**Detecting Unusual Changes and Increased Systematic Risk in Time-Series Data**

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*The author explains and implements financial turbulence, which was introduced by Kritzman and Li in 2010, in this paper. The implemented Financial Turbulence Index (FTI) can be used for detecting unusual relative and/or absolute changes of a time-series data such as asset price returns. The FTI can be calculated for changes in any group of time-series data you may choose. The FTI does not need any estimates or future forecasts as inputs. The FTI only needs historical realized changes; generated and unrealized data based on hypothesis can be used as inputs though. When the FTI value spikes, namely, detects unusualness of a set of changes, the following phenomena are observed: [A] an extreme positive or negative change in absolute terms compared to the historical norm (i.e., historical average and standard deviation), and/or [B] the divergence of historically correlated changes and/or the convergence of previously uncorrelated changes, both in relative terms. The FTI is expected to have an explanatory power at any circumstances if parameters, such as lookback time periods for [1] moving average of changes, a set of standard deviation, and correlations, [2] moving average of calculated FTI, and [3] calculating the percentile rank of the moving-average of the FTI, are pre-set appropriately.*

*The FTI can be further decomposed into the Magnitude Surprise Index (MSI) and the Correlation Surprise Index (CSI). The former MSI evaluate the impact from [A], that is, unusualness of individual data series in absolute terms; on the contrary, the CSI gauges the effect of [B], i.e., unusualness of correlations amongst multiple data series in relative terms. The author elaborates on and implements both of these indices as well.*

*Furthermore, the author explains and implements another separate method for inferring systematic risk from changes in multiple data series (changes in asset prices for instance). The level of systematic risk is evaluated by calculating the absorption ratio (AR). It is equal to the fraction of a set of each data series’ total variance explained (=absorbed) by a finite number of engenvectors, e.g., 1/5th=20% of the number of variables in time-series data as a heuristic justification. A high AR implies that changes of variables in time- series data are relatively combined/compact. When variables are compact in mathematical space, they are more fragile because shocks propagate more quickly and broadly. A low AR suggests that variables are less tightly coupled and therefore more resilient to external shocks.*

*A compact variables space does not always lead to a huge change in a variable or variables, but most significant changes in variables, especially asset returns in financial markets, have been preceded by spikes in the AR. This suggests that spikes in the AR are a near necessary, but not sufficient, condition for extreme changes in time-series variables.*

*The author implanted all the metrics in this paper in the Python programming language and shared them on GitHub. Please visit and see:*

<https://github.com/yoshisatoh/Stat/tree/main/FTI_CSI_AR>

<https://github.com/yoshisatoh/Stat/blob/main/FTI_CSI_AR/readme.txt>

**1. Financial Turbulence Index (FTI)**

**1.1. Introduction**

The FTI can be used for any time-series data of changes in variables, and one of the most significant use cases are portfolio management and trading in financial markets.

The ultimate goal of both portfolio optimization theories in academics and portfolio optimization practices in the financial industry is to optimally allocate currency amount or risk budget among various investment instruments. A portfolio optimization (e.g., simple traditional mean-variance, full-scale with a search algorithm, Black-Litterman) is a process to keep a portfolio in better shape (i.e., higher return-to-risk efficiency with lower estimation error) than any other options; there are usually some hard or soft constraints such as upper limit of estimated risks or incurred loss. Optimization criteria include maximizing a utility function with an expected absolute return or a relative return as a reward, a penalty for an absolute or relative risk, and a transaction cost penalty. Shape Ratio or Information Ratio maximization is an option too. Some other financial risk measures which are derived by a scenario analysis, for instance, could also be considered.

As written above, optimization criteria combine, directly or indirectly, expected returns as well as the return's dispersion (ex-ante risk). Most importantly, returns, risks (typically volatilities/standard deviation of asset returns), and correlations among allocated assets / individual investment instruments have to be stationary to achieve full portfolio optimization effect as expected.

An inconvenient and cold truth is that asset owners (investors) and managers cannot expect consistent average returns, volatilities, and correlations to be realized over long periods of time. If you see a specific and short time horizon, this is not always the case as these numbers dynamically fluctuate. Portfolios are often sub-optimal or even inappropriate because of the changes in a pattern of returns and volatilities/correlations as a result; portfolios could be less diversified and more concentrated, at least in the specific time frame. Furthermore, if you mistakenly assume the world goes back to the original static state and mean-reversion always works forever, you would miss structural changes. In reality, there are both cyclical and structural changes in this world. Even worse, a temporarily underperforming portfolio due to a short-term cyclicality could get terminated by a sense of disappointment before regaining the incurred loss; because nobody has an infinite time horizon and a sure prospect for the future world economy and markets. Holding period returns can be dramatically reduced by untimely drawdowns. This is because the world economy including financial markets can never be stationary. It typically moves around the four states: 1) a steady, low-volatility state characterized by accelerating economic growth and risk-on market conditions, 2) a mid-volatility state characterized by decelerating economic growth, 3) a panic-driven, high-volatility state characterized by accelerating economic contraction and risk-off market conditions, and 4) a mid-volatility state characterized by decelerating economic contraction.

