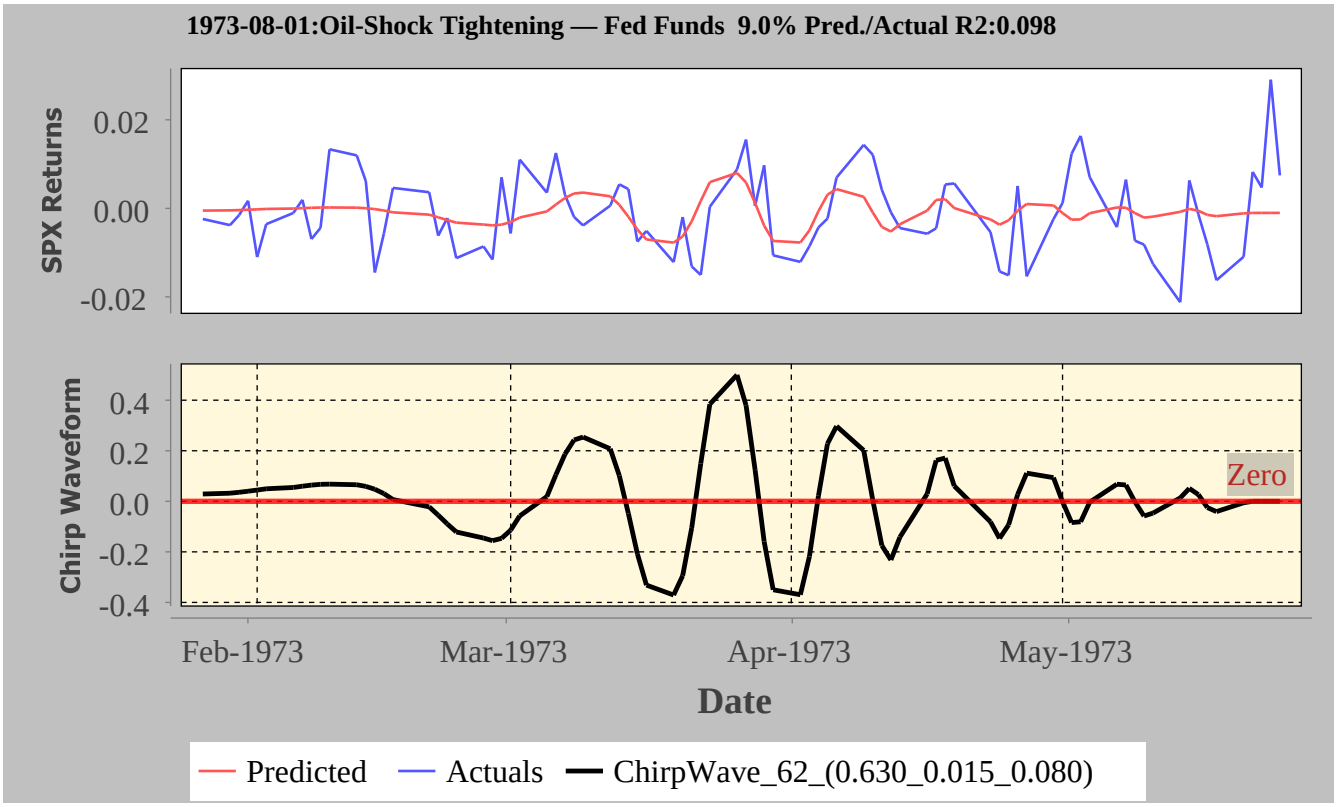

Figure (110) 1973-08-01:Oil-Shock Tightening — Fed Funds 9.0% Pred./Actual R2:0.098 v:14.627%

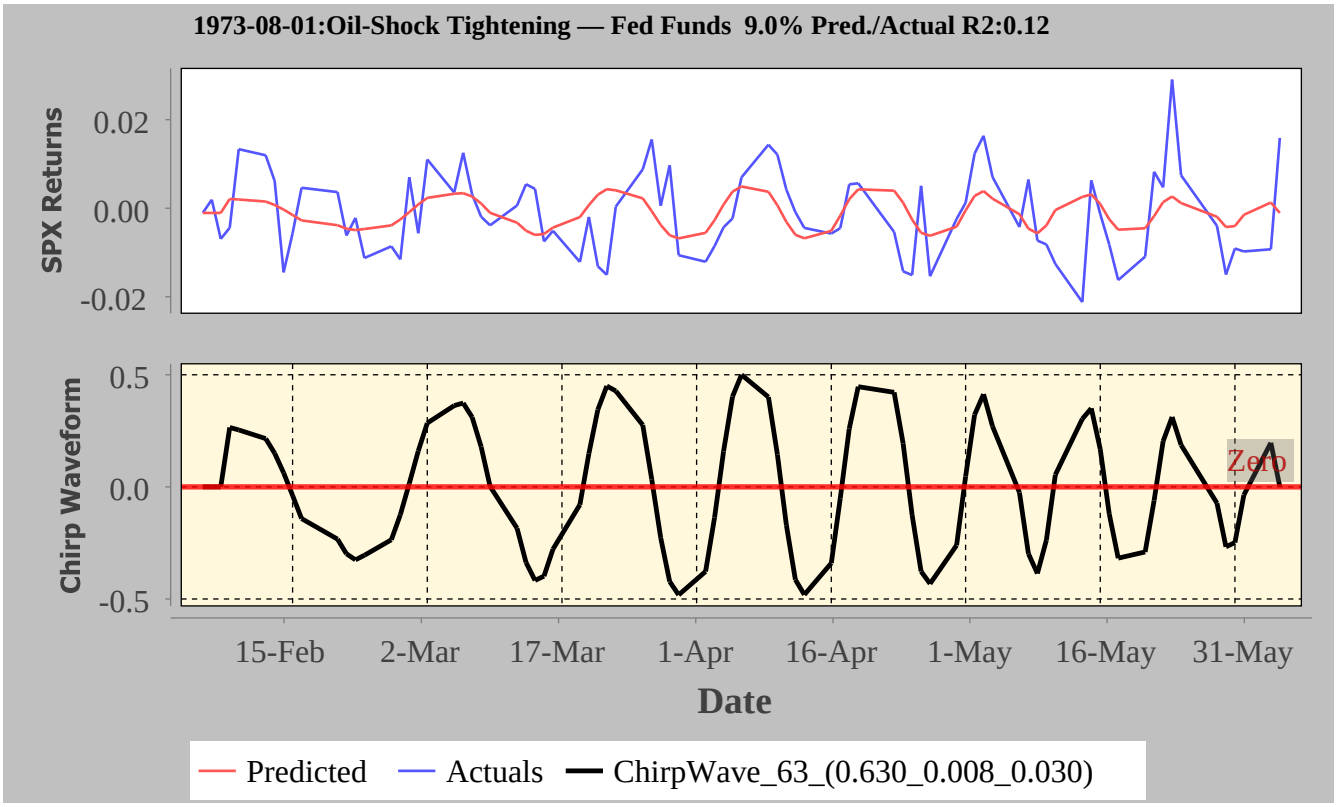

Figure (110) 1973-08-01:Oil-Shock Tightening — Fed Funds 9.0% Pred./Actual R2:0.12 v:15.215%

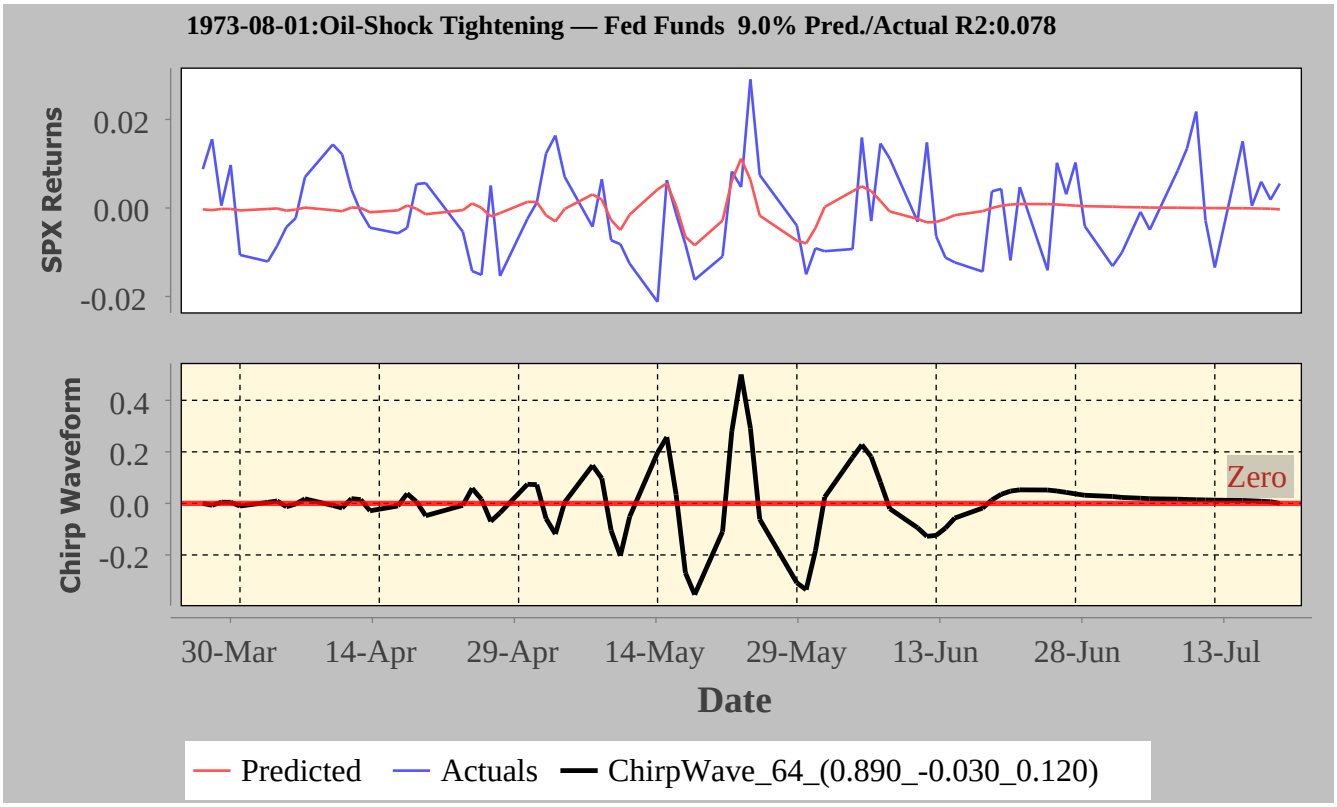

Figure (110) 1973-08-01:Oil-Shock Tightening — Fed Funds 9.0% Pred./Actual R2:0.078 v:16.535%

