

# TSLA 1 to 16 October 2024

|                                                                                   |                         |
|-----------------------------------------------------------------------------------|-------------------------|
| trades on 16 October 2024                                                         | 693,626                 |
| average trading rate                                                              | 44.4 per second         |
| presample for the diurnal profile                                                 | 17 to 30 September 2024 |
| outliers on 16 October 2024, $o$                                                  | 16,860 (2.43%)          |
| price half-life: run / minimizer <sup>1</sup>                                     | 3.0 / 2.2 trades        |
| cost of running 3 trades                                                          | +2.23%                  |
| scale half-life: run / minimizer <sup>2</sup>                                     | 240 / 45 s              |
| cost of running 240 s                                                             | +0.18%                  |
| direction half-life <sup>3</sup>                                                  | 14 s [11, 21]           |
| Mandelbrot $a$ minimizing QLIKE                                                   | 359 trades              |
| $a$ within 0.0005 of the minimum                                                  | 210 to 614              |
| linear $\hat{\sigma}$ , before $\rightarrow$ at the largest residual <sup>4</sup> | 72% $\rightarrow$ 92%   |
| Huber $\hat{\sigma}$ , before $\rightarrow$ peak                                  | 71% $\rightarrow$ 93%   |
| median spot volatility, Huber / linear input <sup>5</sup>                         | 35.6 / 38.3 %           |
| hyperbolic against HExp, correlation of logs                                      | 0.9985                  |
| HExp QLIKE advantage, leave-one-day-out <sup>6</sup>                              | −0.00069                |
| 15-minute signature level                                                         | 27 to 54 %              |
| Huber signature, 1 min over 1 s, 12 day average                                   | 1.09                    |

TSLA over the 12 trading days 1 to 16 October 2024, and on 16 October 2024. <sup>1</sup>the median over  $k$  from 2 to 100 of the half-life minimizing the  $k$ -trade-ahead Huber forecast loss, and the largest cost over those  $k$  of running the common 3 trades. <sup>2</sup>the 1-minute-ahead check loss of the noise scale. <sup>3</sup>the half-life maximizing the mean predictive log-likelihood per scored trade on 16 October 2024, with the range within  $10^{-4}$  of the maximum. <sup>4</sup>the largest Huber residual after 09:45, at 09:55; before is the median over  $t^* - 15$  to  $t^* - 3$  minutes and at is the maximum over  $t^* - 6$  to  $t^* + 12$  minutes. <sup>5</sup>over the 12 days, sampled every 300 trades. <sup>6</sup>hyperbolic minus HExp, so positive favours HExp.

| $k$ | Mean of $ \hat{X}_t - \hat{X}_{t-k} /\sqrt{k}$ in cents |       |        |        | Sqrt of Mean of $(\hat{X}_t - \hat{X}_{t-k})^2/k$ in cents |       |        |        |
|-----|---------------------------------------------------------|-------|--------|--------|------------------------------------------------------------|-------|--------|--------|
|     | median                                                  | Huber | linear | trades | median                                                     | Huber | linear | trades |
| 1   | 0.355                                                   | 0.264 | 0.276  | 1.225  | 0.948                                                      | 0.561 | 0.564  | 3.311  |
| 2   | 0.340                                                   | 0.295 | 0.317  | 1.000  | 0.841                                                      | 0.569 | 0.593  | 2.457  |
| 5   | 0.392                                                   | 0.342 | 0.370  | 0.770  | 0.780                                                      | 0.601 | 0.623  | 1.670  |
| 10  | 0.415                                                   | 0.372 | 0.394  | 0.645  | 0.721                                                      | 0.607 | 0.622  | 1.261  |
| 25  | 0.415                                                   | 0.386 | 0.397  | 0.529  | 0.633                                                      | 0.575 | 0.581  | 0.903  |
| $k$ | ACF of $\hat{X}_t - \hat{X}_{t-1}$ at lag $k$           |       |        |        | Hill tail index of $ \hat{X}_t - \hat{X}_{t-k} $           |       |        |        |
|     | median                                                  | Huber | linear | trades | median                                                     | Huber | linear | trades |
| 1   | -0.21                                                   | 0.03  | 0.10   | -0.45  | 2.76                                                       | 2.43  | 2.13   | 2.16   |
| 2   | 0.05                                                    | 0.07  | 0.04   | -0.01  | 2.75                                                       | 2.31  | 2.33   | 2.19   |
| 5   | -0.01                                                   | 0.00  | -0.01  | 0.00   | 2.48                                                       | 2.23  | 2.49   | 2.24   |
| 10  | -0.01                                                   | -0.01 | -0.01  | 0.00   | 2.28                                                       | 2.19  | 2.50   | 2.30   |
| 25  | 0.00                                                    | -0.01 | -0.01  | 0.00   | 2.43                                                       | 2.43  | 2.87   | 2.45   |

