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The fine structure of equity-index option dynamics[☆]

Torben G. Andersen[a,b,c,*], Oleg Bondarenko[d], Viktor Todorov[a], George Tauchen[e]

[a] Department of Finance, Kellogg School of Management, Northwestern University, Evanston, IL 60208, United States
[b] NBER, Cambridge, MA, United States
[c] CREATES, Aarhus, Denmark
[d] Department of Finance, University of Illinois at Chicago, Chicago, IL 60607, United States
[e] Department of Economics, Duke University, Durham, NC 27708, United States

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ABSTRACT

We analyze the high-frequency dynamics of S&P 500 equity-index option prices by constructing an assortment of implied volatility measures. This allows us to infer the underlying fine structure behind the innovations in the latent state variables driving the evolution of the volatility surface. In particular, we focus attention on implied volatilities covering a wide range of moneyness (strike/underlying stock price), which load differentially on the different latent state variables. We conduct a similar analysis for high-frequency observations on the VIX volatility index as well as on futures written on it. We find that the innovations over small time scales in the risk-neutral intensity of the negative jumps in the S&P 500 index, which is the dominant component of the short-maturity out-of-the-money put implied volatility dynamics, are best described via non-Gaussian shocks, i.e., jumps. On the other hand, the innovations over small time scales of the diffusive volatility, which is the dominant component in the short-maturity at-the-money option implied volatility dynamics, are best modeled as Gaussian with occasional jumps.

1. Introduction

Volatility risk is a major concern for investors and they require compensation for bearing it. Over the last two decades trading in derivatives, allowing for speculation and hedging vis-a-vis volatility risk, has grown dramatically. These instruments include plain vanilla options but also, more directly, so-called variance swaps, which are forward contracts on realized volatility (which in turn are nonparametric estimates for the unobserved quadratic variation). The price of a variance swap can be recovered in model-free fashion from the price of a portfolio of out-of-the-money (OTM) options on the underlying asset. The Chicago Board Options Exchange (CBOE) relies on this methodology in computing the well-known VIX volatility index based on S&P 500 index options. In recent years, the VIX index itself has become the underlying instrument for futures and options, further expanding the opportunities for managing exposures to equity market volatility risk.

The abundance of reliable data on volatility-related derivative contracts enables us to take a closer look at the properties of the process driving the innovations to spot (stochastic) volatility and jump intensity, which are otherwise latent, or "hidden", within the stock returns. Todorov and Tauchen (2011b) show that, although the VIX is a risk-neutral expectation of future realized volatility, under conventional model settings, the VIX index preserves important information about the behavior of the latent stochastic volatility over small time scales. In particular, the presence of VIX jumps can be traced back to discontinuities in the spot volatility process itself, even if the magnitudes of the jumps in the two series generally differ. Similarly, the "degree of concentration" of small jumps, known as the jump activity or Blumenthal–Getoor index, in (spot) volatility and the VIX index coincides. Finally, the presence of a diffusive component is preserved when going from spot volatility to VIX. Based on this line of reasoning, using high-frequency VIX data, Todorov and Tauchen (2011b) conclude that the VIX index – and by extension spot volatility – contains jumps

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* Corresponding author at: Department of Finance, Kellogg School of Management, Northwestern University, Evanston, IL 60208, United States.

E-mail addresses: t-andersen@northwestern.edu (T.G. Andersen), olegb@uic.edu (O. Bondarenko), v-todorov@northwestern.edu (V. Todorov), george.tauchen@duke.edu (G. Tauchen).

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and is best characterized as a pure-jump process with infinite variation jumps.

The existing literature on the activity level of spot volatility is extremely limited, with the main contribution being Todorov and Tauchen (2011b), which is based solely on high-frequency data for the VIX index and relies on ad hoc procedures in dealing with the confounding effects of market microstructure noise. This state-of-affairs reflects the fact that, until recently, we neither had access to high-frequency data for alternative volatility-sensitive derivatives nor suitable theoretical tools for drawing inference regarding the activity index for volatility series.[1] The goal of the current paper is to generate new and robust empirical evidence concerning the properties of the latent spot volatility and jump intensity over small time scales by exploiting high-frequency data across a greatly expanded set of derivative contracts relative to prior studies in the literature.

Under the common assumption that the risk-neutral jump intensity is a sole function of (components of) spot volatility, the corresponding Black–Scholes implied volatility (BSIV) measures, extracted from S&P 500 index options, are also functions of volatility alone (along with the characteristics of the option contracts). Hence, they likewise typically "inherit" the behavior of volatility over small scales. Furthermore, the identical logic applies to derivatives on the VIX index such as VIX futures. Therefore, data for an extended set of volatility derivatives will enhance efficiency and robustness in evaluating existing findings based strictly on high-frequency VIX series.