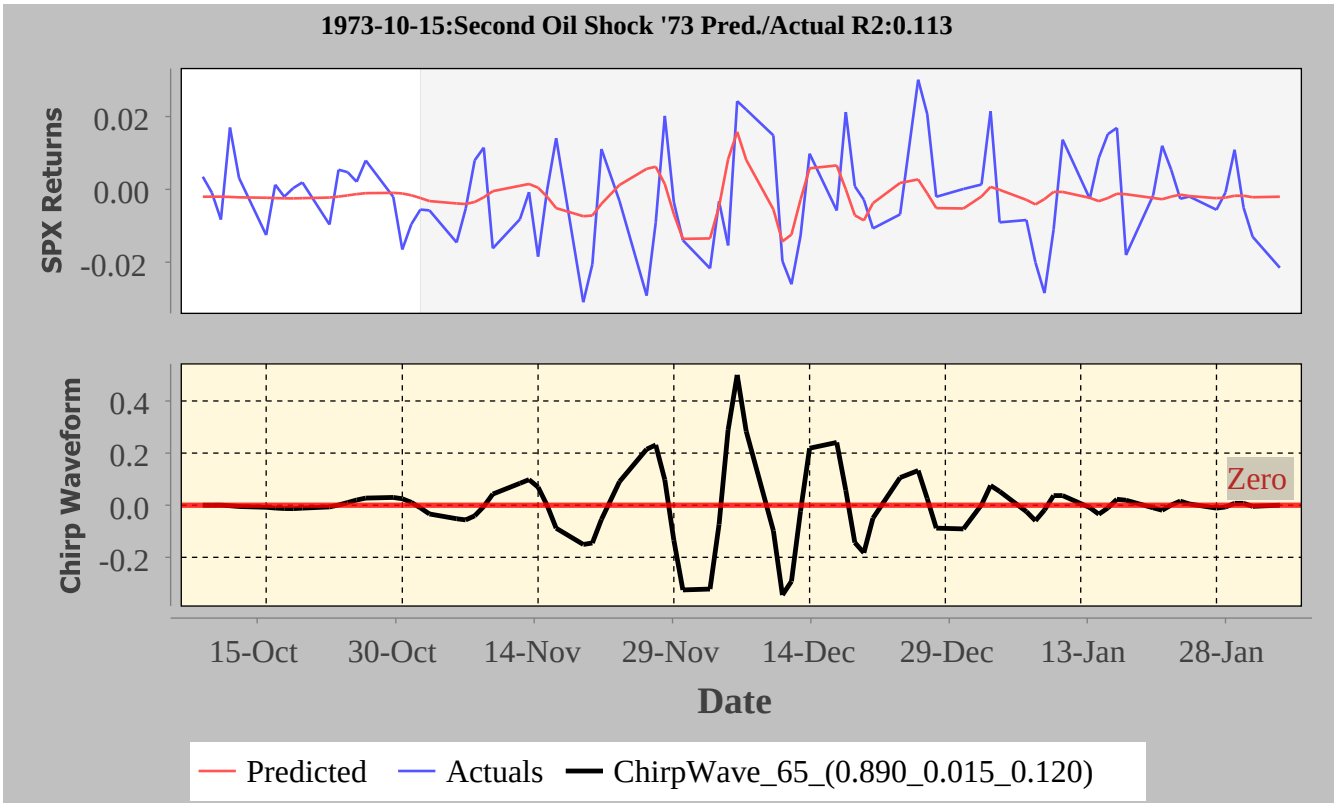

Figure (110) 1973-10-15:Second Oil Shock '73 Pred./Actual R2:0.113 v:21.199%

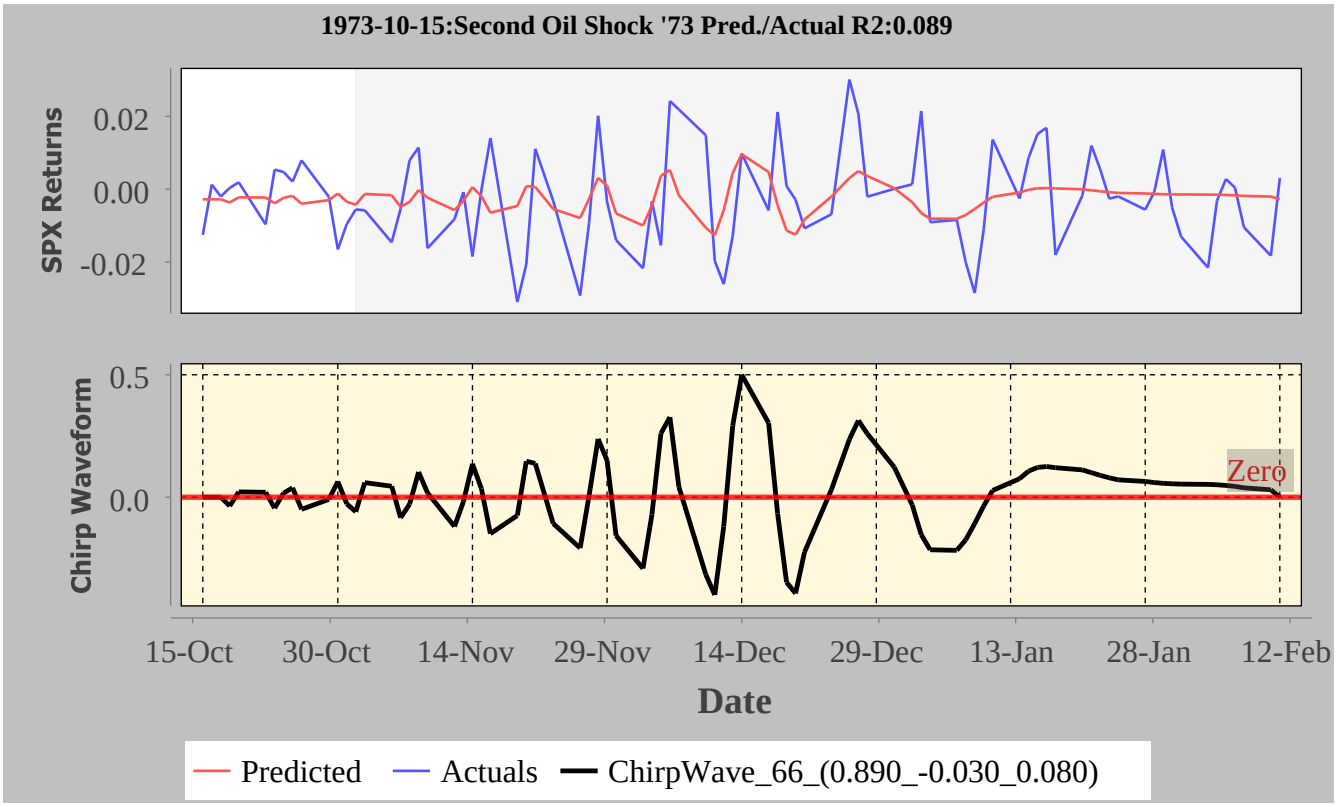

Figure (110) 1973-10-15:Second Oil Shock '73 Pred./Actual R2:0.089 v:21.013%

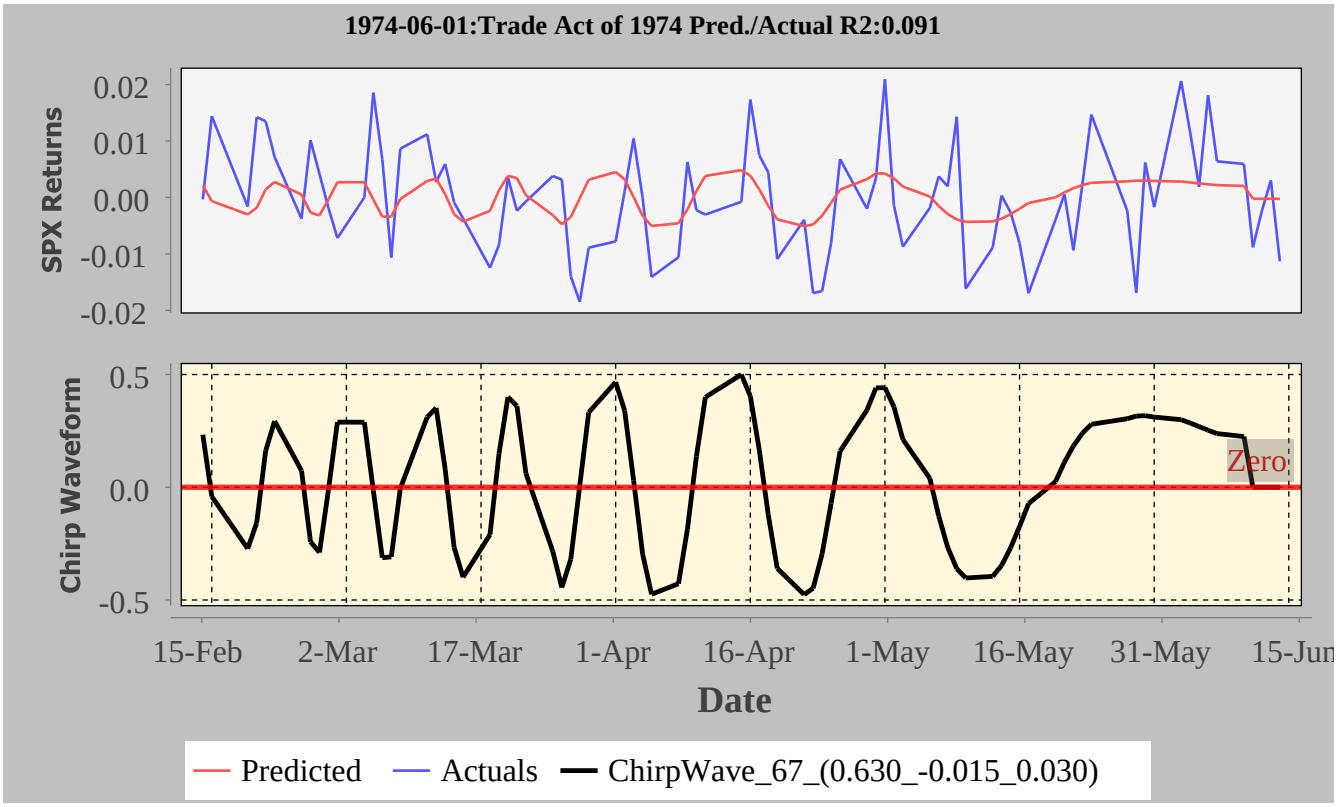

Figure (110) 1974-06-01:Trade Act of 1974 Pred./Actual R2:0.091 v:15.099%

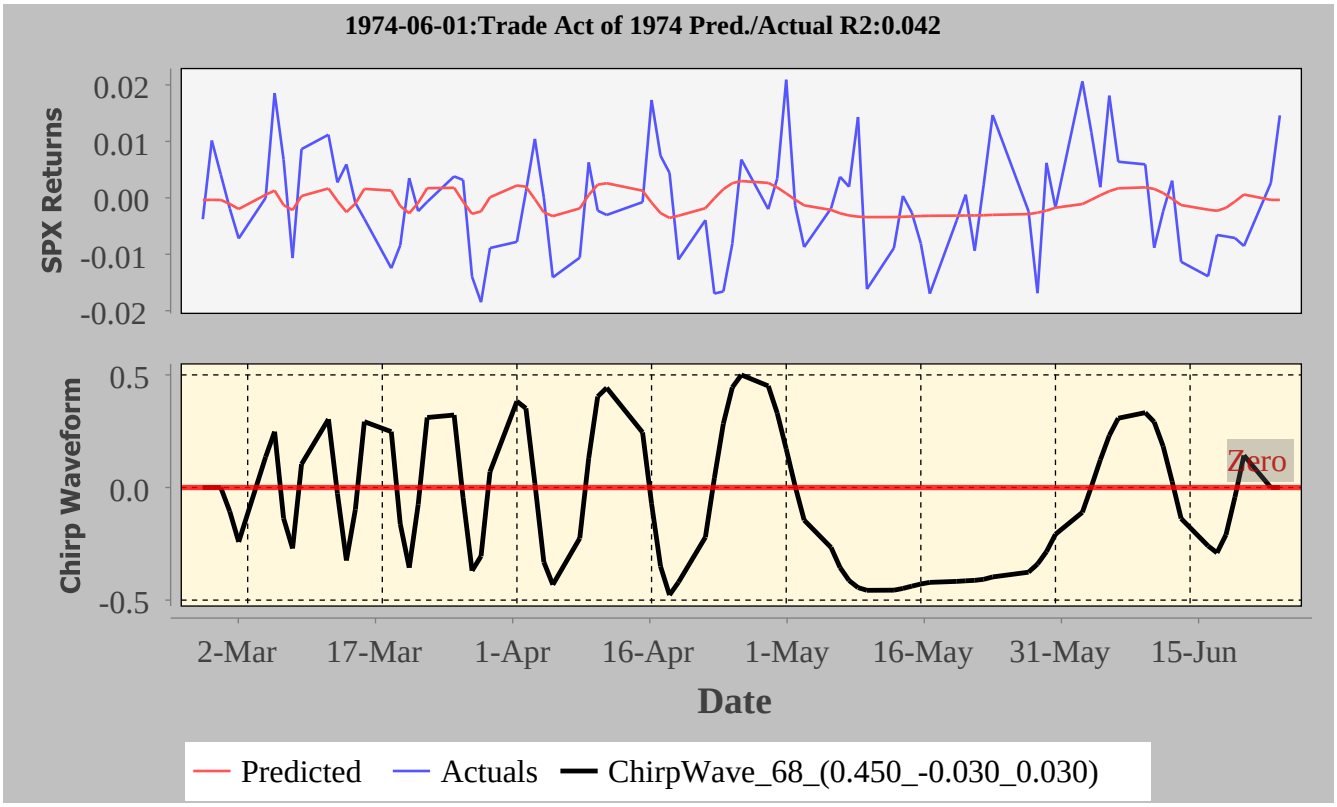

Figure (110) 1974-06-01:Trade Act of 1974 Pred./Actual R2:0.042 v:14.933%

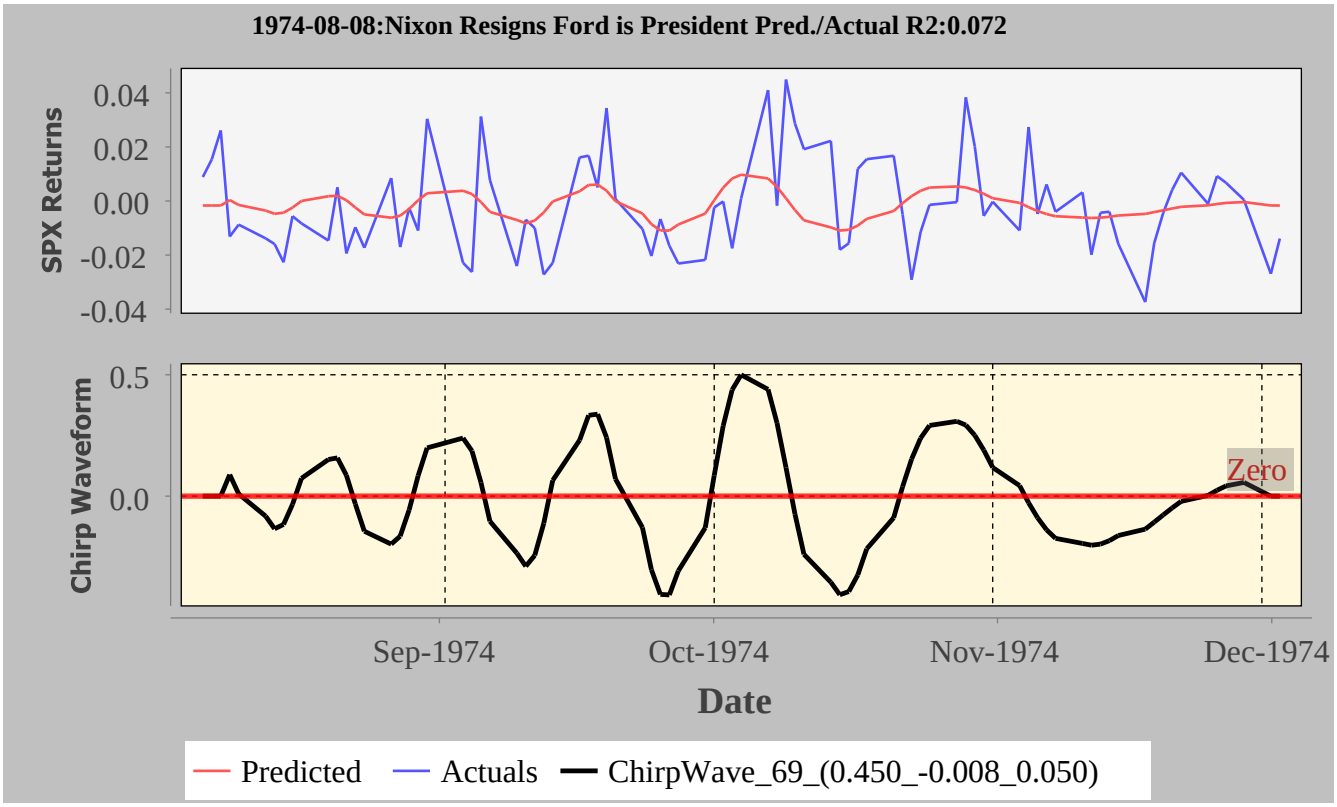

Figure (110) 1974-08-08:Nixon Resigns Ford is President Pred./Actual R2:0.072 v:28.251%

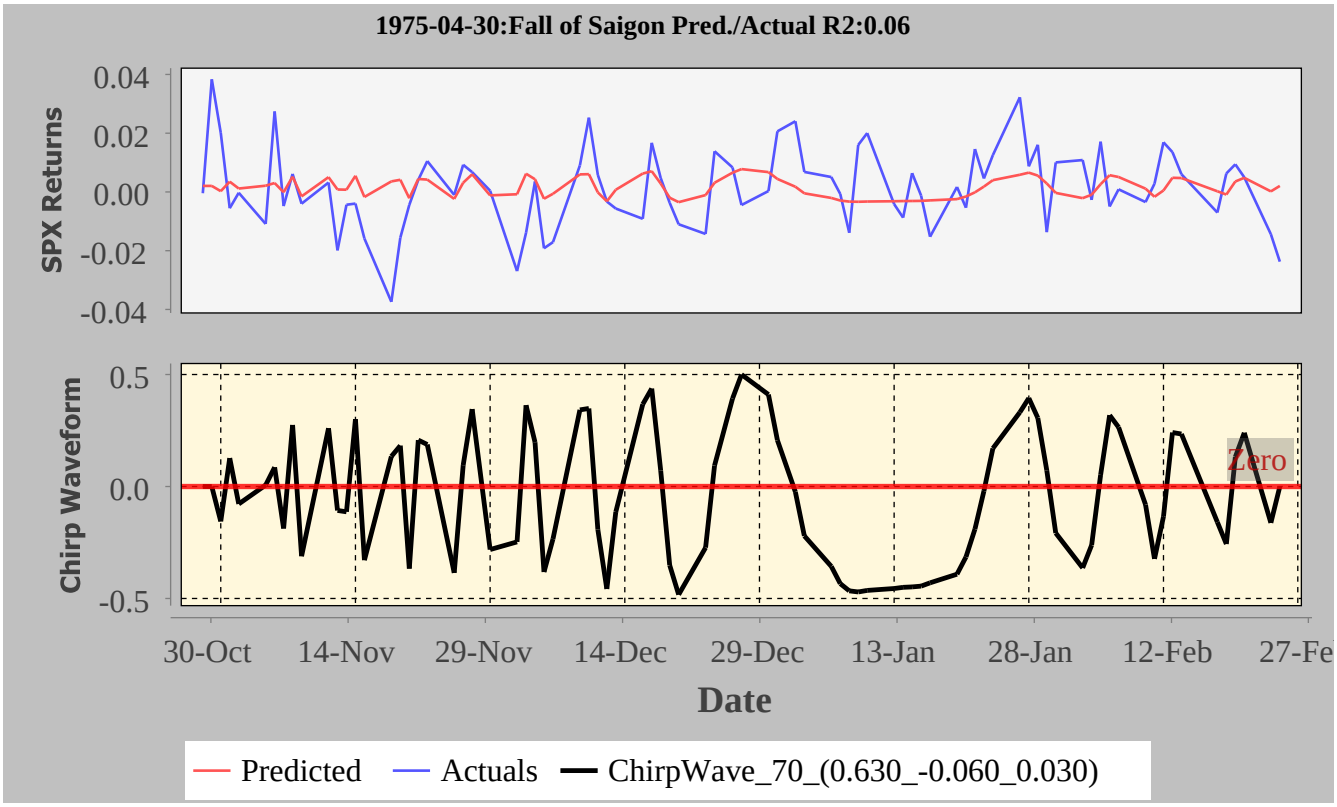

Figure (110) 1975-04-30:Fall of Saigon Pred./Actual R2:0.06 v:21.462%

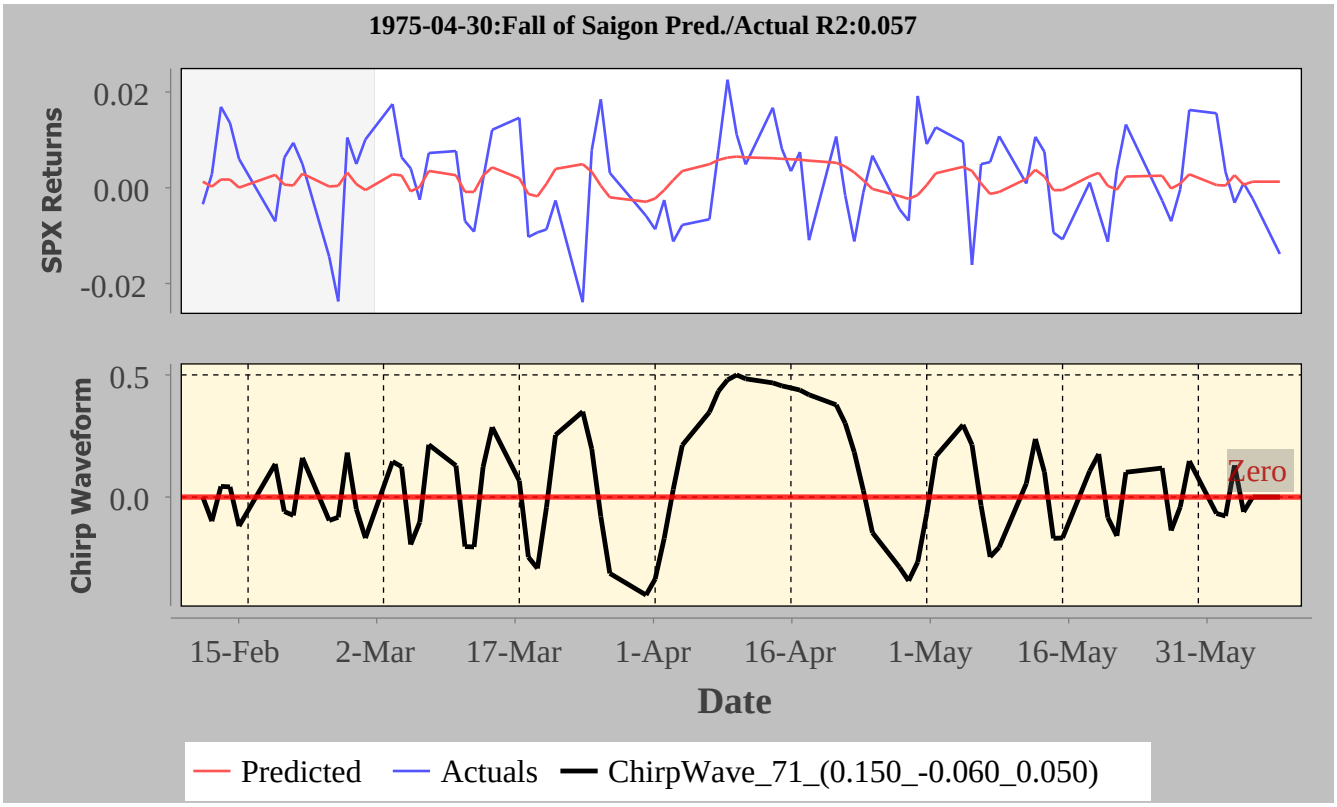

Figure (110) 1975-04-30:Fall of Saigon Pred./Actual R2:0.057 v:15.966%

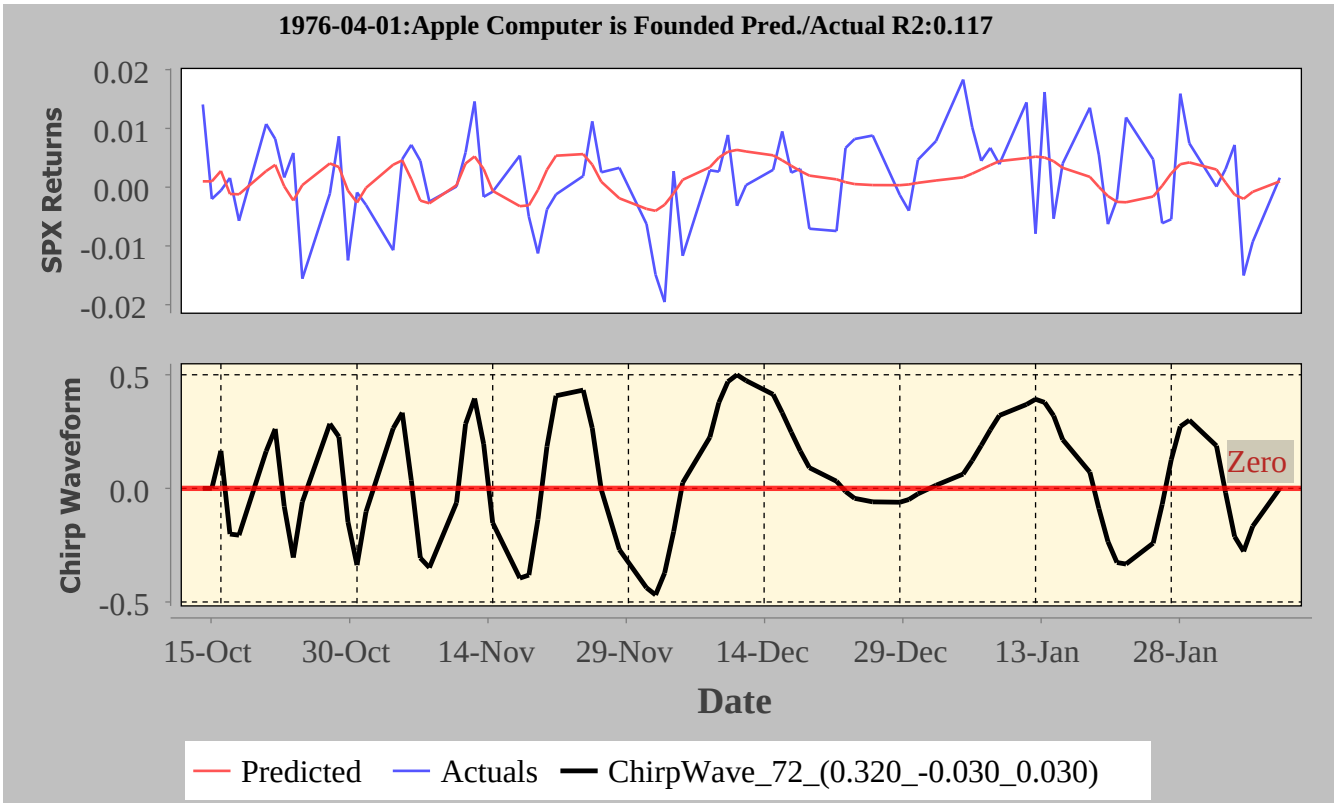

Figure (110) 1976-04-01:Apple Computer is Founded Pred./Actual R2:0.117 v:12.695%