Table 1: Trade-lag differences, TSLA, 16 October 2024.

| $s$    | Mean of $\frac{ \hat{X}_t - \hat{X}_{t,s} }{\sqrt{\tau_t - \tau_{t,s}}}$ in cents |       |        |        | Annualized volatility: $\hat{\sigma}_{\text{Annual};s}$ |       |        |        |
|--------|-----------------------------------------------------------------------------------|-------|--------|--------|---------------------------------------------------------|-------|--------|--------|
|        | median                                                                            | Huber | linear | trades | median                                                  | Huber | linear | trades |
| 0.1 s  | 5.69                                                                              | 5.18  | 5.35   | 8.29   | 36.6                                                    | 29.5  | 32.7   | 108.3  |
| 1 s    | 3.64                                                                              | 3.51  | 3.58   | 4.29   | 33.1                                                    | 31.3  | 32.4   | 50.9   |
| 5 s    | 3.55                                                                              | 3.51  | 3.52   | 3.73   | 33.8                                                    | 33.4  | 33.5   | 38.0   |
| 10 s   | 3.43                                                                              | 3.40  | 3.41   | 3.52   | 33.8                                                    | 33.5  | 33.5   | 35.7   |
| 1 min  | 3.27                                                                              | 3.26  | 3.26   | 3.28   | 34.4                                                    | 34.3  | 34.2   | 34.5   |
| 15 min | 2.50                                                                              | 2.50  | 2.49   | 2.50   | 26.8                                                    | 26.8  | 26.7   | 26.8   |
| $s$    | Cor( $\hat{X}_t - \hat{X}_{t,s}, \hat{X}_{t,s} - \hat{X}_{t,2s}$ )                |       |        |        | Hill tail index of $ \hat{X}_t - \hat{X}_{t,s} $        |       |        |        |
|        | median                                                                            | Huber | linear | trades | median                                                  | Huber | linear | trades |
| 0.1 s  | -0.10                                                                             | -0.07 | -0.12  | -0.40  | 3.34                                                    | 3.02  | 2.70   | 2.23   |
| 1 s    | 0.17                                                                              | 0.22  | 0.21   | -0.03  | 3.96                                                    | 4.37  | 4.31   | 3.47   |
| 5 s    | 0.13                                                                              | 0.14  | 0.15   | 0.06   | 9.66                                                    | 9.75  | 9.40   | 9.35   |
| 10 s   | 0.15                                                                              | 0.16  | 0.16   | 0.13   | 8.23                                                    | 8.06  | 8.83   | 7.07   |
| 1 min  | -0.08                                                                             | -0.08 | -0.08  | -0.08  |                                                         |       |        |        |

Table 2: Clock-lag differences, TSLA, 16 October 2024.

|                                          | median   | Huber      | linear     |
|------------------------------------------|----------|------------|------------|
| Mean of $ \hat{\epsilon}_t $ in cents    | 0.82     | 1.02       | 1.06       |
| s.d. of $\hat{\epsilon}_t$ in cents      | 2.41     | 2.34       | 2.17       |
| Tail index of $\psi(\hat{\epsilon}_t)$   | $\infty$ | $\infty$   | 2.13       |
| ACF of $\psi(\hat{\epsilon}_t)$ , lag 1  | 0.18     | 0.21       | 0.10       |
| ACF of $\psi(\hat{\epsilon}_t)$ , lag 2  | 0.05     | 0.12       | 0.04       |
| ACF of $\psi(\hat{\epsilon}_t)$ , lag 5  | 0.01     | 0.02       | -0.01      |
| ACF of $\psi(\hat{\epsilon}_t)$ , lag 10 | 0.00     | 0.00       | -0.02      |
| ACF of $\psi(\hat{\epsilon}_t)$ , lag 25 | 0.00     | -0.01      | -0.01      |
| 80% C.I. for $\theta_t - X_t$            | —        | -0.76,0.68 | -0.80,0.73 |
| 95% C.I. for $\theta_t - X_t$            | —        | -1.35,1.25 | -1.49,1.40 |
| 99% C.I. for $\theta_t - X_t$            | —        | -2.02,2.00 | -2.47,2.46 |
| s.e. of $\theta_t - X_t$ in cents        | —        | 0.61       | 0.80       |