Importantly, the additional derivatives data also allow us to gain qualitatively new insights. For example, many studies conclude that the return variation is governed by multiple factors. Further, recent evidence suggests that the dynamics of the risk-neutral negative jump intensity for the equity index cannot be captured fully by (components of) spot volatility, see, e.g., Bollerslev and Todorov (2011) and Andersen et al. (forthcoming). In this case, VIX is governed by the factors driving both the jump intensity and the spot volatility. The use of derivative data loading differentially on such factors (or state variables) helps us discern the properties of those factors and thus fosters a deeper understanding of the fine structure of the VIX dynamics. For example, the BSIV of short-maturity OTM put options load primarily on the risk-neutral intensity of negative jumps, so their high-frequency increments reflect the small scale behavior of the factors driving the jump intensity. Similarly, the BSIV of short-maturity at-the-money (ATM) options is mostly determined by spot volatility and, hence, provides more direct evidence on the fine structure of spot volatility.

The issue of microstructure noise in high-frequency volatility indices is also not trivial. Andersen et al. (2013) document problems associated with the construction of the VIX at high frequencies. These are mostly related to the rules for truncating deep OTM options in the computation of the index.[2] Using high-frequency S&P 500 index options data directly allows us to construct implied volatility measures whose increments are much less sensitive to such features.

In summary, our empirical analysis exploits the following high-frequency series. First, we use short-maturity S&P 500 futures and futures options traded on the Chicago Mercantile Exchange (CME). Using the option prices, we construct one-month BSIV series with fixed log moneyness (strike/futures price) relative to the ATM BSIV. Second, we use data on the S&P 500 index futures and the VIX index. Finally, we use data on the two nearby VIX futures. Combined, our data cover January 2007 till May 2012, but we filter out problematic observations and there is a bit of mismatch in the our high-frequency data across the different types of derivatives contracts.

We apply two very different procedures in our investigation of the fine structure of the asset price and volatility dynamics at small time scales. The first technique relies on the ratio of power variations at two different frequencies, which allows us to estimate the activity index of the given process. Estimators of this type have been studied by Ait-Sahalia and Jacod (2010) and Todorov and Tauchen (2010, 2011a). The activity index for a process is two if it has a diffusion component. On the other hand, if no diffusion term is present, the activity index is smaller and equals the jump activity index for the (alternative) pure-jump model. Our second econometric tool is the empirical cumulative distribution function (cdf) of the nonparametrically de-volatilized high-frequency increments of the process and was developed by Todorov and Tauchen (2014). The de-volatilized high-frequency increments should be approximately Gaussian if the process is jump-diffusive and, alternatively, follow a stable distribution if the process is of pure-jump type.

Our empirical results display an intriguing pattern. The lowest point estimates for the activity index, of around 1.6, are obtained for the BSIV of deep OTM put options. As we move from OTM puts to ATM options, the estimates gradually increase to the maximal value of two, indicative of a jump-diffusive process. Our additional test based on the empirical cdf of the de-volatilized increments corroborates this finding, i.e., it also suggests the BSIV for deep OTM puts are pure-jump processes, while pointing towards the opposite conclusion for the BSIV of near-the-money options. These results are consistent with the risk-neutral intensity of the negative price jumps being driven, solely or predominantly, by state variable(s) of pure-jump type, and the spot volatility being governed by a jump–diffusion. Moreover, the value of volatility related indices and contracts, such as the VIX and VIX futures, are functions of the state variables driving the volatility as well as those determining the jump intensity. Hence, in finite samples, we would expect point estimates for the activity index of such series to be close to, or fall within, the range of the activity estimates obtained across the moneyness dimension of the S&P 500 implied volatility surface. And this is what we find: the estimated activity indices for VIX fall just below the values obtained for the deep OTM IV measures while those for the VIX futures are around the values attained for IV4.

The rest of the paper is organized as follows. Section 2 introduces notation and formally defines the option-based quantities that we study in the paper. In Section 3, we describe the separate datasets used in our analysis and we conduct an initial analysis regarding the liquidity of the individual instruments. Section 4 reviews the econometric tools we use, while Section 5 contains the main empirical results, and Section 6 concludes.

2. Setup

We assume the underlying asset price process, X, is an Itô semimartingale under the statistical measure $\mathbb{P}$, characterized through the following return dynamics,

$$\frac{dX_t}{X_t} = \alpha_t\, dt + \sqrt{V_t}\, dW_t + \int_{\mathbb{R}} x\, \widetilde{\mu}^{\mathbb{P}}(ds, dx), \quad \text{under } \mathbb{P}, \tag{1}$$

[1] Studying the properties of the underlying S&P 500 index, by contrast, is much easier as it is directly observable and high-frequency data are readily available. By now, there is ample evidence that the index contains both a diffusion (Todorov and Tauchen, 2011b) and jump components (Ait-Sahalia and Jacod, 2009; Barndorff-Nielsen and Shephard, 2006; Lee and Mykland, 2008). In addition, Carr and Wu (2003) find support for a jump-diffusive characterization via nonparametric analysis of the time decay of short-maturity options.

[2] Theoretically, the VIX index involves option prices for log-moneyness across the whole real line. In practice, we have a limited set of option prices available and this inevitably induces (time-varying) approximation errors.