It should be noted that realized returns, risks, and correlations change more frequently and significantly than a rigid policy framework for a strategic asset allocation expects. A strategic asset allocation is based on a belief in cyclicality (seasonality) and mean-reversion of markets and it requires rebalancing back to its static policy weights. Many investors have been reluctant to deviate from strategic portfolios backed by a basic belief in mean-reversion because of explicit and implicit expenses of implementing allocation changes and a lack of confidence for successful allocation changes to enhance investment performance. On the other hand, the recent proliferation of low-cost and high-liquidity investment products such as ETFs, index funds, futures, forwards, and other derivatives allow for efficient changes through overlays in allocations. Smart institutional investors are looking for ways to intelligently and unemotionally restructure their portfolios in response to regime shifts in the financial markets.

**1.2. Definition and Interpretation of Financial Turbulence Index (FTI)**

Kritzman and Li (2010) introduced the measure of financial turbulence, including its derivation, empirical properties, and usefulness.1 It was originally developed to detect financial market turbulence from asset allocation, portfolio construction, and risk management perspectives.

The author defines the financial turbulence divided by the number of variables (e.g., investment instruments) N as the Financial Turbulence Index (FTI):

(1)

where

The Financial Turbulence Index at a particular time period *t* (scalar)

Changes of variables for period t (1×N vector)

Sample moving average of historical changes at a period t (1×N vector) (\*)

Sample moving average covariance matrix of historical changes at a period t (N×N vector) (\*)

N = Number of variables

(\*) In the latter sample case, the author chose a moving average window of 20-day (~ 1 month) without decay.

The higher the FTI, the more turbulent the current status is. The FTI evaluates the degree of unusualness, in which changes of variables, given their historical patterns of behavior, behave in an uncharacteristic fashion.

A pair of **(yt - μ)** terms capture extreme negative or positive changes of each variable compared to the historical norm and are located on both sides of **Σ-1**, which is an inverse matrix of a sample covariance of historical changes. This inverse matrix of a sample covariance **Σ-1** works as a standardization term by historical patterns of volatilities and correlations. To put it differently, the characteristic deviations are scaled by the covariance matrix **Σ**. The FTI is a measure for standardized differences in each variable (pair) by standard deviations of changes (not differences in absolute changes) and directions of changes (positive or negative).

Additionally, Kinlaw and Turkington (2014) showed a case of a single variable to understand the financial turbulence in an intuitive way.2 Similarly, if we consider a case of a single variable here, the FTI, the equation (1), is simply equal to the squared z-score of the variable change, as shown in the equation (2).

FTI for a single investment (2)

**1.3. Empirical Features of Financial Turbulence Index (FTI) in Financial Markets**

In financial markets, variables are often investment instruments, and changes of variables are returns of the investment instruments.

By definition, the FTI gets higher by [A] extreme returns (ups and downs) of individual instruments compared to the historical norm and [B] decoupling of historically correlated instruments and coupling of uncorrelated instruments. Empirically, it coincides with [C] lower lower return-to-volatility for risky assets and [D] a deteriorated diversification effect for an entire portfolio with a static allocation, and [E] high persistence of turbulence. It is also accompanied by excessive risk aversion, herding behavior of investors and asset managers, depreciation of risky assets and appreciation of safer assets, and illiquidity (trades strongly biased toward one-direction, selling or buying).

These features, [A], [B], [C], [D], and [E] in turbulent periods explain why many investors who believed their portfolios were well diversified suffered catastrophic losses during crisis periods, for example, the Global Financial Crisis of 2007–2008. Rather than only relying on a static historical norm to optimize portfolios and manage risk, investors should use conditional measures that take into account the behavior of individual investments during turbulent periods. A portfolio should be differently constructed in a turbulent period, an extremely stable period, and other periods in between, respectively, to improve performance (i.e., return-to-risk efficiency) of a portfolio in the long run.