Table 3: Residual summaries, TSLA, 16 October 2024. Median C.I. and s.e. cells are omitted (price discreteness); the linear s.e. is printed because the Hill index of its score, 2.13, is above two, while the Hill index of the Huber residual itself on this day is 1.77, below two: the two estimates of the noise’s index straddle two.

|                                | 16 October 2024 |       | 12 days, min to max |              |
|--------------------------------|-----------------|-------|---------------------|--------------|
|                                | upper           | lower | upper               | lower        |
| All trades (as in the paper)   | 1.77            | 1.78  | 1.48 to 1.77        | 1.46 to 1.84 |
| Residual divided by $\delta_t$ | 1.62            | 1.74  | 1.43 to 1.62        | 1.38 to 1.74 |
| Repricing windows removed      | 1.77            | 1.82  | 1.46 to 1.95        | 1.41 to 1.98 |
| Calm windows only              | 1.67            | 1.85  |                     |              |
| Every 10th trade               | 1.83            | 1.87  | 1.43 to 1.84        | 1.48 to 1.90 |
| Six-trade half-life            | 1.86            | 1.84  | 1.55 to 1.88        | 1.53 to 1.90 |

Table 4: Hill estimator of the tail index of the Huber filter residual, TSLA, 12 analysis days. The index is the mean of Hill estimates over the largest 0.1% to 1% of residuals, each tail separately, which for this stock is an average over 13 to 14 depths a day in row 1; the masked and thinned rows use fewer. Second row: divides the residual by its own threshold  $\delta_t$ . Third row: drops trades where the filtered price moves more than 6.8 times the day’s median  $\delta_t$  within  $\pm 1$  second, which is 20.1 to 22.5 cents over the days and removes 8% to 20% of a day; the fourth keeps only trades where it moves less than 3.4 times that median within  $\pm 5$  seconds, 10.1 cents on 16 October 2024, 37% of that day. Fifth row: keeps every 10th trade. Sixth row: doubles the filter’s half-life with the thresholds held fixed. The ranges run over the days on which the row can be estimated.