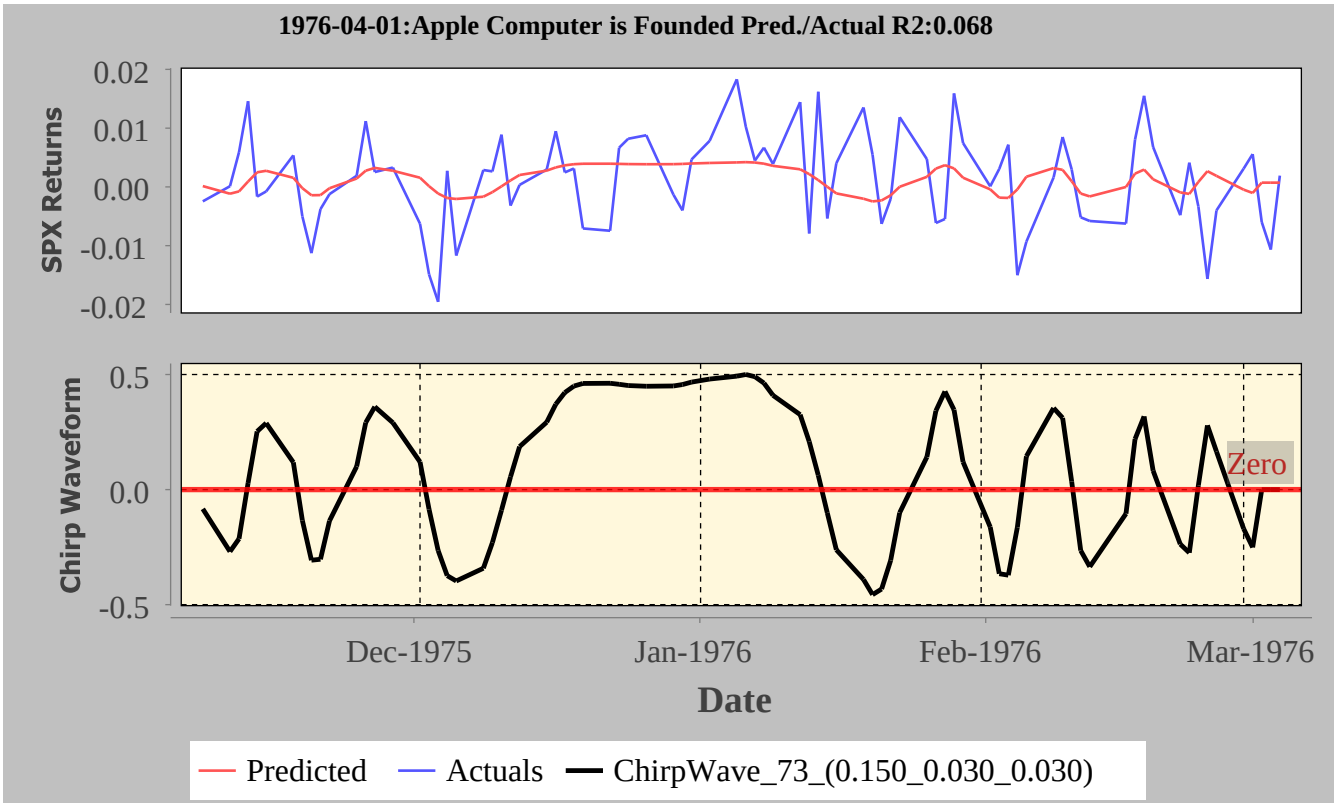

Figure (110) 1976-04-01:Apple Computer is Founded Pred./Actual R2:0.068 v:12.701%

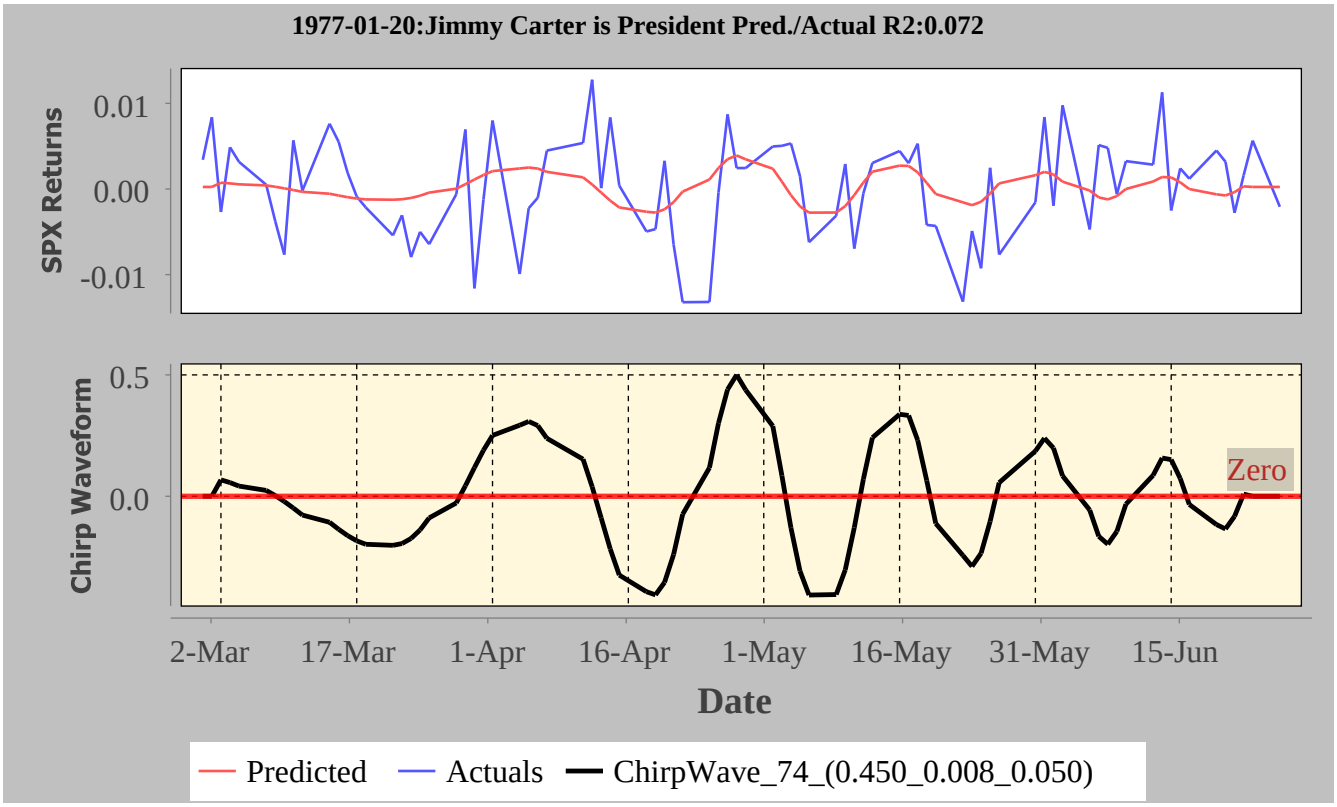

Figure (110) 1977-01-20:Jimmy Carter is President Pred./Actual R2:0.072 v:9.186%

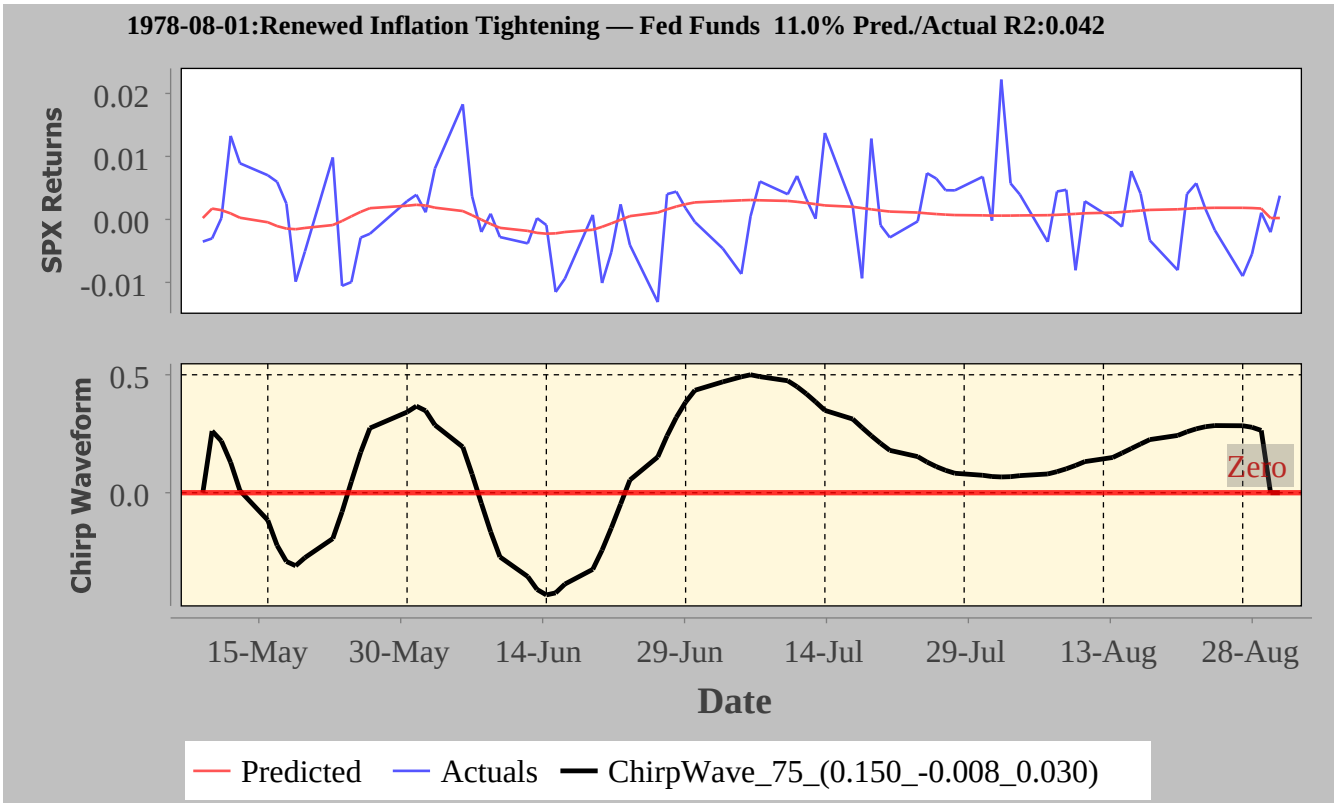

Figure (110) 1978-08-01:Renewed Inflation Tightening — Fed Funds 11.0% Pred./Actual R2:0.042 v:10.595%

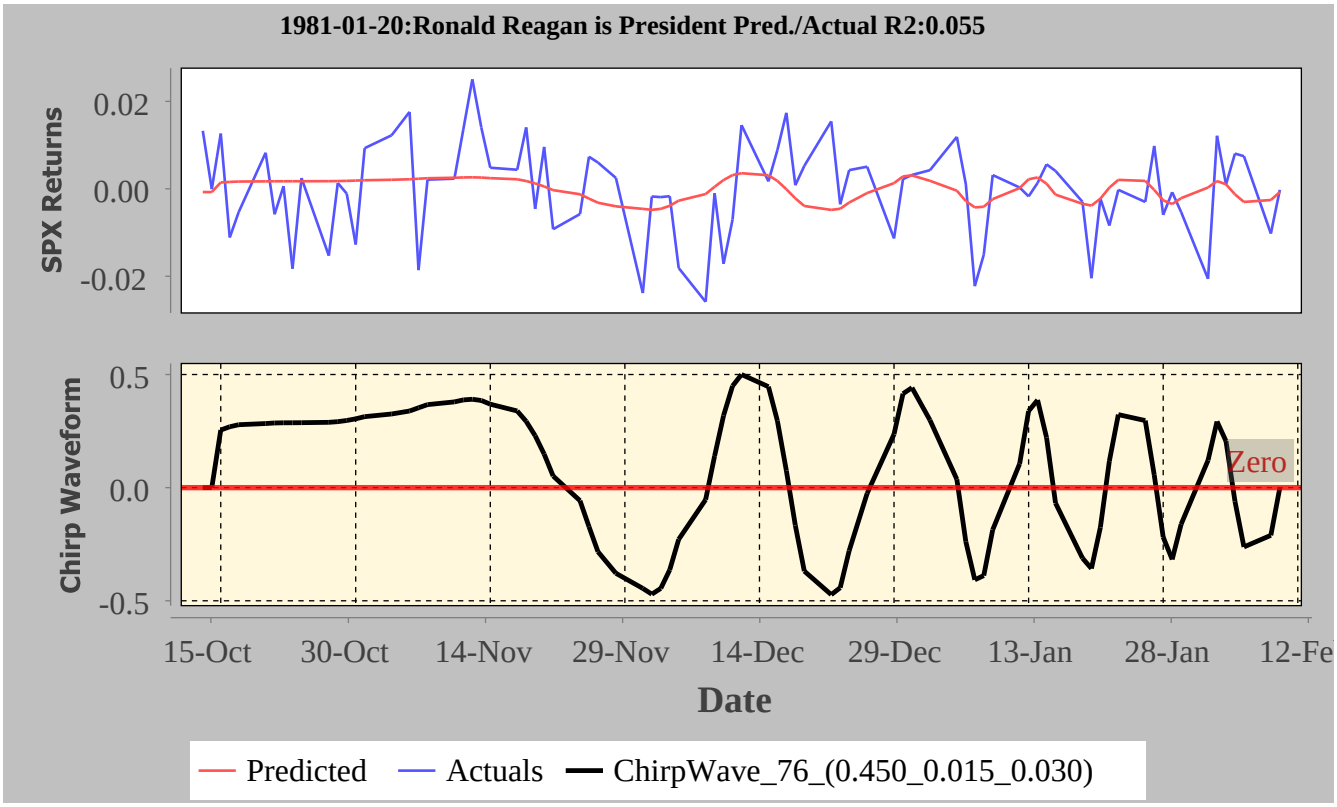

Figure (110) 1981-01-20:Ronald Reagan is President Pred./Actual R2:0.055 v:16.82%

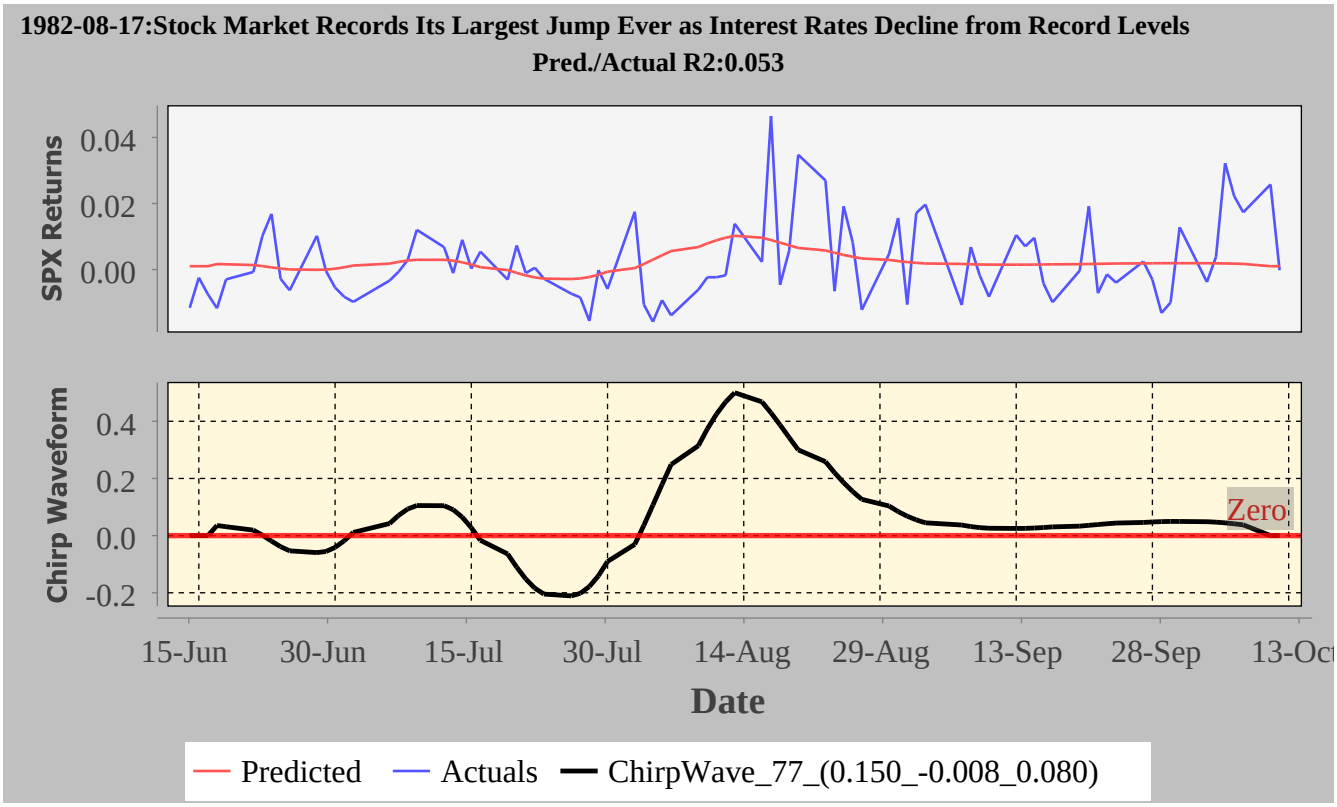

Figure (110) 1982-08-17:Stock Market Records Its Largest Jump Ever as Interest Rates Decline from Record Levels Pred./Actual R2:0.053 v:19.355%