Concerning [C], liquid risky assets (e.g., listed stocks, G10 currencies) are usually severely impacted than illiquid ones (e.g., mortgage derivatives, private assets). It is said that as subprime mortgage fell in value during the Global Financial Crisis, some bigger players were likely to have been hit by the losses and were required to sell its more liquid portfolios to raise capital for margin calls of highly leveraged investments and investor withdrawals of illiquid investments. Since the subprime mortgage market is relatively illiquid, they thus turned to more liquid components of their overall portfolios—publicly traded securities. Losses hammered market participants with similar trades and triggered fresh rounds of liquidation.

Regarding [E], although we may not be able to anticipate the initial onset of financial turbulence, once it begins, it usually continues for weeks, months, even a year, as the markets digest and react to the events causing the turbulence.

Thus, if investors could dynamically increase/decrease ex-ante estimated risk of a total portfolio by implementing a dynamic allocation, i.e., move in and out of markets, based on the degree of the FTI, it could improve long-term portfolio performance (i.e., return-to-risk efficiency) after costs.

Here is the beauty of the FTI. First, it can be calculated for any set of liquid assets with frequent historical returns. Second, it captures interactions among combinations of investments in addition to the magnitude of the investment returns. Third, rather than directly dealing with the FTI itself, an absolute measure, we can calculate the %FTI, the percentage rank of moving average of the FTI for a certain period of time, which is a relative measure. If the world becomes more turbulent on a continuing basis, the absolute value threshold of the FTI for separating turbulent periods from non-turbulent periods will eventually rise. With %FTI, we can avoid this increases of absolute threshold in the FTI. It could capture both cyclical seasonality and structural trends depending on time period windows chosen. These features are quite a contrast to currently popular indicators, such as, implied volatilities in liquid option markets (e.g., VIX), yield spreads, and so on.

It should be noted that the FTI is not meant to offer a reliable estimate of when and how an extreme event will occur; rather, as a coincide index based on realized returns without forecasts, it gives a more reliable estimate of the consequences of such an extreme event. A turbulent period may arrive unexpectedly, but it does not immediately subside; it does tend to sustain for a certain period of time. The FTI keeps tracking of the sustained turbulent period.

**1.4. Magnitude Surprise Index (MSI) and Correlation Surprise Index (CSI)**

Kinlaw and Turkington (2014) extend Kritzman and Li’s study (2010) by disentangling the volatility and correlation components of financial turbulence to derive a measure of correlation surprise.2

Similarly, the author defines the Correlation Surprise Index (CSI) as follows:

(3)

The Financial Turbulence Index at a particular time period *t* (scalar)

The Magnitude Surprise Index at a particular time period *t* (scalar)

MSI is equal to the FTI, given in equation (1), where all off-diagonal elements in the covariance matrix are set to zero. This ‘correlation-blind’ financial turbulence measure captures magnitude surprises of [A] as in the section 1.3., but ignores whether co-movement is typical or atypical. Since the CSI is the FTI divided by the MSI, the CSI is expected to evaluate the component [B] directly. Apparently, the FTI contains both the components [A] and [B].

**2. Absorption Ratio (AR)**

**2.1. Introduction**

The author explains and implements another separate method for inferring systematic risk from changes in multiple data series (changes in asset prices for instance). The level of systematic risk is evaluated by calculating the absorption ratio (AR). It is equal to the fraction of a set of each data series’ total variance explained (=absorbed) by a finite number of engenvectors, typically 1/5th=20% of the number of variables in time-series data as a heuristic justification. A high AR implies that changes of variables in time-series data are relatively combined/compact. When variables are compact in mathematical space, they are more fragile because shocks propagate more quickly and broadly. A low AR suggests that variables are less tightly coupled and therefore more resilient to external shocks.

**2.2. Definition and Interpretation of Absorption Ratio (AR)**

Kritzman et al. (2011) introduced a measure of implied systemic risk called absorption ratio, which equals the fraction of the total variance of a set of asset returns explained or “absorbed” by a fixed number of eigenvectors, and a standardized shift in the absorption ratio.3 The absorption ratio captures the extent to which markets are tightly coupled. When markets are tightly coupled, namely, the absorption ratio is higher, they are more fragile in the sense that negative shocks propagate more quickly and broadly than when markets are loosely linked.

The author uses the same definition by

Kritzman et al. (2011) and calls it as the Absorption Ratio, AR in short:

(4)

where

The Absorption Ratio

number of eigenvectors, typically integer of N\*0.20

number of variables (e.g., investment instruments)

variance of the *i*th eigenvector (\*)

variance of the *j*th investment (\*)

(\*) The author chose a moving average window of 20-day (~ 1 month) without decay.