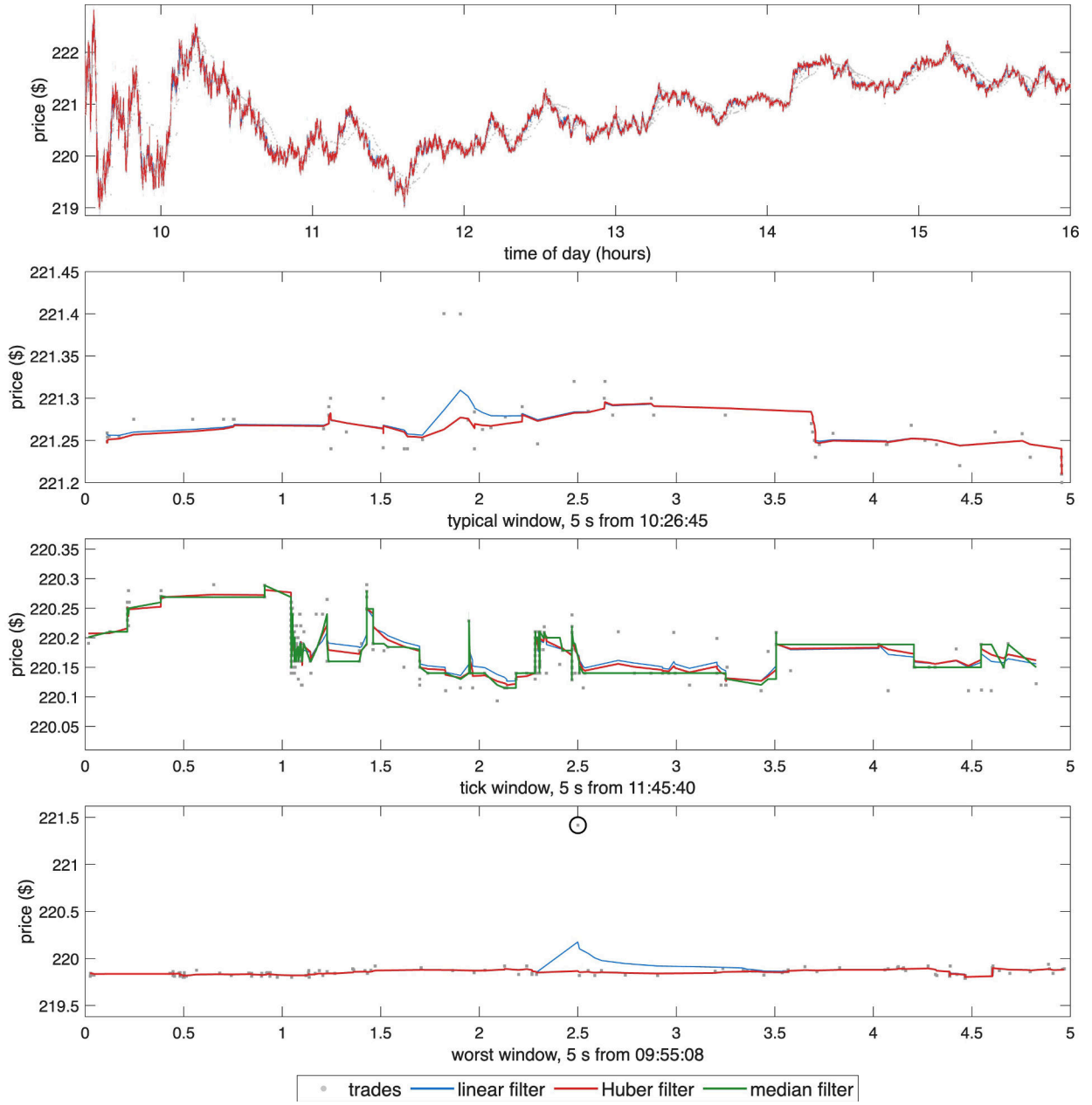


Figure 1: TSLA trades (grey points), the linear filter and the Huber filter, 16 October 2024. Top: full trading day. 2nd: 5-second window at the day's median trade count, from 10:26:45. 3rd: 5-second window at 11:45:40 in which the price reverses direction most often, with the median filter  $m_t$  added. Bottom: 5-second window around the largest Huber residual after 09:45, circled.

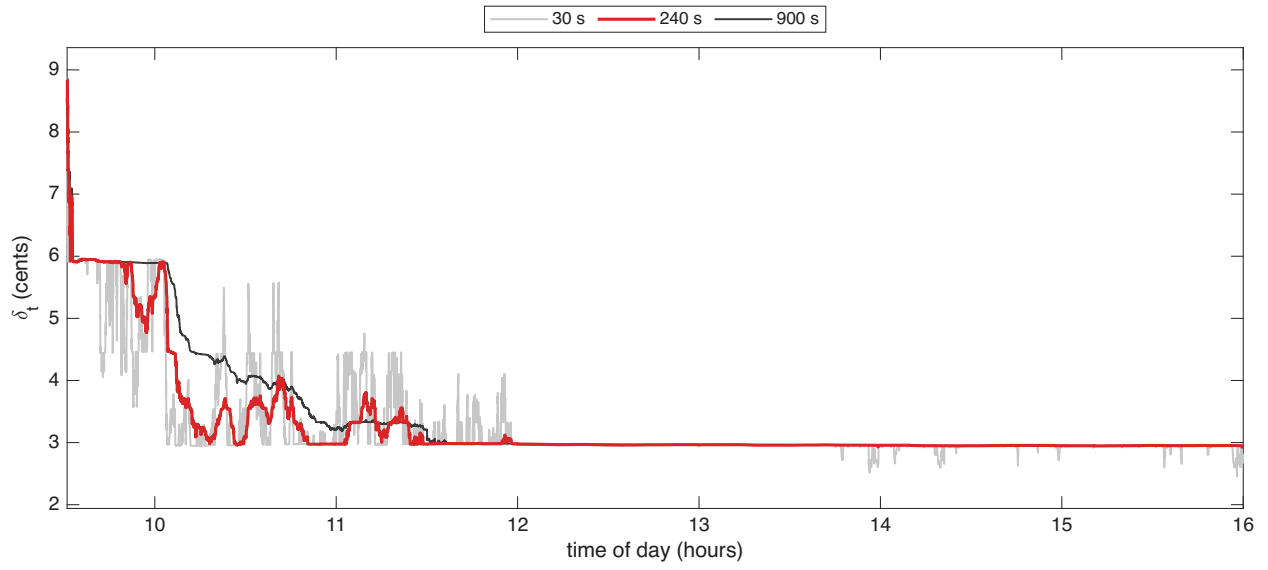


Figure 2: The Huber threshold  $\delta_t$  in cents for TSLA on 16 October 2024, with half-lives of 30, 240, 900 seconds. The 240-second half-life, in red, is used.