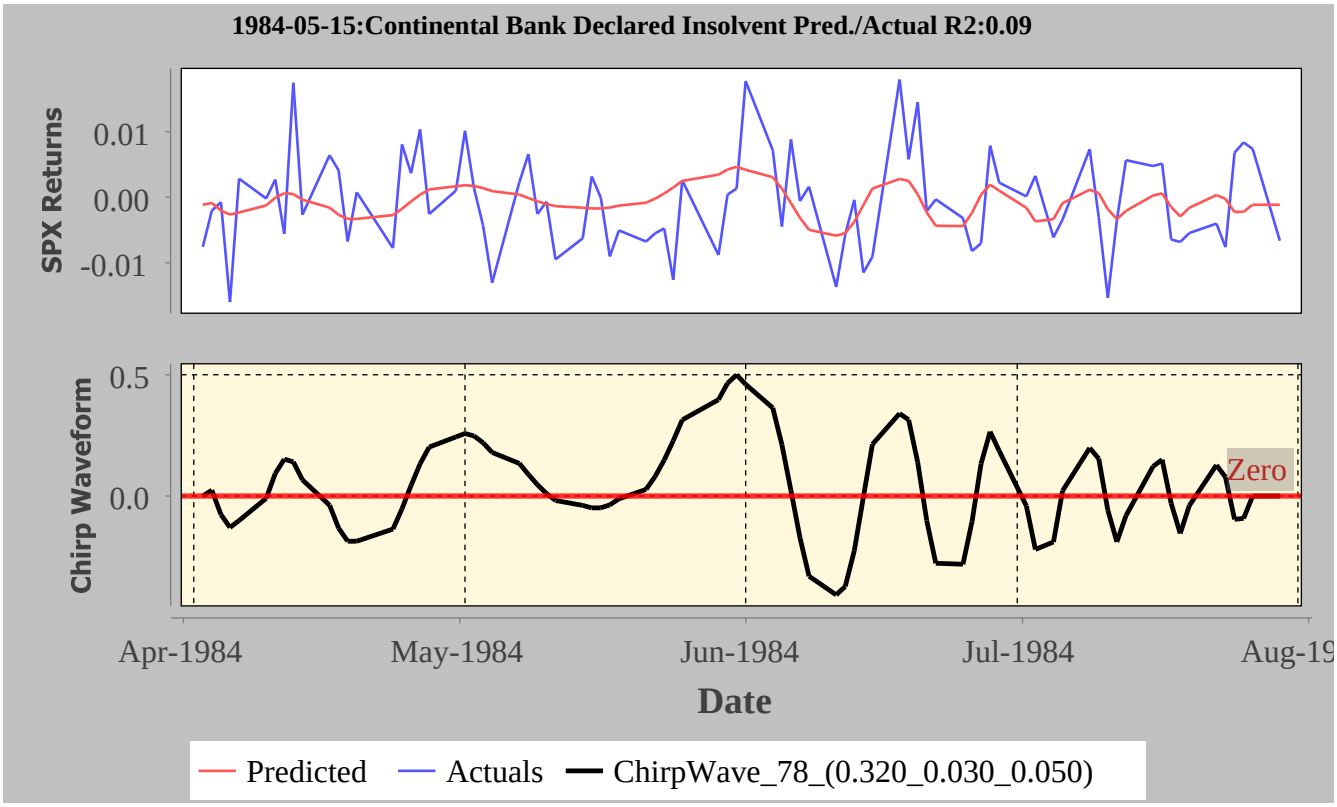

Figure (110) 1984-05-15:Continental Bank Declared Insolvent Pred./Actual R2:0.09 v:11.703%

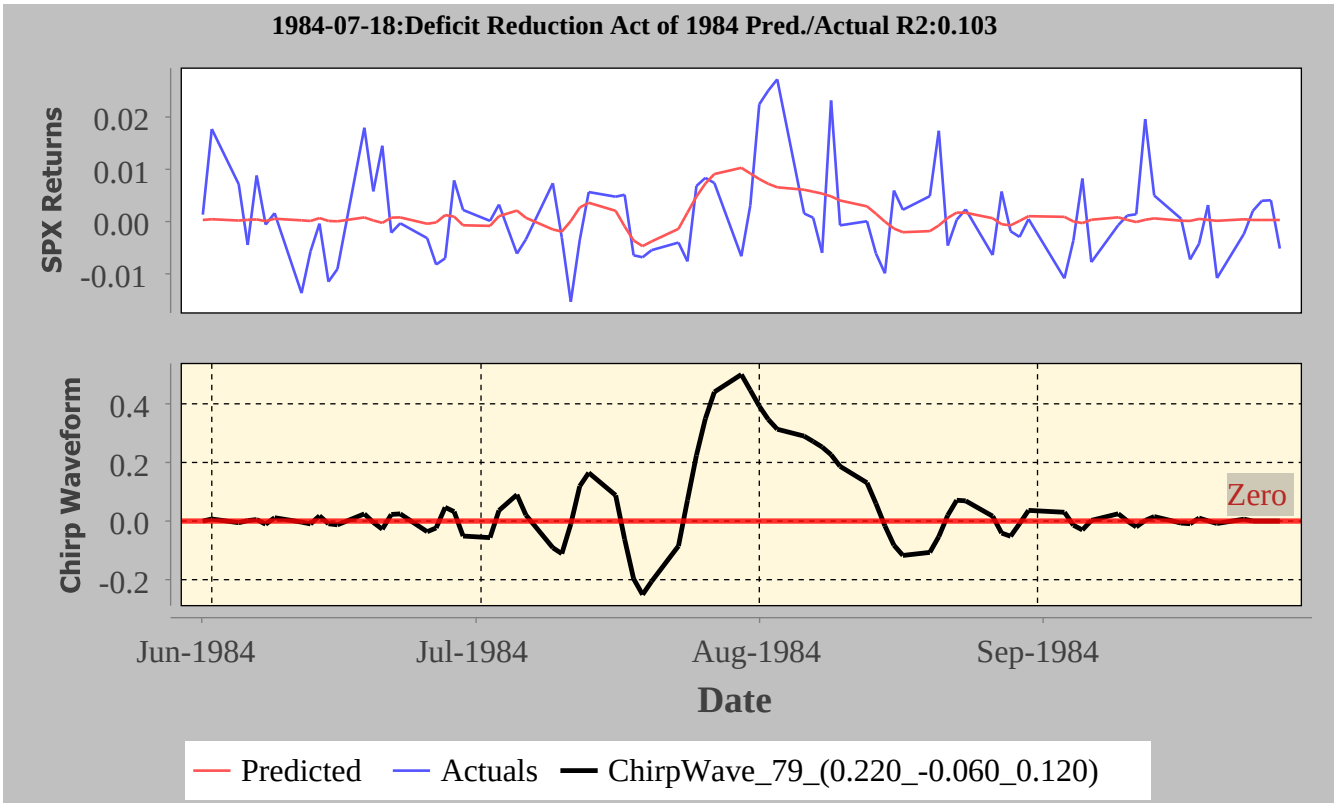

Figure (110) 1984-07-18:Deficit Reduction Act of 1984 Pred./Actual R2:0.103 v:13.879%

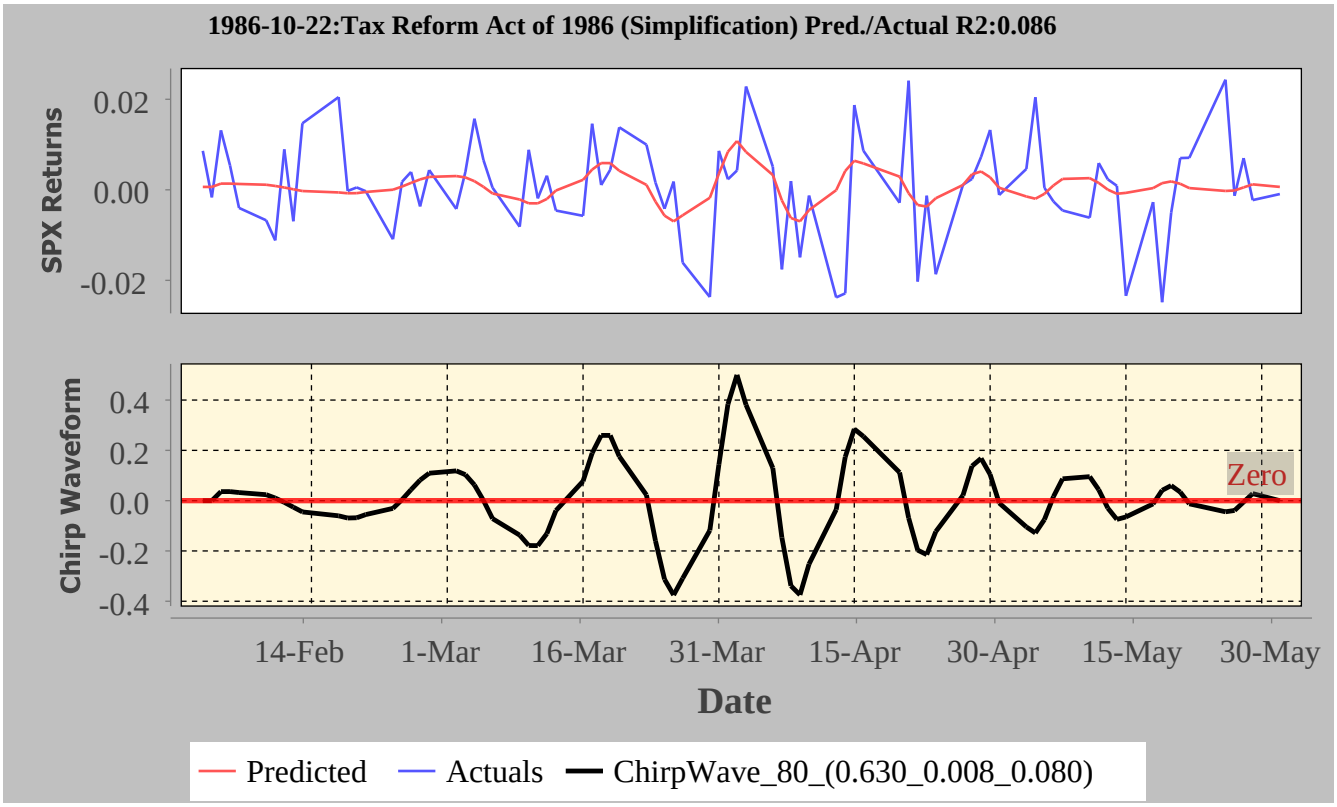

Figure (110) 1986-10-22:Tax Reform Act of 1986 (Simplification) Pred./Actual R2:0.086 v:17.564%

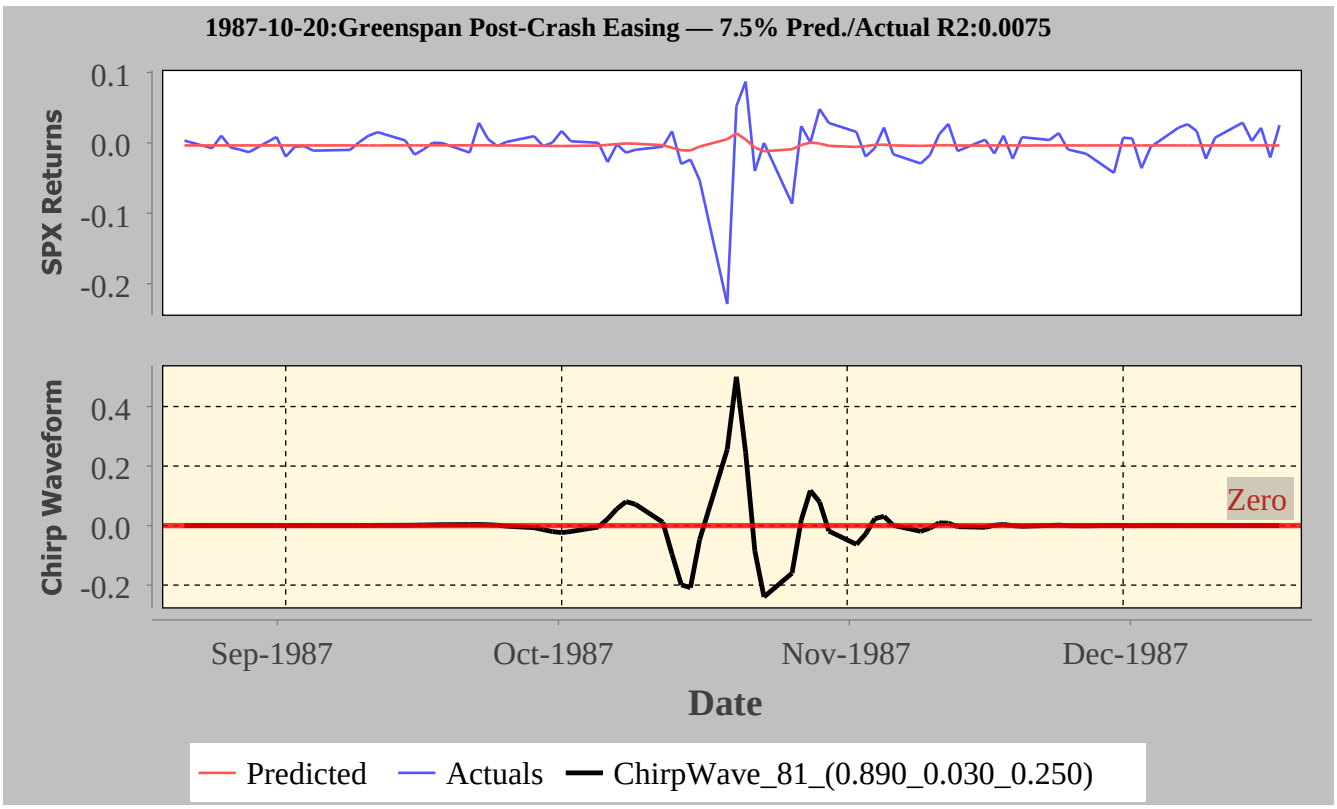

Figure (110) 1987-10-20:Greenspan Post-Crash Easing — 7.5% Pred./Actual R2:0.0075 v:54.011%

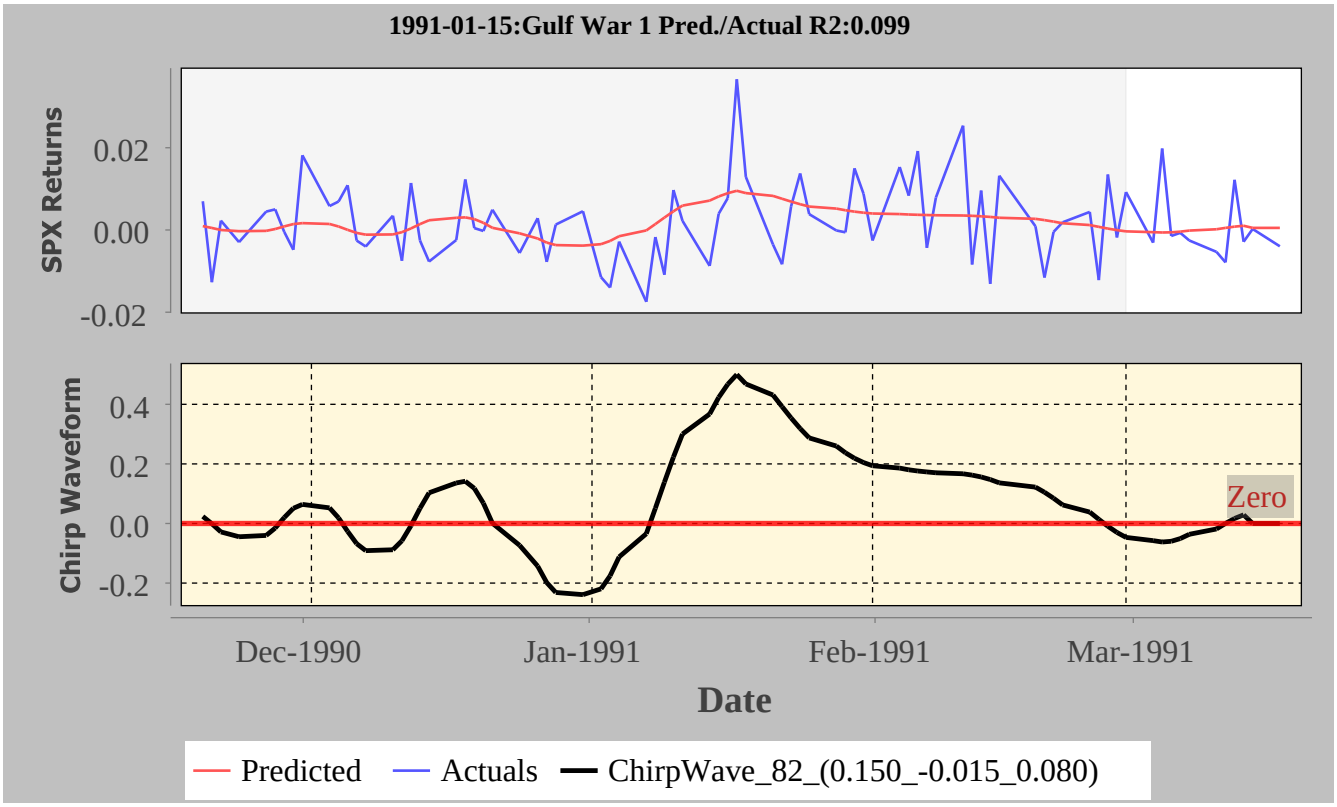

Figure (110) 1991-01-15:Gulf War 1 Pred./Actual R2:0.099 v:15.182%

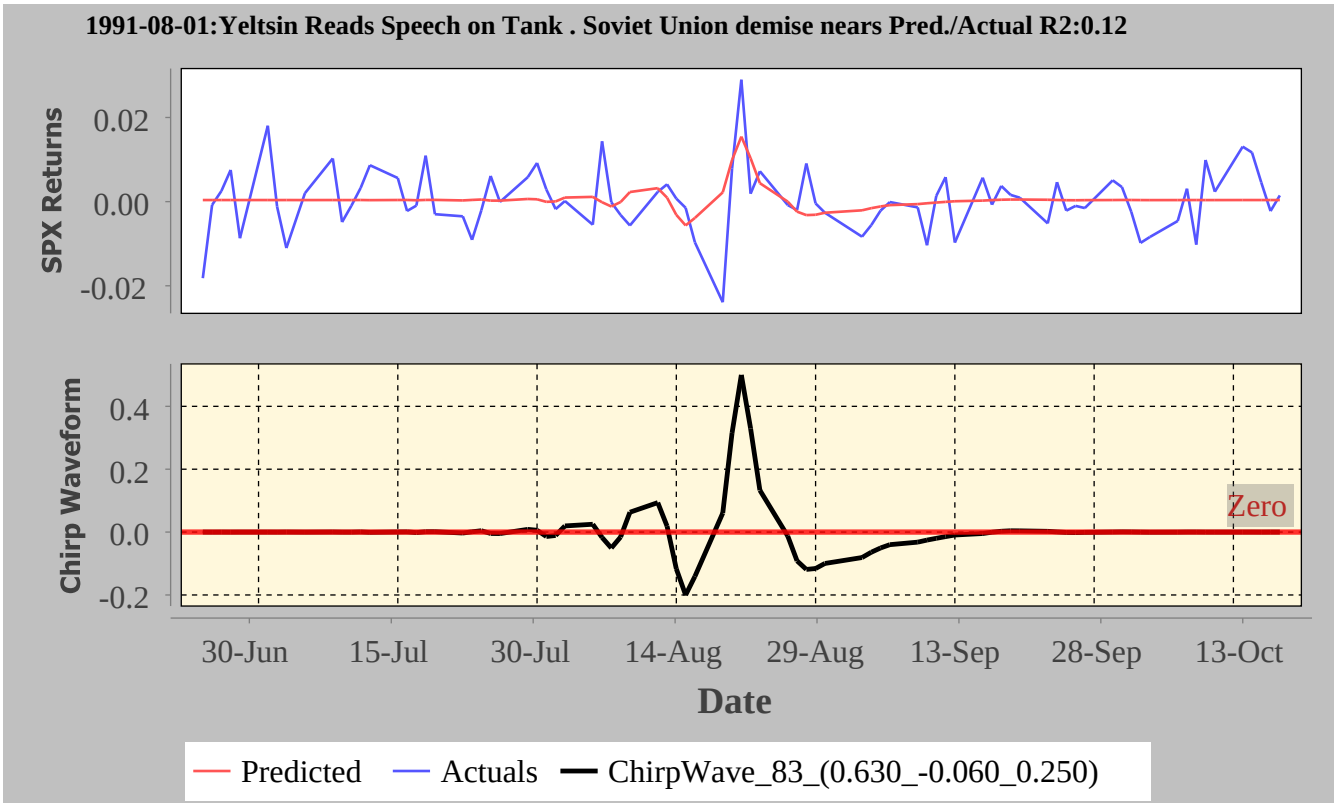

Figure (110) 1991-08-01:Yeltsin Reads Speech on Tank . Soviet Union demise nears Pred./Actual R2:0.12 v:12.156%