The first eigenvector is a linear combination of variable weights that explains the greatest fraction of the variables’ total variance. The second eigenvector is a linear combination of variable weights orthogonal to the first eigenvector that explains the greatest fraction of remaining variance of variables, that is, variance not yet explained or “absorbed” by the first eigenvector. The third eigenvector and beyond are identified the same way. They absorb the greatest fraction of leftover variance and are orthogonal to preceding eigenvectors. These n eigenvectors together explain the total variance of the variables; if the fraction of the total variance of a set of N variables explained or “absorbed” by a finite set of the n eigenvectors gets higher, then variables are considered to be unified, highly vulnerable to negative shocks, and thus fragile, showing a high degree of systemic risk.

**2.3. Empirical Features of Absorption Ratio (AR) in Financial Markets**

The AR has some empirical features: [A] most significant risky asset market drawdowns, financial crises/contagions were preceded by spikes in the AR, [B] risky assets appreciated significantly in the wake of sharp declines in the AR, and [C] the AR can be considered as an early warning signal of market stress because it evaluates how fragile markets are. It does not necessarily mean that it can accurately forecast when and how market drawdowns happen. Rather, a spike in the AR is a near necessary condition for a significant drawdown, just not a sufficient condition. A high AR is merely an indication of market fragility to negative shocks; we need other metrics, if any, to precisely evaluate when and how shocks are caused and markets actually collapse as a result. However, it is out of scope for this paper.

The beauty of the AR is as follows. First, it can be calculated for any set of liquid investments with frequent historical returns while not forecasting anything; this is the same as the FTI. Second, it can continuously tracks sources of systemic risk which are likely to change from period to period. Although n eigenvectors are statistically derived, these vectors have various economic exposures embedded in many investments. Rather than identifying and interpreting a particular source of risk and betting on it, the AR is a measure to evaluate whether or not certain sources of a systemic risk with the highest explanatory power at a particular time period are becoming more or less significant. Generally speaking, the estimation of systemic risk is extremely challenging because it is directly unobservable, and its impact on asset prices is often uncertain. The AR accounts for the importance of a set of investments’ contribution to a systemic risk, whereas other metrics, e.g., correlations, do not.

A compact variables space from the AR perspective does not always lead to a huge change in valuation of an investment instrument or investments, but most significant changes in variables, especially asset returns in financial markets, have been preceded by spikes in the AR. This suggests that spikes in the AR are a near necessary, but not sufficient, condition for extreme changes in time-series variables.

**3. A Hypothetical Case Study**

**3.1. Sample Time-Series Data**

The author generates the following sample data, rather than real market data, to clearly illustrate how the FTI, %FTI, MSI, CSI, and AR can be calculated.

**Table 1. Sample time-series data (before adding extreme returns)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Column** | **A (\*4)** | **B** | **C** |
| **Day (\*1)** | 1,250 | 1,250 | 1,250 |
| **Mean** | **(\*2)** 0.10/(250)^0.50 | **(\*5)** | **(\*6)** |
| **SD** | **(\*3)** 0.20/(250)^0.50 | **(\*5)** | **(\*6)** |

**(\*1)** Number of data points in days

**(\*2)** Mean of absolute returns, Daily. Days per annum is considered to be 250 here. The average annual return is 0.10 = 10%.

**(\*3)** Standard deviation of absolute returns, Daily. The annualized standard deviation is 0.20 = 20%.

**(\*4)** This time-data series is generated by using NumPy, a library for the Python programming language.

**(\*5)** B = 1.20 \* A + (random value from a normal distribution with the mean=0 and standard deviation=0.05 per annum)

**(\*6)** C = 0.80 \* A + (random value from a normal distribution with the mean=0 and standard deviation=0.05 per annum)

**Table 2. How extreme returns are added to the time-series data A)**

|  |  |
| --- | --- |
| **Days (\*7)** | **A** |
| 500-519 | **(\*8)** A - 6 SD |
| 750-769 | **(\*9)** A\*(-1) |
| 1,000-1,019 | **(\*10)** A\*(-1) ± 6 SD |

**(\*7)** Day starts from 0, and then move on to 1, 2, 3, …, and so on.

**(\*8)** Six standard deviation of daily returns is subtracted.

**(\*9)** Signs of returns for each day is inverted; if a return of A for a certain day is positive (negative), then it is inverted to negative (positive).

**(\*10)** Signs of returns for each day is inverted. Furthermore, if a return of A for a certain day is inverted to positive (negative), then six standard deviation of daily returns is added (subtracted).

**3.2. Results**

**3.3. Analysis**

**Figure 1. Raw Time-Series Data**

**Figure 2. FTI**

**Figure 3. %FTI**

**Figure 4. MSI**

**Figure 5. CSI**

**Figure 6. AR**

**Conclusion**

The author introduced a combined methodology of the FTI and the SFI for evaluating both turbulent period and systemic fragility. The FTI can be calculated for any group of return series you may choose. Similarly, the SFI can also be computed for any group of N variances you may select. Moreover, neither the FTI nor the SFI needs future forecasts as inputs; both indices only need historical realized returns. No holding data is needed.