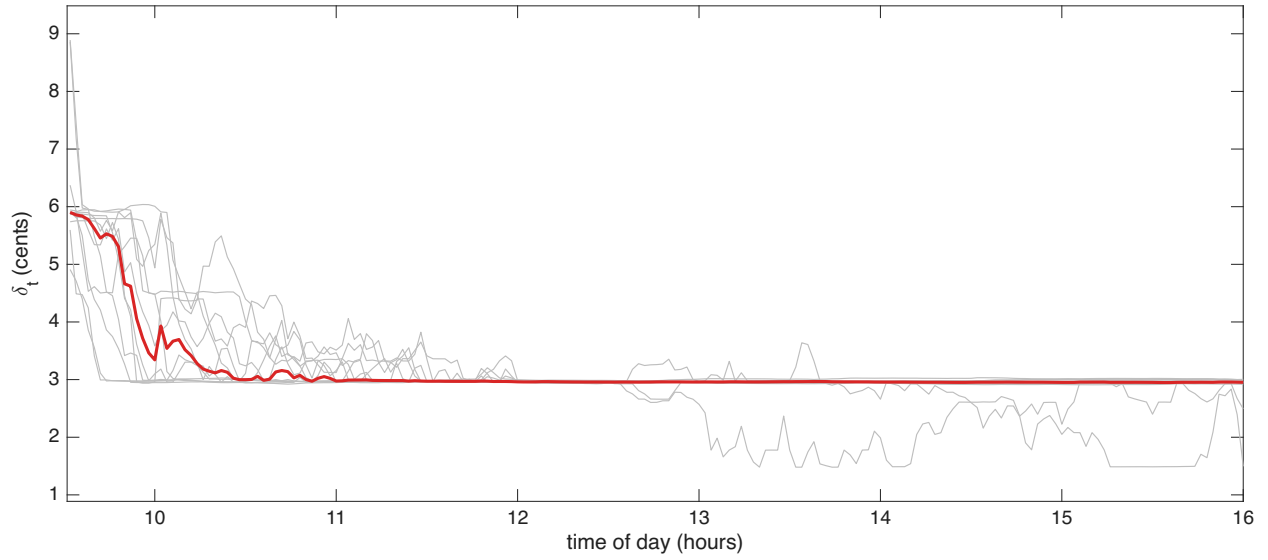


Figure 3: Huber threshold  $\delta_t$  in cents through the trading day, for 12 TSLA trading days in Oct 2024 (grey lines) and their median (red line).