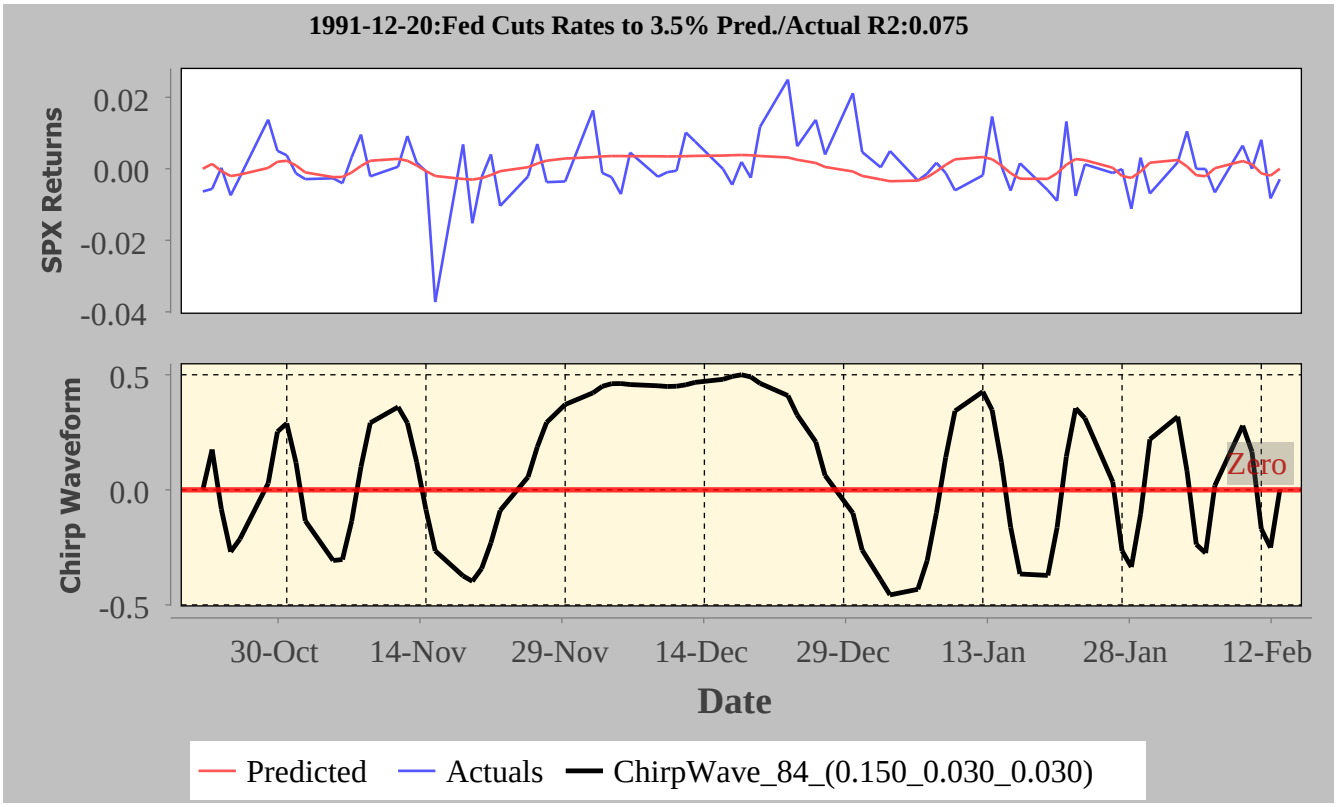

Figure (110) 1991-12-20:Fed Cuts Rates to 3.5% Pred./Actual R2:0.075 v:13.271%

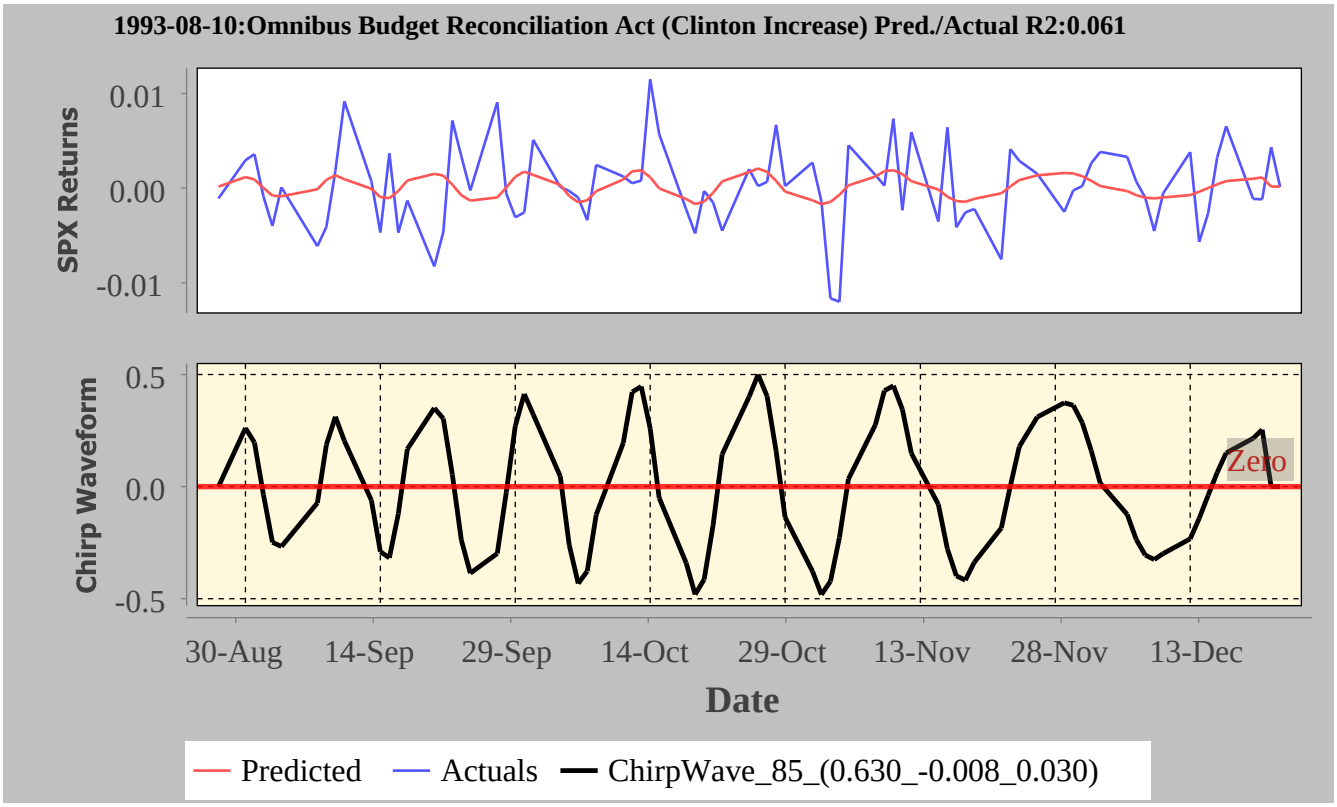

Figure (110) 1993-08-10:Omnibus Budget Reconciliation Act (Clinton Increase) Pred./Actual R2:0.061 v:6.936%

