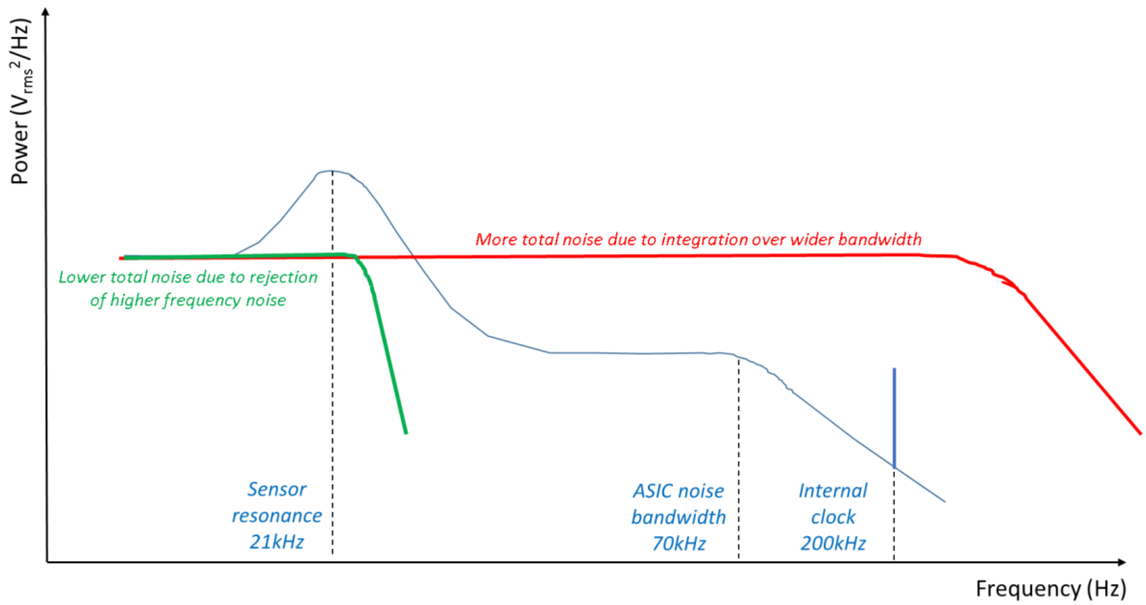
Achieving Best Noise Performance with the ADXL1002

In many accelerometers, the signal bandwidth of the IC is limited by the resonant frequency of the MEMS. The ADXL1002 sensor resonant frequency is equal to 21 kHz, and the noise bandwidth is limited by the signal processing circuitry. Many customers may mistakenly assume that the output noise bandwidth is limited by the sensor resonance and choose to not add a low pass filter, inadvertently ending up with higher noise than expected. The goal of this guide is to present the correct method to measure the output of the accelerometer, such that the noise density of the measurement matches the product specification.

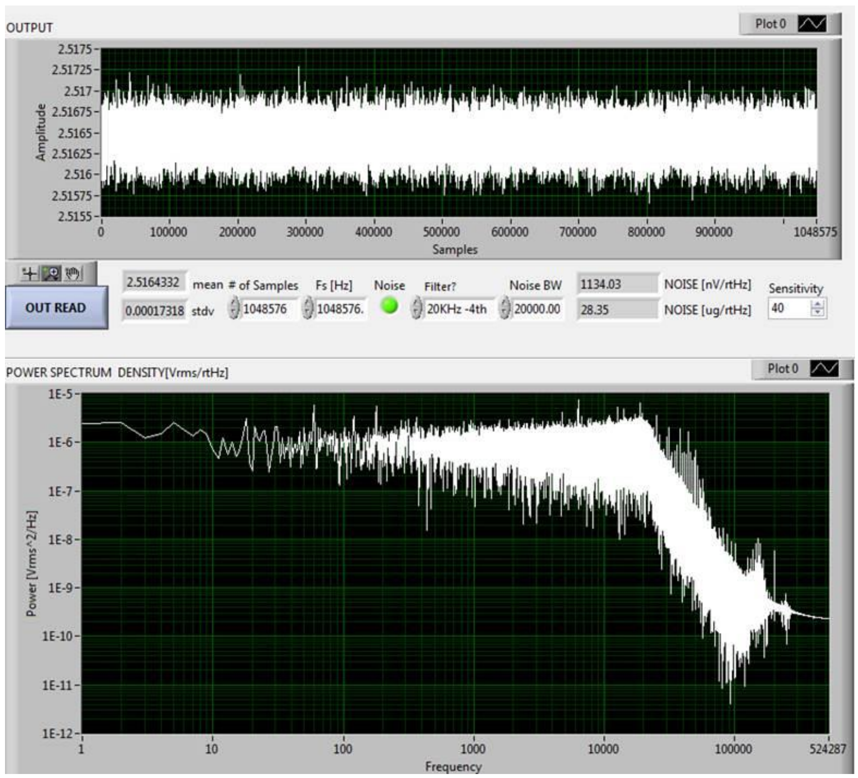
The figure below shows an illustration of the accelerometer output power spectrum (not to scale). This circuitry has a bandwidth of 70 KHz (single pole filter). If one chooses a very wide bandwidth measurement system (>200kHz), then the total RMS noise measured will be higher due to contribution from high frequency noise and the clock. Additionally, to avoid aliasing of high frequency noise, one must choose a sampling rate of at least twice the equivalent noise bandwidth (ENB = $\frac{\pi}{2}$ x 70 kHz ≈ 110 kHz), i.e. sampling rate must be at least 220 kHz.