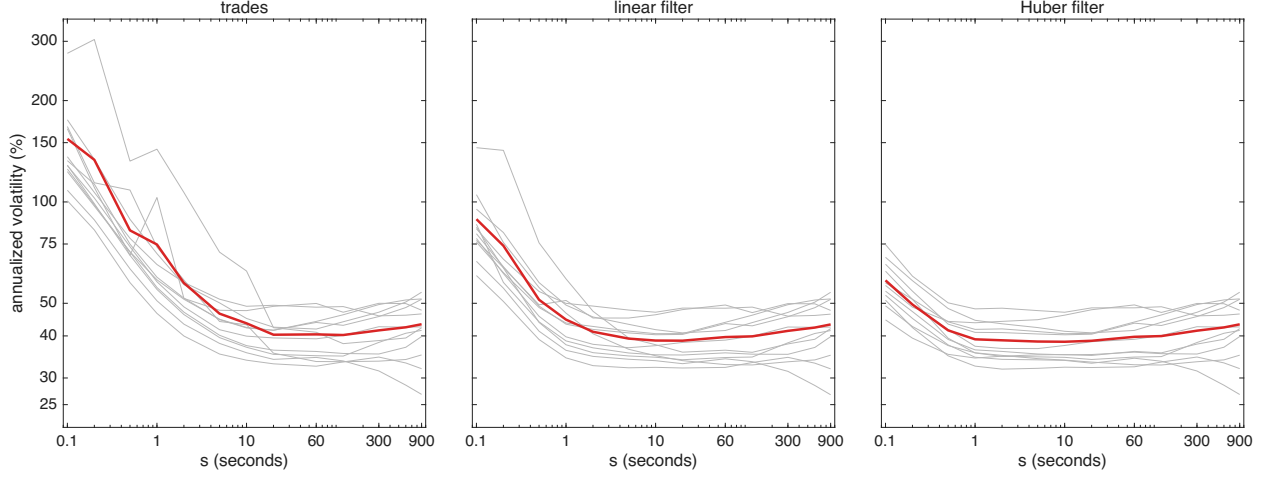


Figure 4: Volatility signature curves for TSLA over the 12 trading days in Oct 2024. The annualized vol  $\hat{\sigma}100\sqrt{252}$  from the returns  $\hat{X}_t - \hat{X}_{t,s}$  of Table 2, against the lag  $s$  in seconds, both axes on log scales, for: raw trades, linear filter & Huber filter. Grey lines are the individual trading days & the red line is the square root of the 12 day average of their squares. The linear & Huber returns carry the finite-sample correction  $c_{t,s}$  of the paper; the raw trades are unaffected by it.

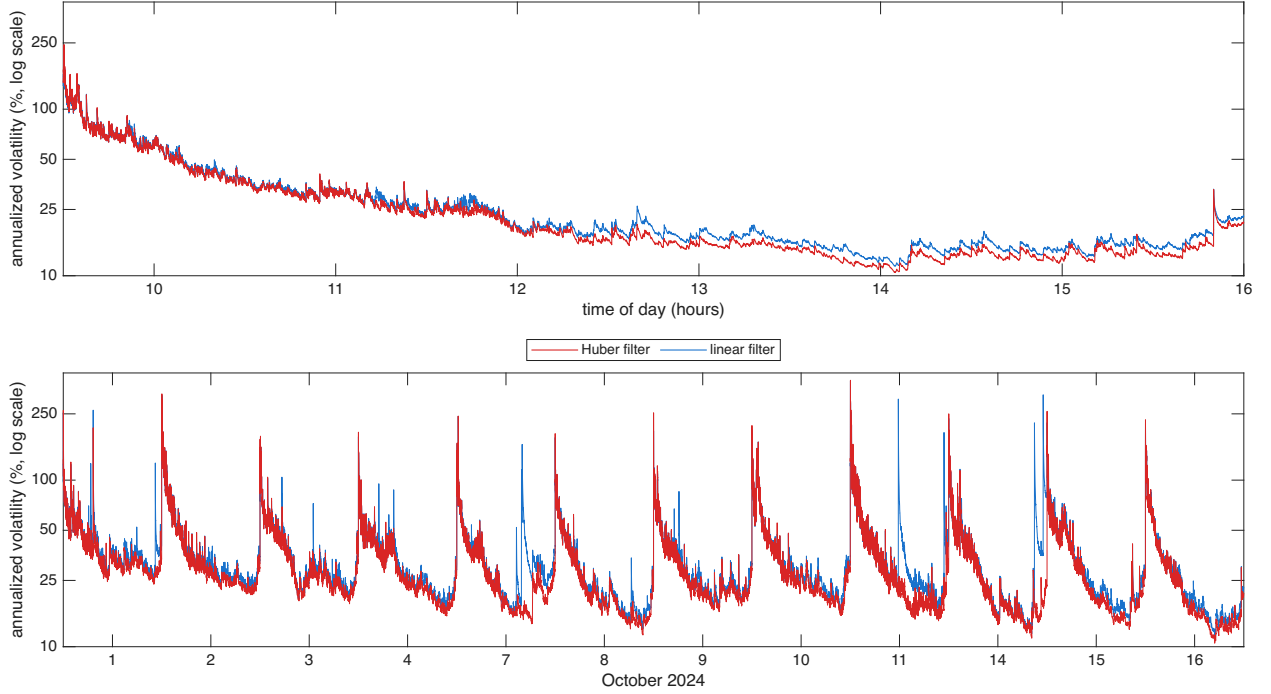


Figure 5: Filtered spot volatility for TSLA over 12 trading days in Oct 2024, the diurnally adjusted estimator  $\hat{\sigma}(u)100\sqrt{252}$  at  $s = 1$  second with hyperbolic weights, Mandelbrot parameter  $a = 359$ , with the input prices computed using the Huber & linear filters, shown as annualized volatility in percent on a log10 scale. Top: 16 October 2024, bottom: 12 days.