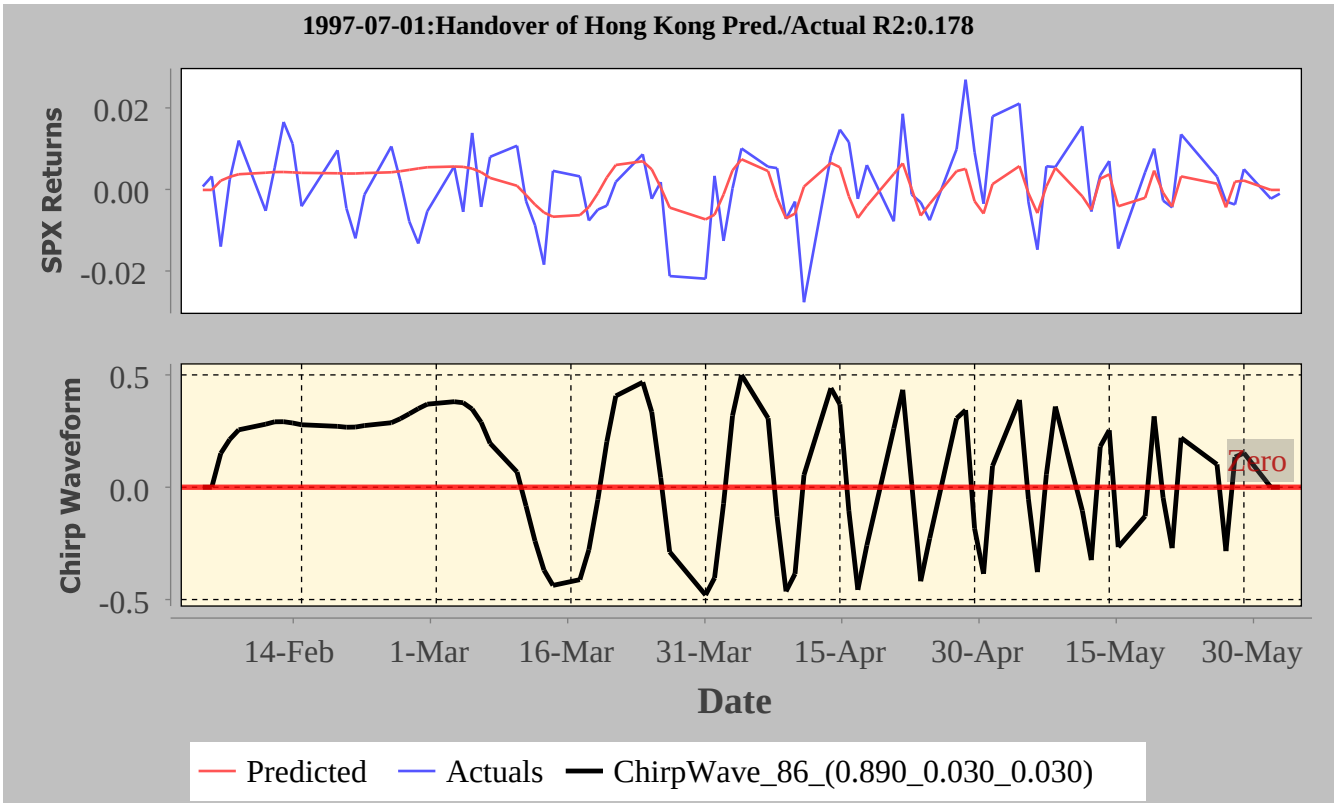

Figure (110) 1997-07-01:Handover of Hong Kong Pred./Actual R2:0.178 v:15.994%

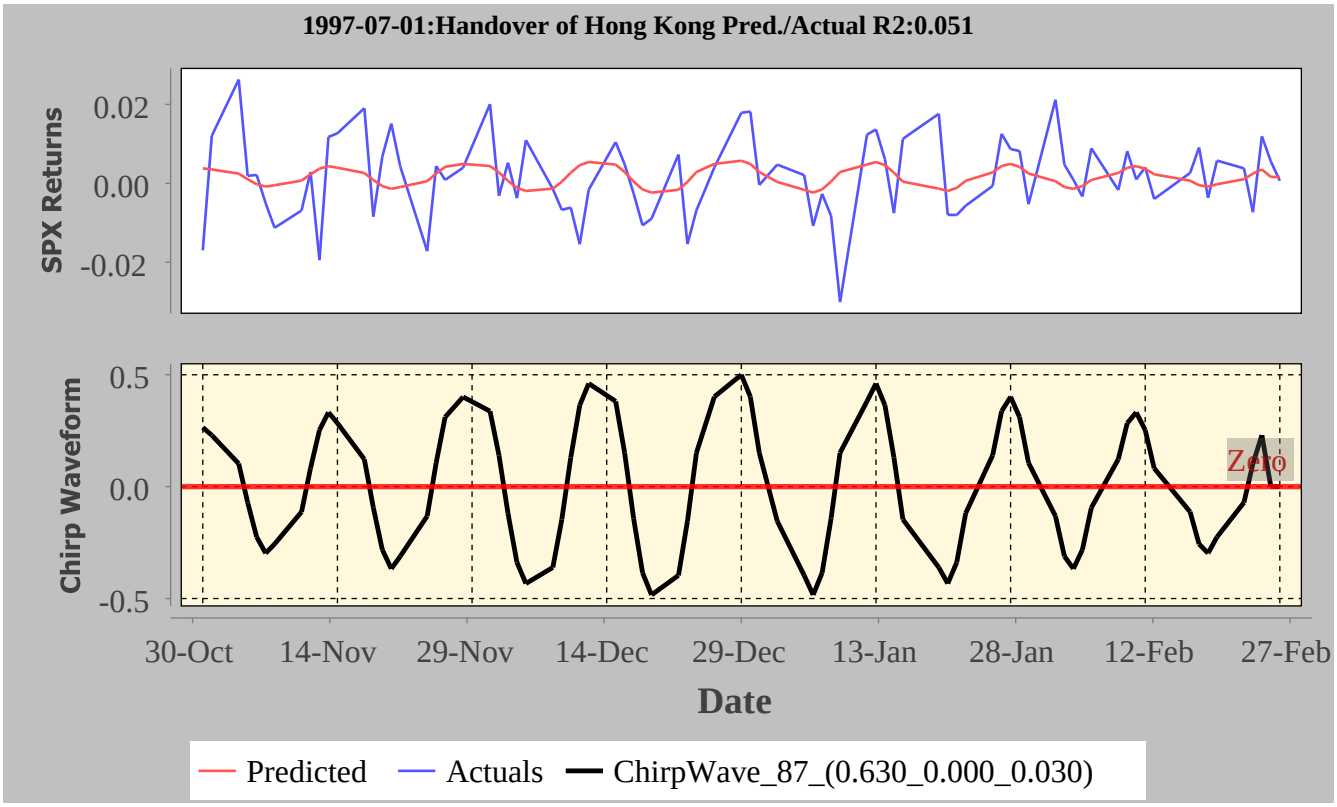

Figure (110) 1997-07-01:Handover of Hong Kong Pred./Actual R2:0.051 v:16.38%

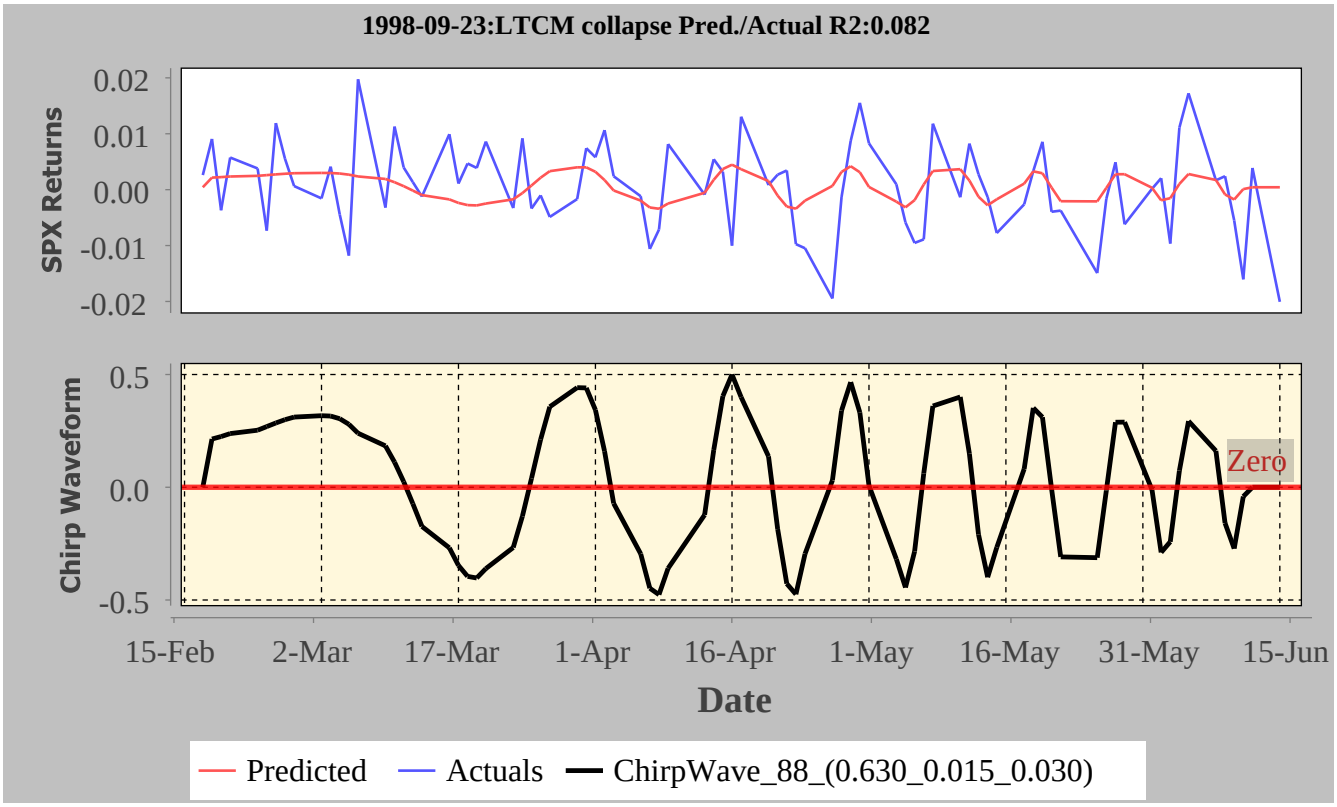

Figure (110) 1998-09-23:LTCM collapse Pred./Actual R2:0.082 v:12.734%

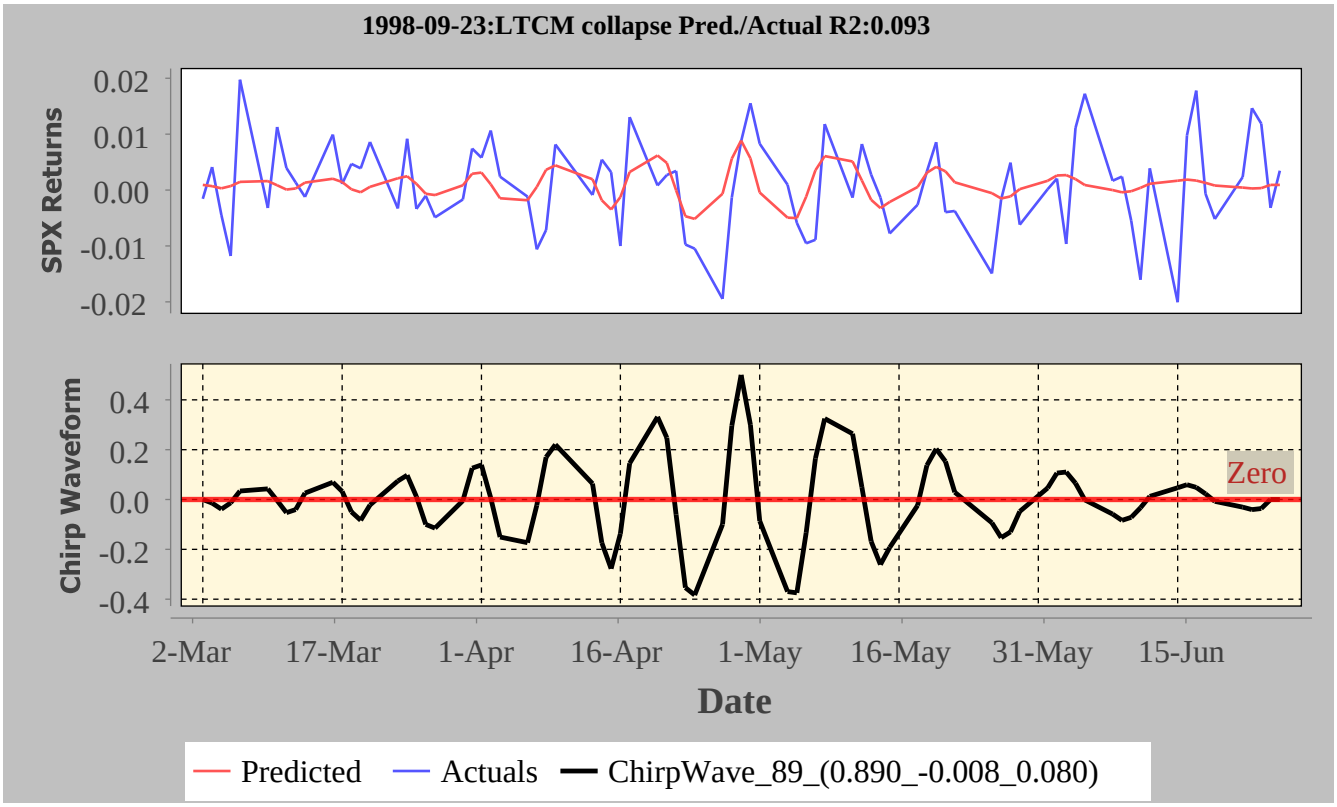

Figure (110) 1998-09-23:LTCM collapse Pred./Actual R2:0.093 v:13.22%

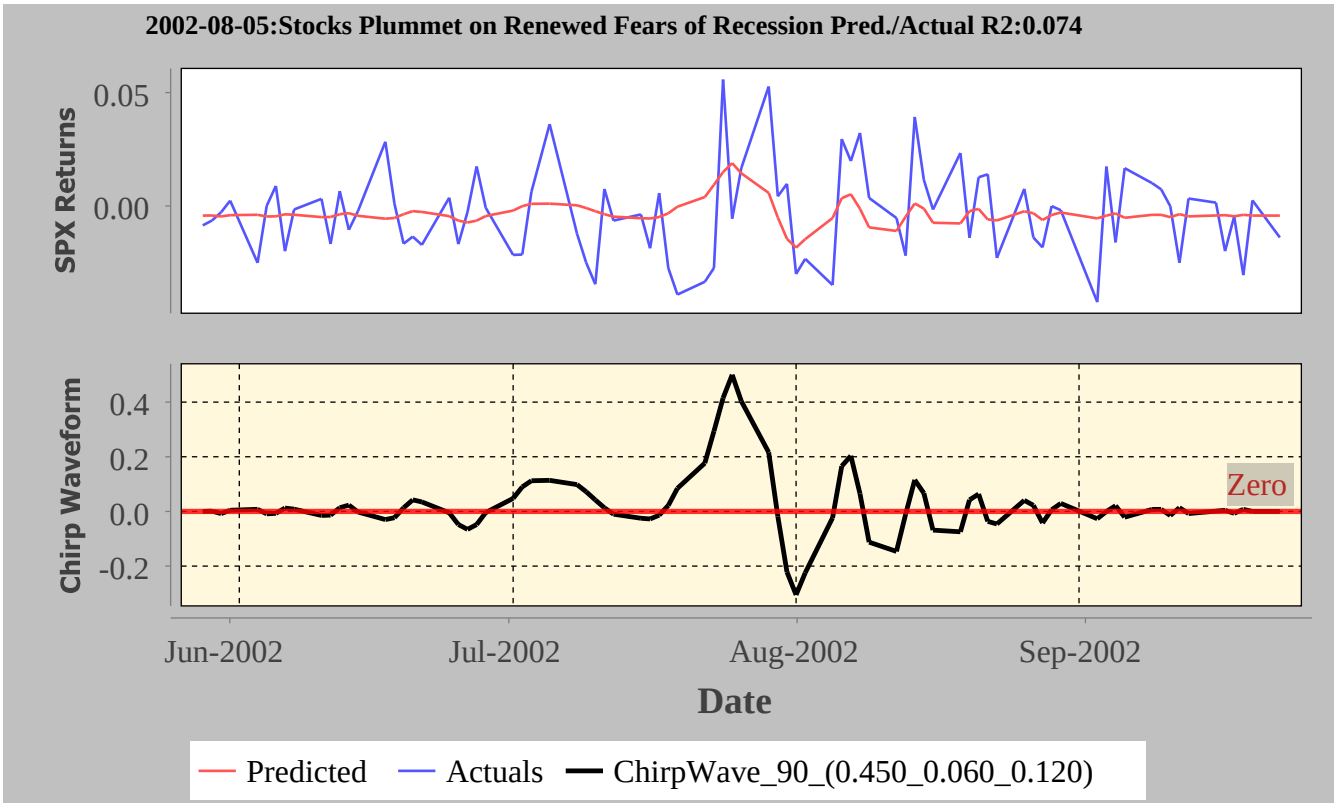

Figure (110) 2002-08-05:Stocks Plummet on Renewed Fears of Recession Pred./Actual R2:0.074 v:31.637%

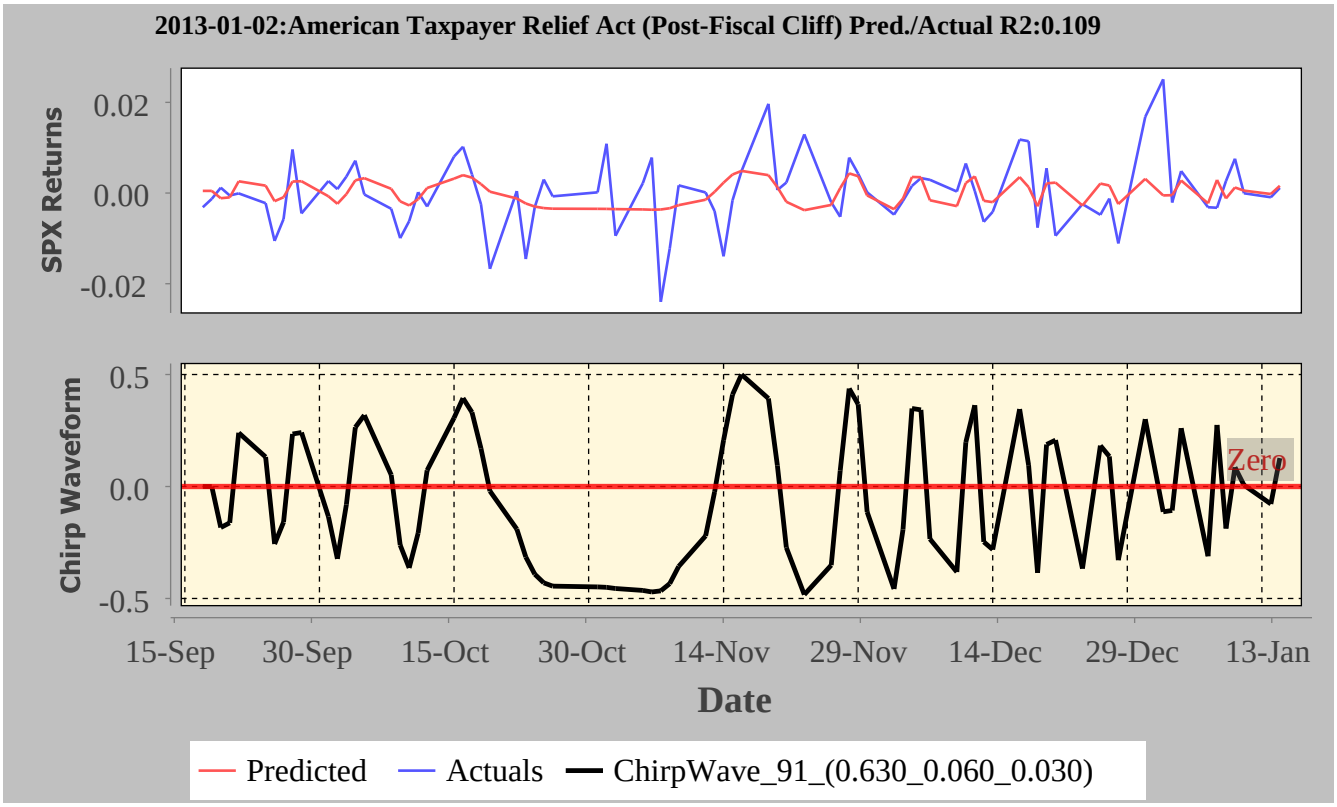

Figure (110) 2013-01-02:American Taxpayer Relief Act (Post-Fiscal Cliff) Pred./Actual R2:0.109 v:12.336%

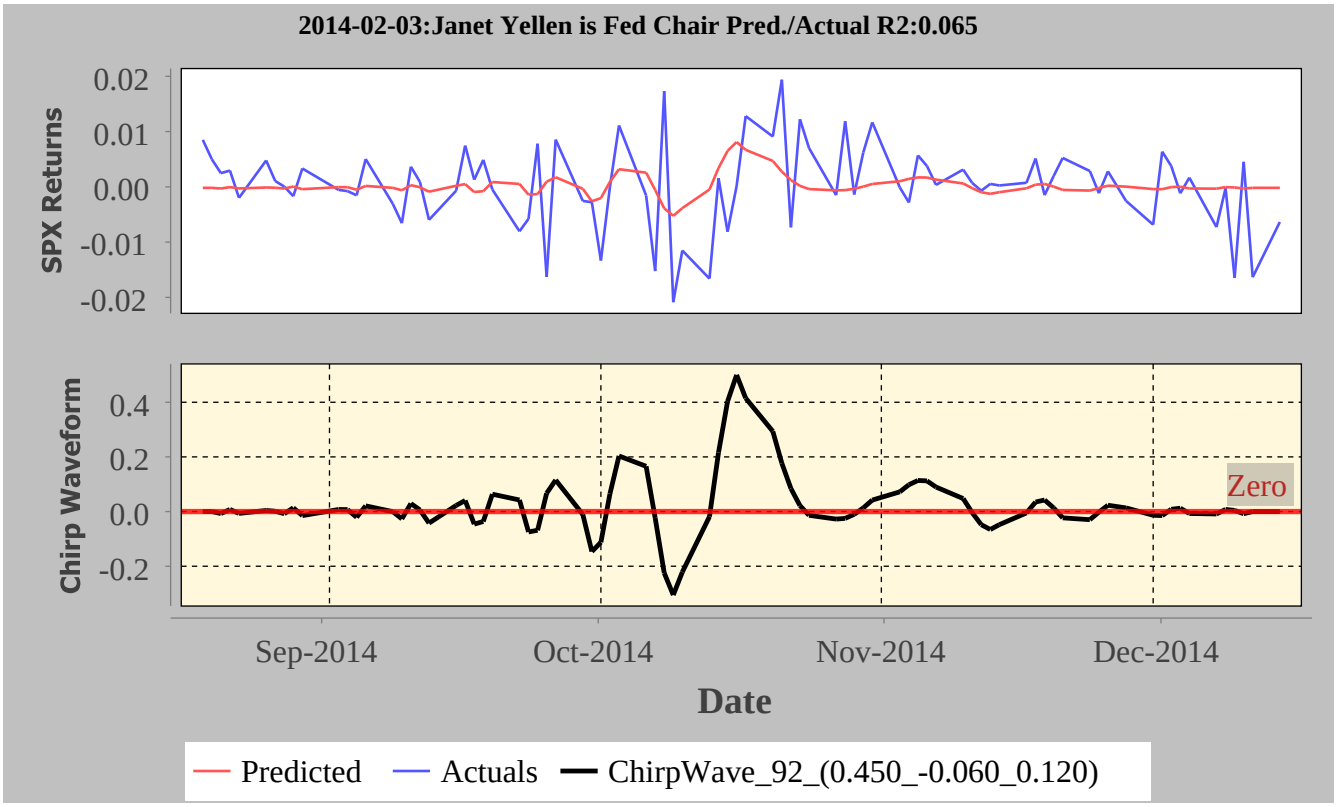

Figure (110) 2014-02-03:Janet Yellen is Fed Chair Pred./Actual R2:0.065 v:11.979%

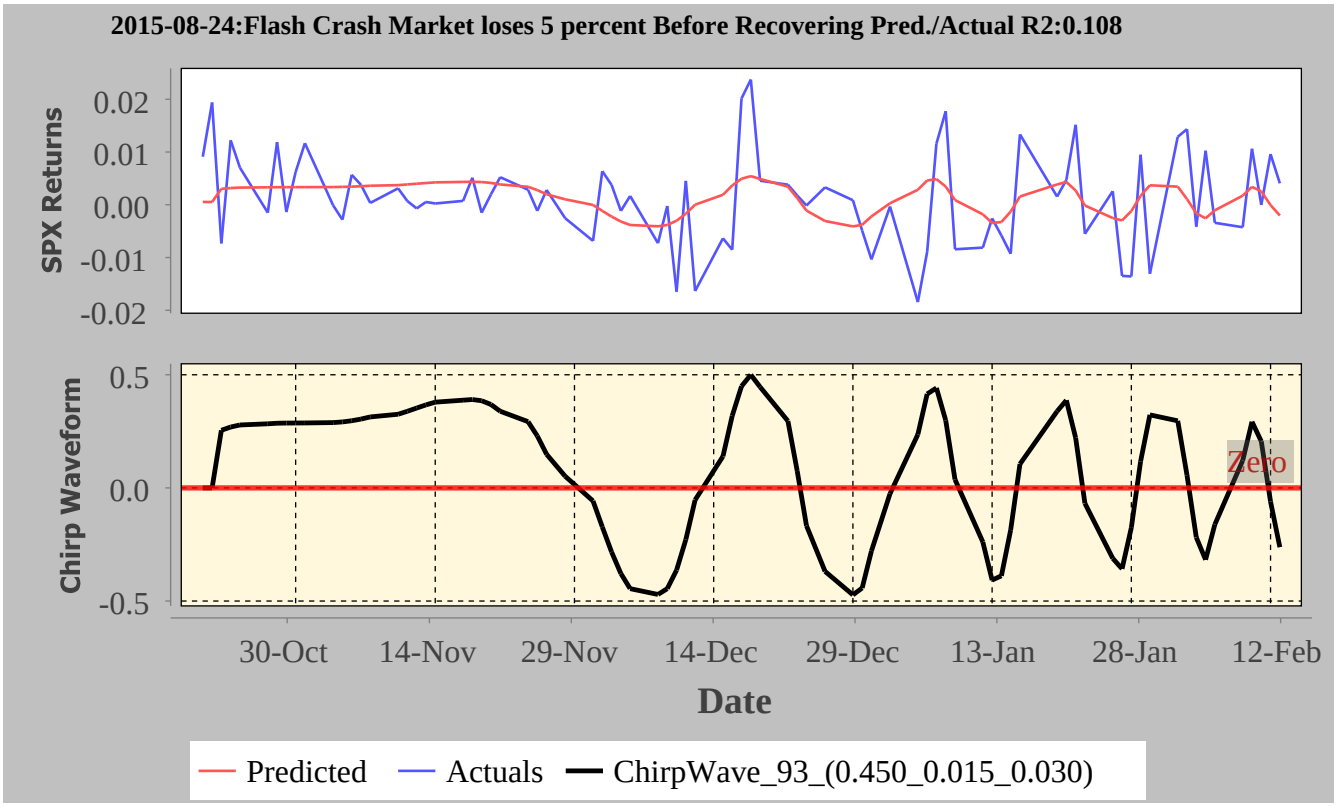

Figure (110) 2015-08-24:Flash Crash Market loses 5 percent Before Recovering Pred./Actual R2:0.108 v:13.746%