To get the best noise performance from the accelerometer, one must use a low pass filter to limit the bandwidth to frequencies no larger than the frequencies of interest in one's application. Note that choosing a bandwidth larger than the sensor resonant frequency is not advisable, as the accelerometer has reduced sensitivity at higher frequencies, and doing so will result in more noise at the output.

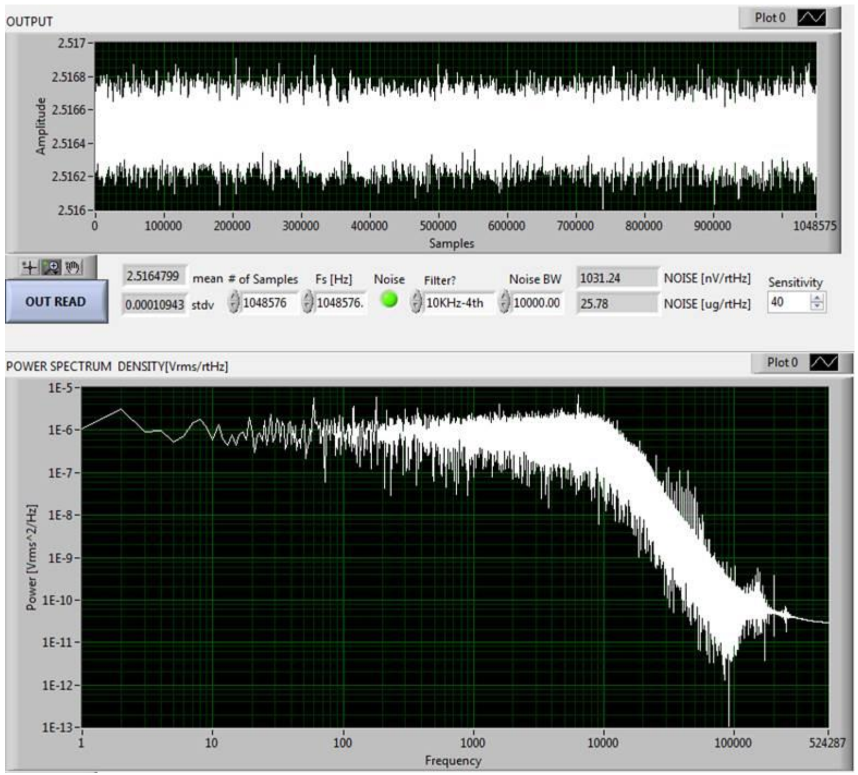


The red curve above illustrates that operating with a wide measurement bandwidth allows multiple sources of noise to impact the output noise performance. Using smaller measurement bandwidth with a well-designed low pass filter rejects higher frequency noise sources and results in the best noise performance from the accelerometer.

We choose a sampling rate of 1MHz, which is sufficiently larger than the 220 kHz limit to avoid aliasing. To achieve adequate attenuation of the out of band noise sources, we use a 4th order digital Butterworth filter with a cutoff frequency of 20 kHz to demonstrate the product performance with approximately the largest achievable bandwidth. The RMS noise measured is 173µV, translating to a calculated noise density of **173 µV/√(20000Hz) = 1.22µV/√Hz = 30.5µg/√Hz**. The power spectral density (PSD) indicates that the noise in 20 kHz bandwidth is **1.13µV/√Hz = 28.35µg/√Hz**, which matches the calculation from the RMS noise.