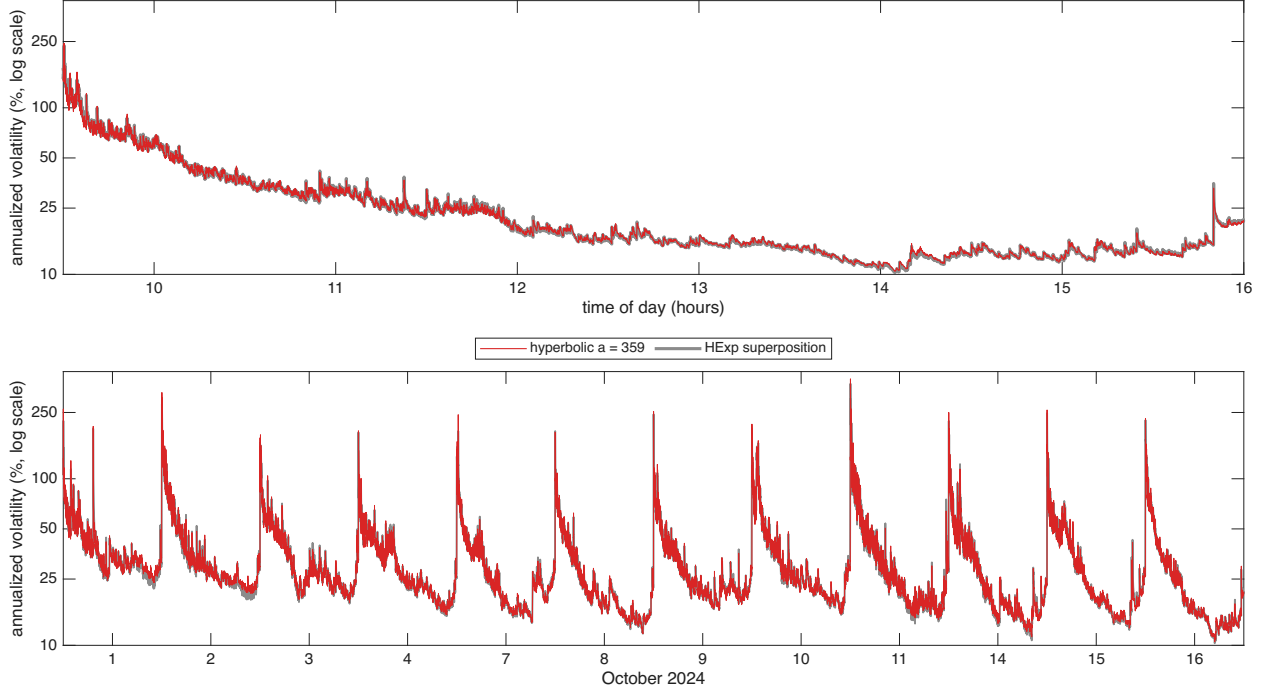


Figure 6: Hyperbolic against superposition weights for TSLA over 12 trading days in Oct 2024, the diurnally adjusted  $\hat{\sigma}(u)100\sqrt{252}$  at  $s = 1$  second from the Huber filter, shown as annualized vol in % on a log10 scale. The only difference between the 2 paths is the weight function: the hyperbolic weights with  $a = 359$  in red, drawn on top, and the HExp superposition in grey, 4 exponential components with half lives of 2, 20, 200, 2000 seconds. Hyperparameters minimize the QLIKE objective. Top: 16 October 2024, bottom: 12 days.