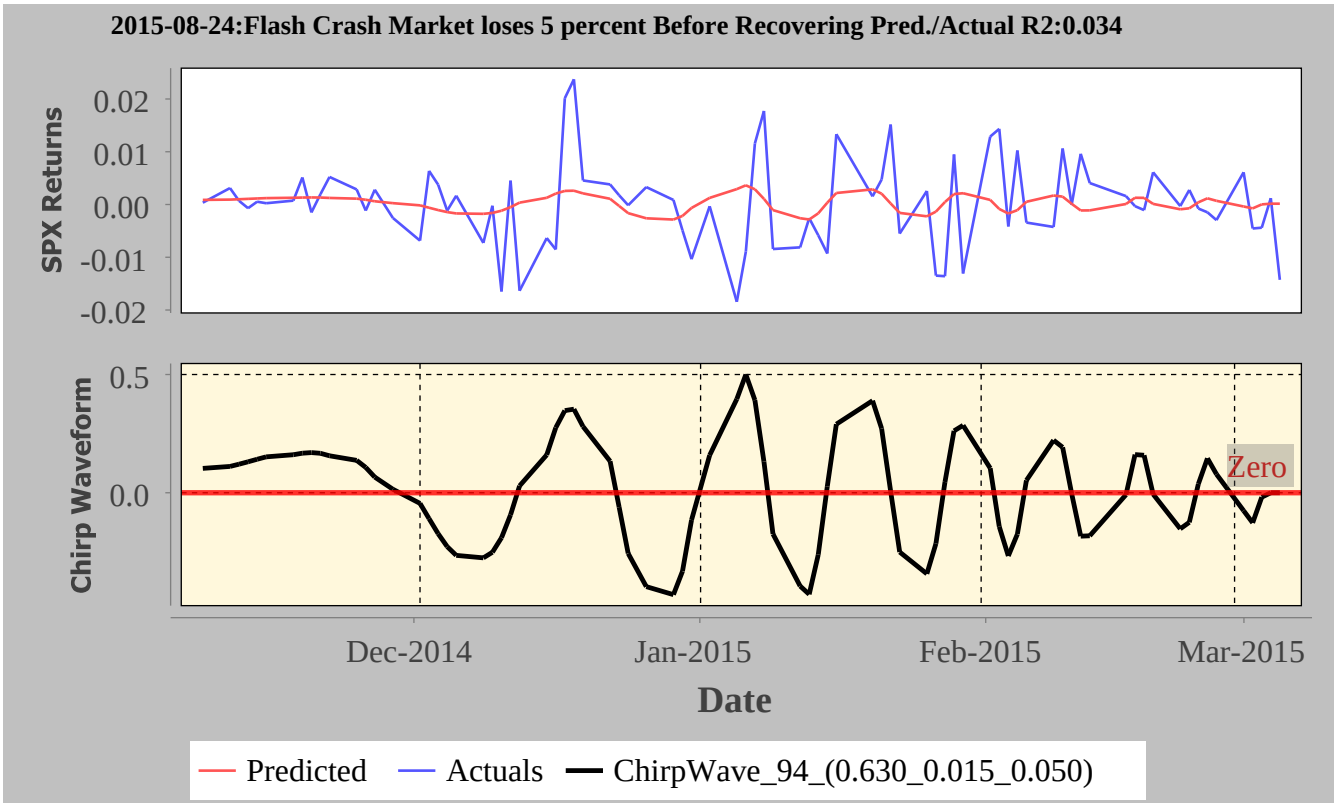

Figure (110) 2015-08-24:Flash Crash Market loses 5 percent Before Recovering Pred./Actual R2:0.034 v:13.029%

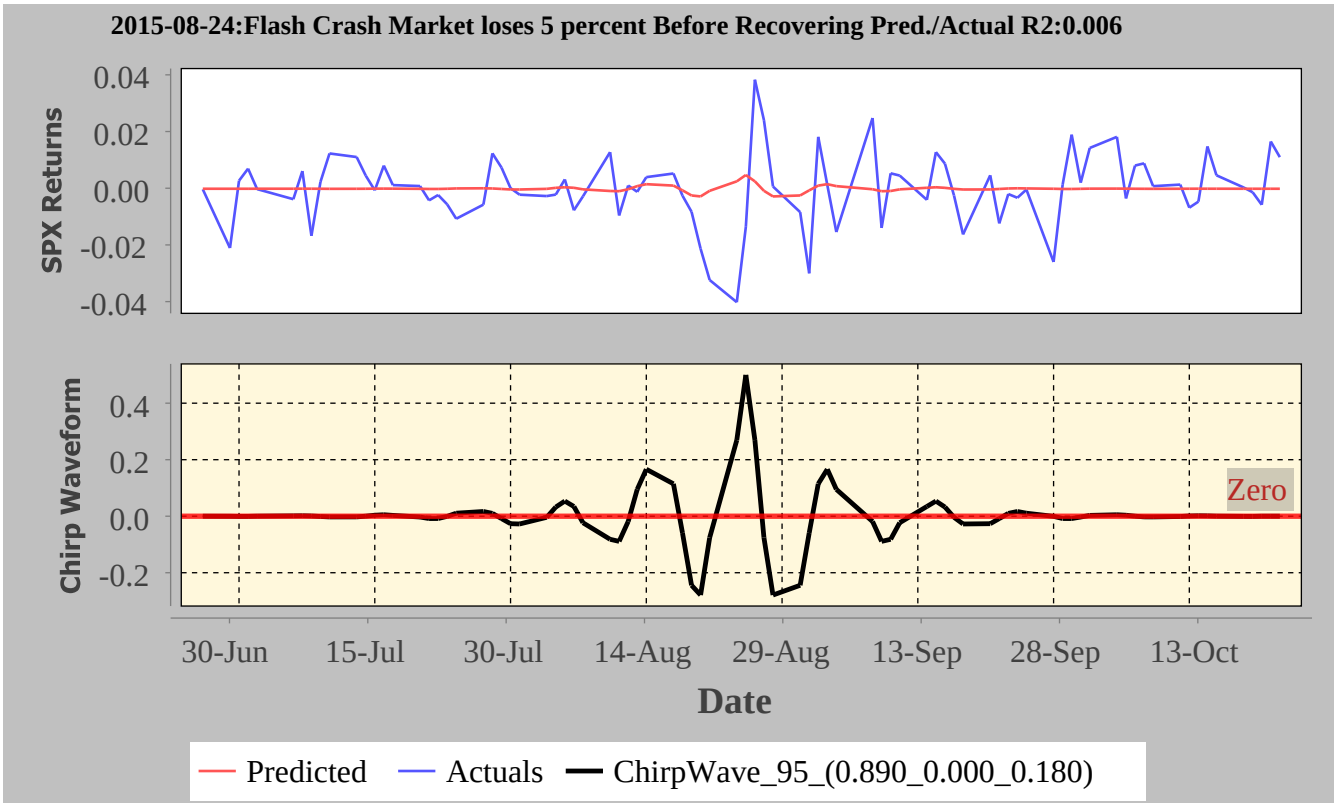

Figure (110) 2015-08-24:Flash Crash Market loses 5 percent Before Recovering Pred./Actual R2:0.006 v:19.867%

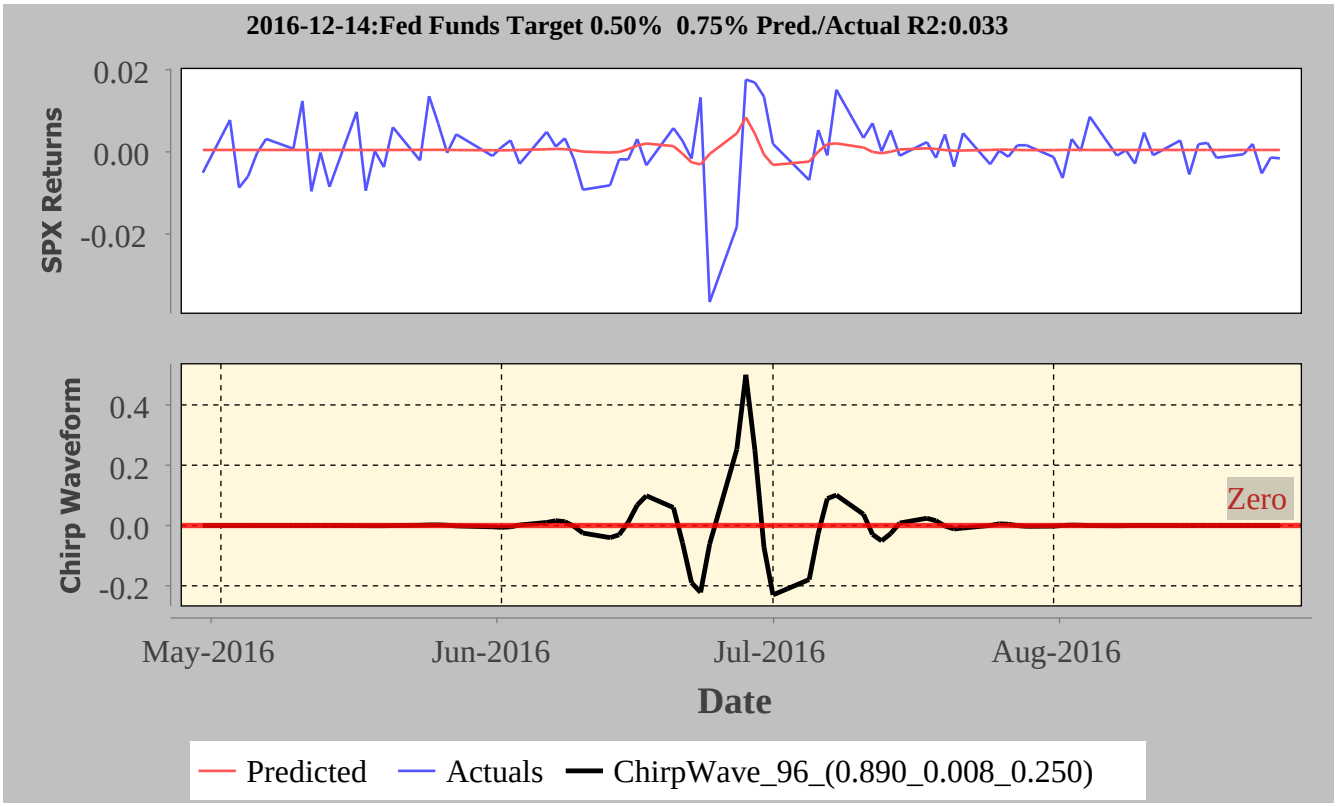

Figure (110) 2016-12-14:Fed Funds Target 0.50% 0.75% Pred./Actual R2:0.033 v:11.837%

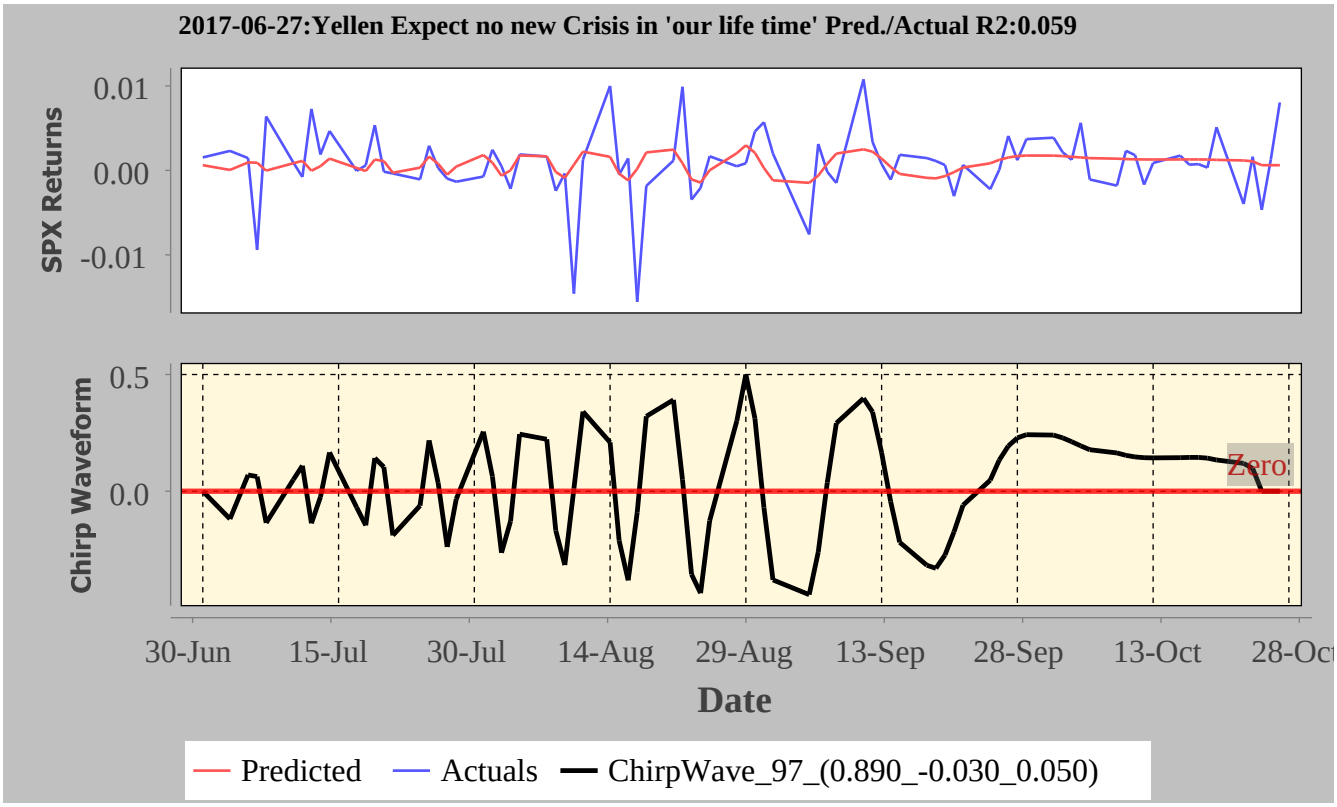

Figure (110) 2017-06-27:Yellen Expect no new Crisis in 'our life time' Pred./Actual R2:0.059 v:6.594%

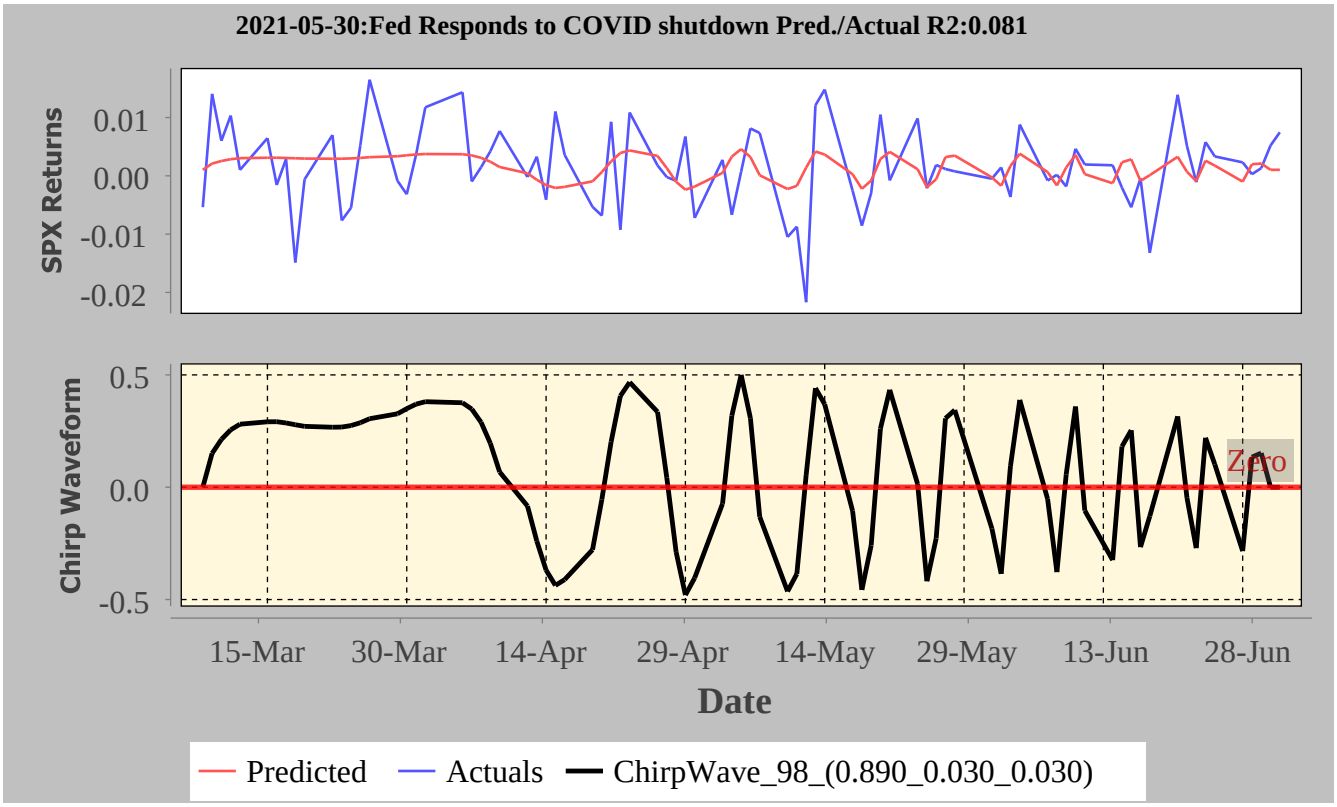

Figure (110) 2021-05-30:Fed Responds to COVID shutdown Pred./Actual R2:0.081 v:11.307%