During turbulent periods, the following phenomena are observed: (a) extreme negative or positive returns of each investment compared to the historical norm, (b) the convergence of uncorrelated investment returns and/or the divergence of correlated investment returns, (c) lower (higher) return-to-risk ratios of risky (safer) assets, (d) a deteriorated diversification effect for an entire portfolio with a static allocation due to varying return/risk/correlation characteristics, and (e) high persistence of turbulence. Both (a) and (b) are directly captured in the %FTI calculation while (c), (d), and (e) are empirically observed.

When a systemic risk rises, markets are considered to be fragile. It does not always lead to risky asset depreciation, but most significant stock market drawdowns have been preceded by spikes in the %SFI. This suggests that spikes in the %SFI are a near necessary, but not sufficient, condition for market crashes.

Both %FTI and %SFI can be applied to dynamic risk management (e.g., increase or decrease total portfolio risk), asset allocation strategies and any liquid investment strategies with any investment philosophy and procedure (e.g., lower allocation to investments with lower return/risk efficiencies when necessary).

Our empirical findings suggest that combining these two methodologies would have shown improved performance of a dynamic asset allocation strategy. Our cross-sectional and time-series analysis reveals the complementary relationship between the %FTI and %SFI; by combining these two, we could have more confidence in the results. Both realized unusual return pattern and systemic fragility are a trigger for risk-averse asset allocation. The investor thinks that investors and asset managers could be very confident in their high-risk estimates backed by both risk indicators.

Ex-post volatilities and correlations are results of returns. Volatilities do not show you a direction of return. Also, correlations do not suggest the absolute value of returns and have various one-on-one relations. The absolute value of returns/volatilities and correlations can change as economic and market conditions change. On the contrary, new normal can be re-defined with FTI and/or SFI on a regular basis. One of the beauties of these models is that we do not need to look at the large number of correlations (e.g., 45 for 10 investments). Please note that both FTI and SFI are coincident indices rather than leading or lagging indices. Raw values of FTI and SFI (without percentile rankings) are not normally distributed and not implying probabilities of a certain event; thus, percentile rankings of them should be used. Moving averaging and percentile rankings make relative comparisons during a certain time window possible. Time periods for moving averages and percentile rankings should be based on simulated results and future forecasts for certain investments and asset classes.

As Kritzman [2013] pointed out, historically investors have avoided portfolio revisions due to expensive cost incurred and/or lack of confidence in successful asset or risk factor allocation6. These two impediments now pose less of a challenge than they might have in the past, thanks to proliferation of relatively inexpensive and liquid investment instruments, such as exchange-traded funds (ETFs), index funds, futures and forwards.

Samuelson [1998] offered the dictum that the stock market is “micro efficient” but “macro inefficient.”7 That is, the efficient markets hypothesis works much better for individual stocks than it does for the aggregate stock market. The Samuelson dictum states that markets are relatively micro-efficient because a smart investor (asset manager) who spots mispriced securities trades to exploit the inefficiency and the inefficiency is corrected as a result. However, when an aggregation of securities, such as an asset class, is mispriced and a smart investor trades to exploit it, that action is insufficient to revalue the entire asset class. Macro-inefficiencies typically require an exogenous shock to jolt many investors to trade in concert in order to revalue an entire asset class. Hence, macro-inefficiencies persist sufficiently long for investors to act on them.

It should be warned that like any other market-timing strategies/models, if there are enough adopters who constantly use metrics in this paper, it will become a self-fulfilling prophecy in that it will cause its own crashes. We saw the stock market crash on October 19, 1987 by portfolio insurance, and extraordinary quant factor drawdowns at virtually the same time (the quant liquidity crunch) early in August 2007. Furthermore, as more people follow these metrics, it will be hard to differentiate yourself from others and become less valuable. However, these metrics are considered to remain valuable for some time, because it is unlikely that everyone will always follow them and allocate assets accordingly. Finally, evaluating crowdedness of metrics has been, and always will be, important.

**Notes**

The material presented is for informational purposes only. The views expressed in this paper are the view solely of the author and are subject to change; moreover, the views do not necessarily represent the official views of the author’s employer.

1. See Kritzman and Li (2010)
2. See Kinlaw and Turkington (2014)
3. See Mark Kritzman, Yuanzhen Li, Sébastien Page, and Roberto Rigobon (2011)

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