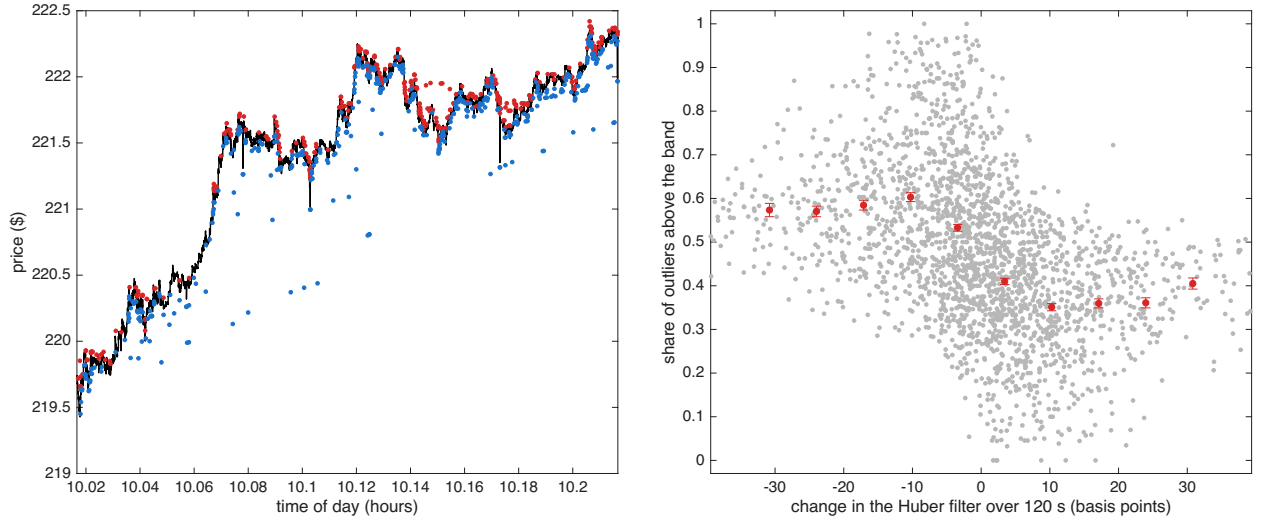


Figure 7: Outliers & robust price for TSLA on 16 October 2024. Left: the 12 minutes with the largest move in the Huber filter that day; outliers above  $Y_t - \theta_t > \delta_{t-1}$  in red, outliers below  $Y_t - \theta_t < -\delta_{t-1}$  in blue, Huber filter in black. Right: over the 12 trading days, the 120 second empirical conditional probability that outliers are above (rather than below) the Huber band against the 120 second change in the Huber filter in basis points: light points are single bins, the line & bars are means & s.e.

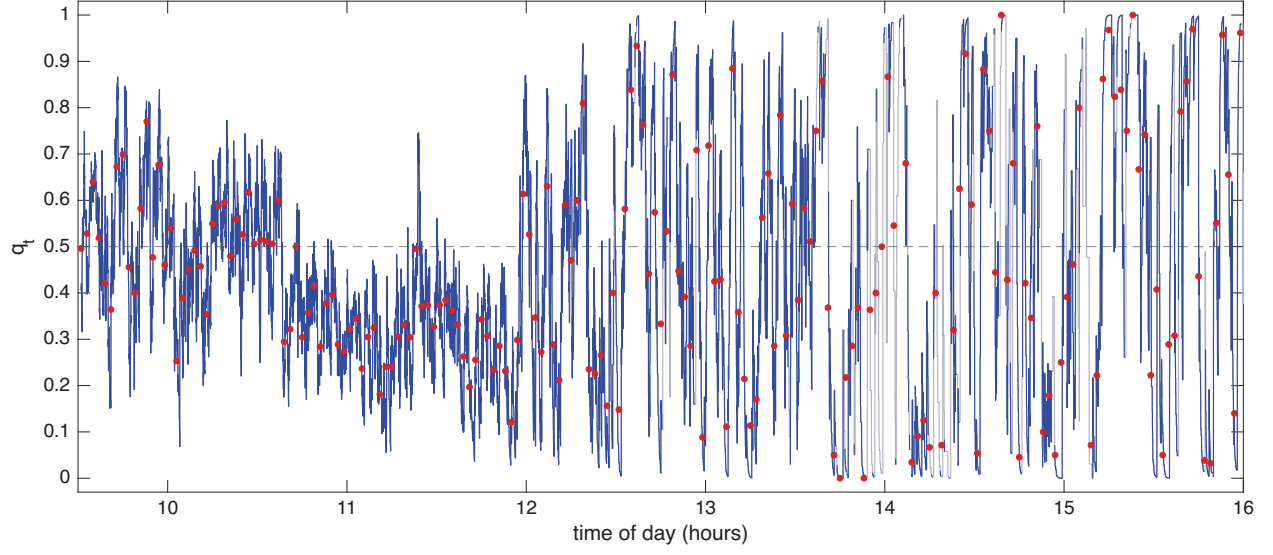


Figure 8: The directional conditional probability for **TSLA**, 16 October 2024. The filtered conditional probability  $q_t$  that an outlier lies above the robust Huber band, under exponential weights decaying in clock time with half life of 14 seconds; where fewer than two outliers remain in the weights it is drawn in grey. The dashed line marks 0.5. The red points are the empirical conditional probability using the 120 second bins of the previous figure.



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On 11 October 2024, 32 per cent of the day's largest one per cent of residuals fall inside its first minute, against at most 22 per cent on any other day. Every number that day contributes to carries that burst.

The largest Huber residual on 16 October 2024 occurs at 09:35, within the opening minutes; the volatility comparison window is placed at the largest residual after 09:45, at 09:55.

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Diagnostics.