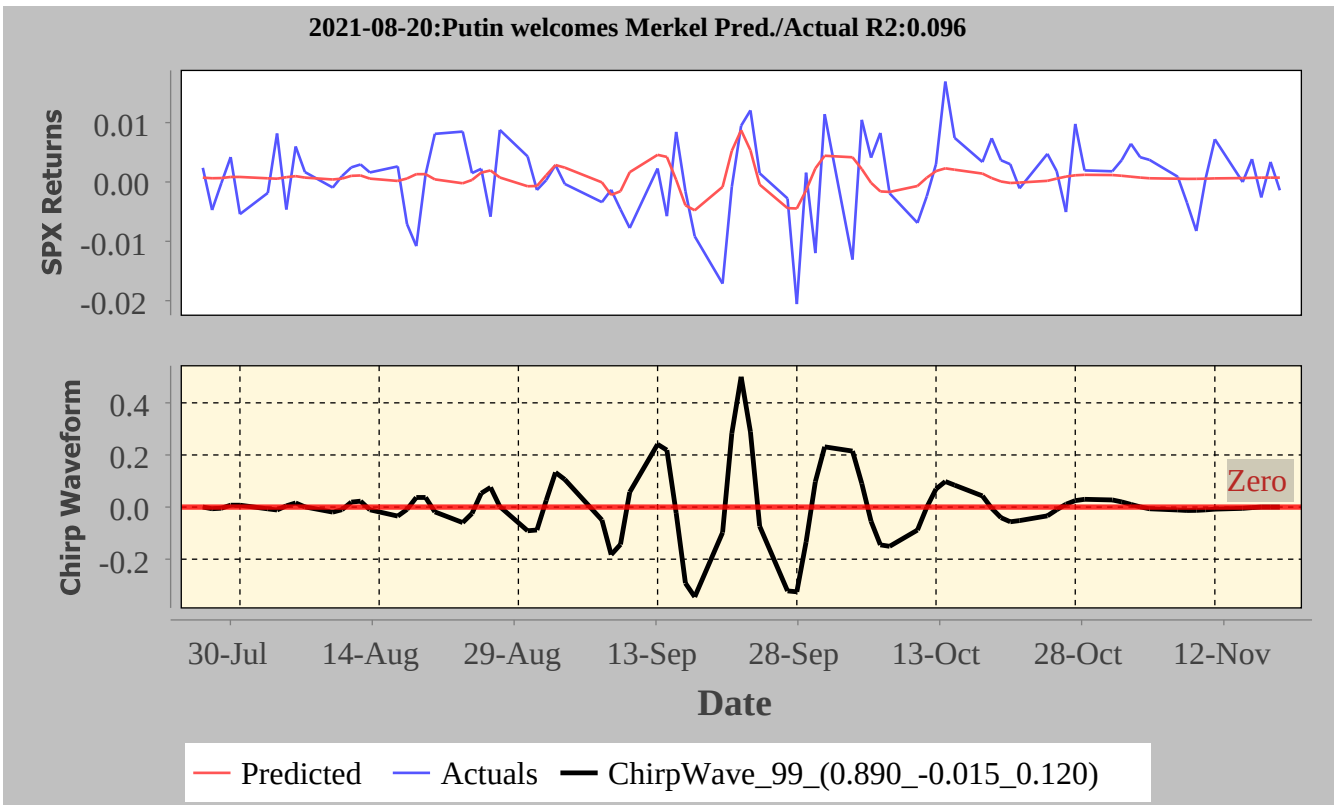

Figure (110) 2021-08-20:Putin welcomes Merkel Pred./Actual R2:0.096 v:10.217%

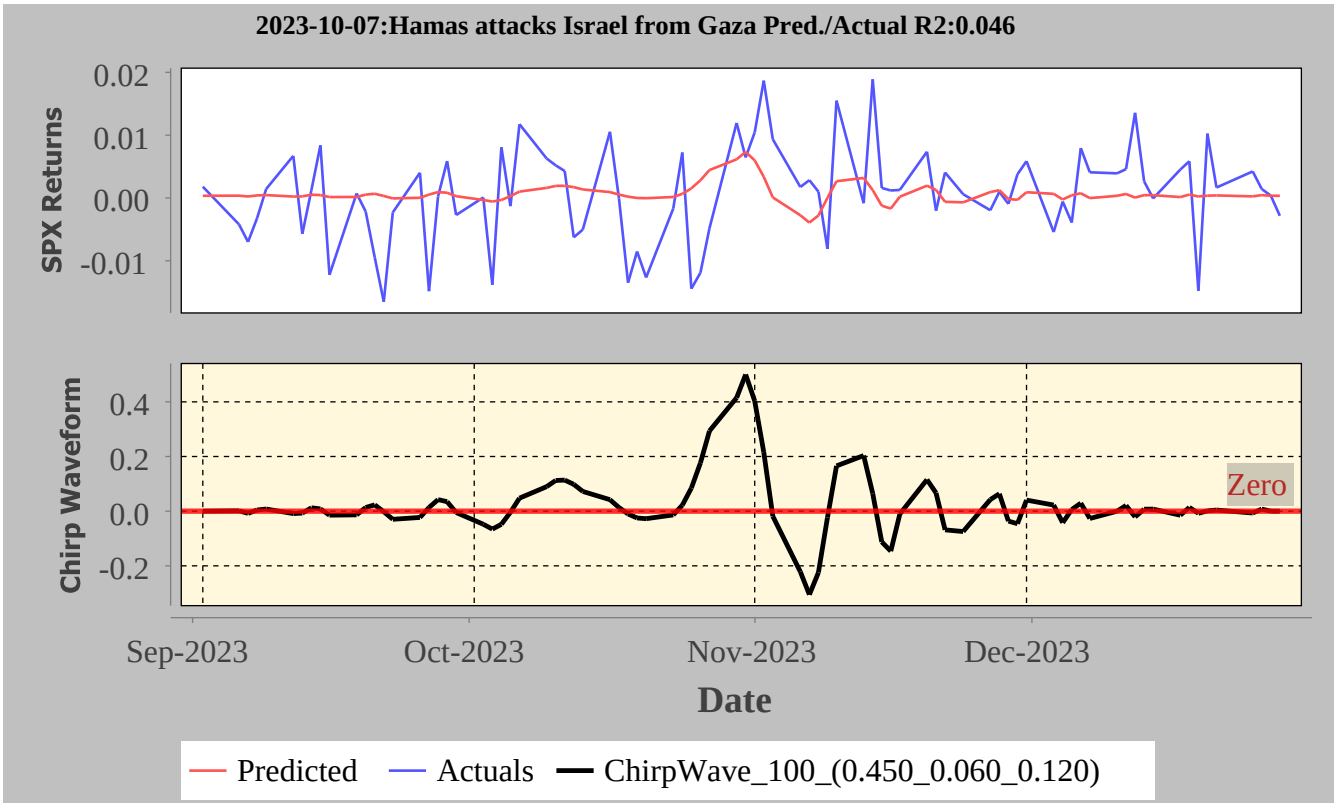

Figure (110) 2023-10-07:Hamas attacks Israel from Gaza Pred./Actual R2:0.046 v:12.141%

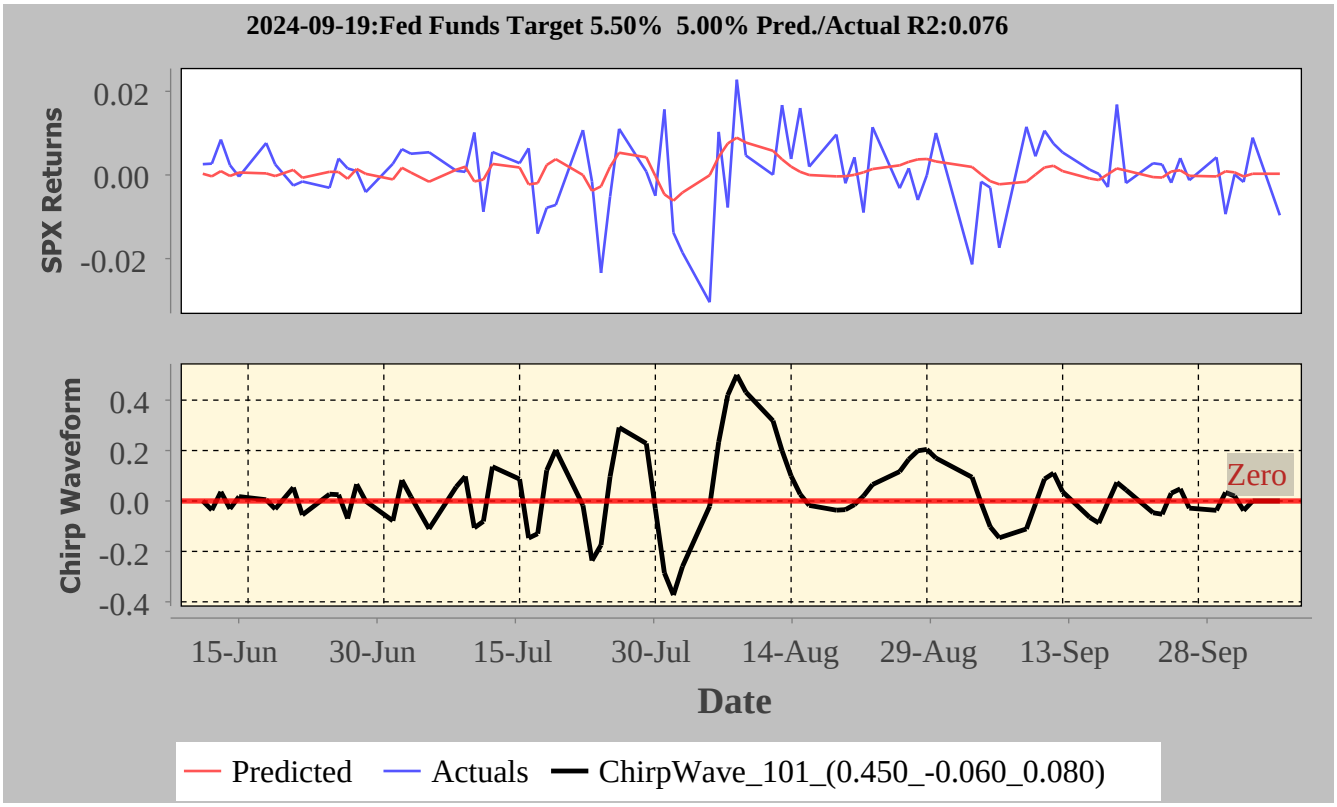

Figure (110) 2024-09-19:Fed Funds Target 5.50% 5.00% Pred./Actual R2:0.076 v:14.509%

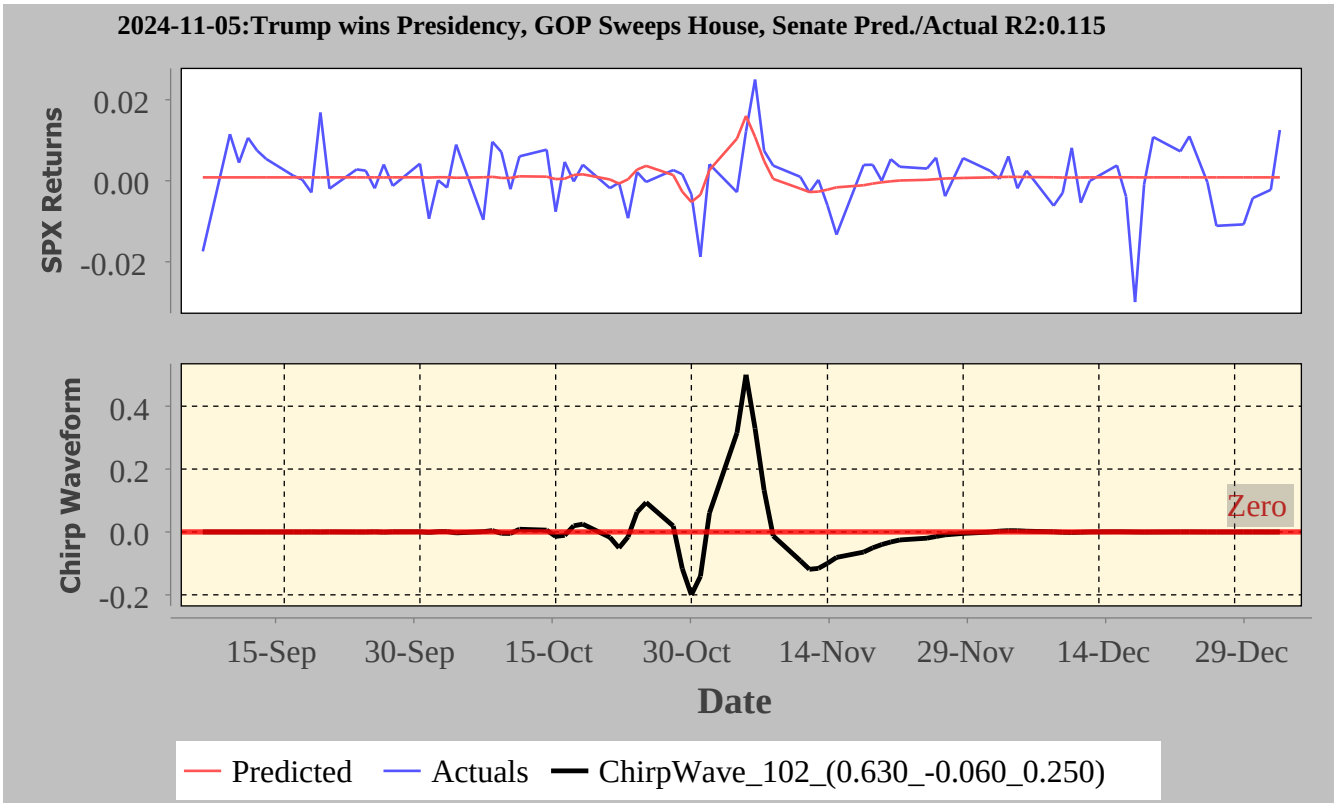

Figure (110) 2024-11-05:Trump wins Presidency, GOP Sweeps House, Senate Pred./Actual R2:0.115 v:12.495%

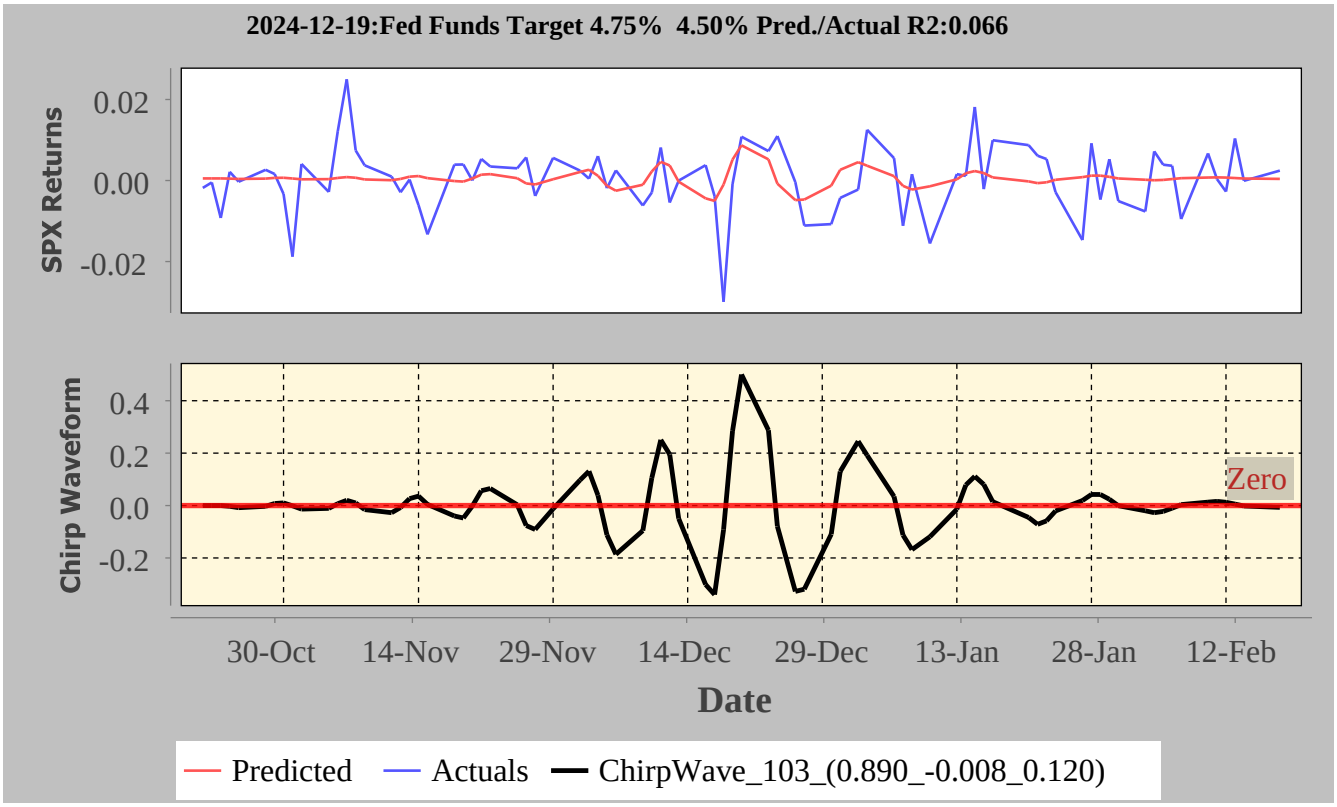

Figure (110) 2024-12-19:Fed Funds Target 4.75% 4.50% Pred./Actual R2:0.066 v:12.893%

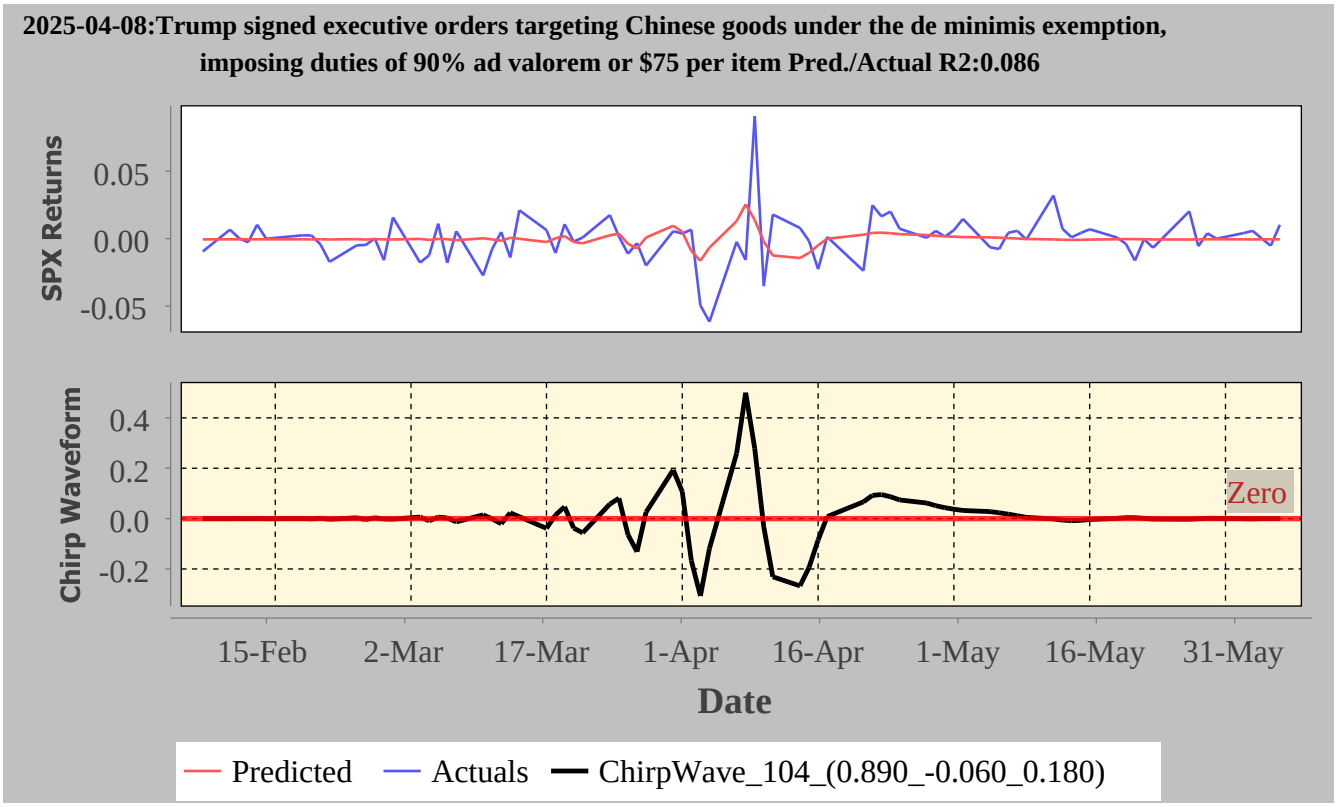

Figure (110) 2025-04-08:Trump signed executive orders targeting Chinese goods under the de minimis exemption, imposing duties of 90% ad valorem or $75 per item Pred./Actual R2:0.086 v:28.337%

Footnotes

1. Eugene F. Fama, "Efficient Capital Markets: A Review of Theory and Empirical Work", *Journal of Finance, Vol. 25, No. 2*, 1970, p. 383–417. https://doi.org/10.2307/2325486

2. Federal Reserve Bank of St. Louis, "Federal Reserve Economic Data (FRED)", *Federal Reserve Bank of St. Louis*, 2025. https://fred.stlouisfed.org

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4. Marc Nerlove, "Adaptive Expectations and Cobweb Phenomena", *Quarterly Journal of Economics*, 1958, p. pp. 227–240. https://doi.org/10.2307/1880597

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6. L. E. Baum and T. Petrie, "Statistical Inference for Probabilistic Functions of Finite State Markov Chains", *Annals of Mathematical Statistics*, 1966, p. 1554–1563. https://doi.org/10.1214/aoms/1177699147