For an application where larger bandwidth is not necessary, it is recommended that the low pass filter be set at a lower cutoff frequency. Consider for e.g. a use case where the signal of interest has no frequency components larger than 10 kHz. Choosing a 4th order Butterworth filter with 10kHz cutoff frequency results in lower RMS noise of 109µV, translating to a calculated noise density of **109 µV/√(10000Hz) = 1.09µV/√Hz = 27.2µg/√Hz**. This matches the noise density in 10 kHz bandwidth measured from the PSD = **1.03µV/√Hz = 25.78µg/√Hz**.



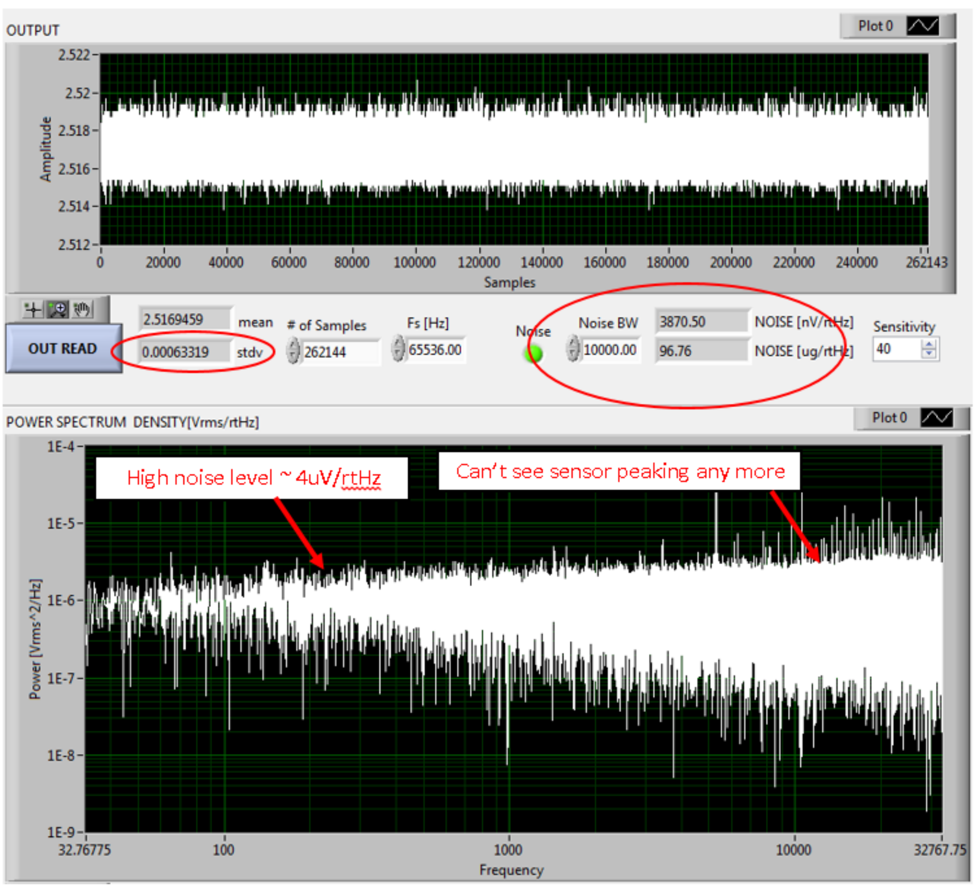
The next section provides some examples of common mistakes that could result in higher than expected noise. These are meant to serve as a quick reference on mistakes that should be avoided.

Examples of incorrect measurement setup, resulting in higher than expected noise

1. Low sampling rate, and no low pass filter

If a low sampling rate is chosen, then the PSD shows higher noise than expected due to aliasing of the high frequency noise. For this illustration, we choose 65 kHz as our sampling rate, which is lower than the recommended minimum of 220 kHz. The measurement is performed without a low pass filter at the output. The RMS noise in this measurement is 636µV, and if one assumes 21kHz as the signal bandwidth (sensor resonance), then the noise density calculated is **636 µV/√(21000Hz) = 4.3µV/√Hz = 107µg/√Hz**, This would make it appear that the noise density in the ADXL1002 is higher than expected. However this simple calculation does not correctly account for the noise bandwidth, and contribution to the noise from the clock signal, and hence is not correct.

The power spectral density (PSD) for this signal shows that the noise inside the measurement bandwidth is high due to aliasing of high frequency noise. For 10 kHz noise bandwidth, one obtains a noise level of **3.87µV/√Hz = 96µg/√Hz**. This shows that choosing a low sampling rate is detrimental to the output noise.

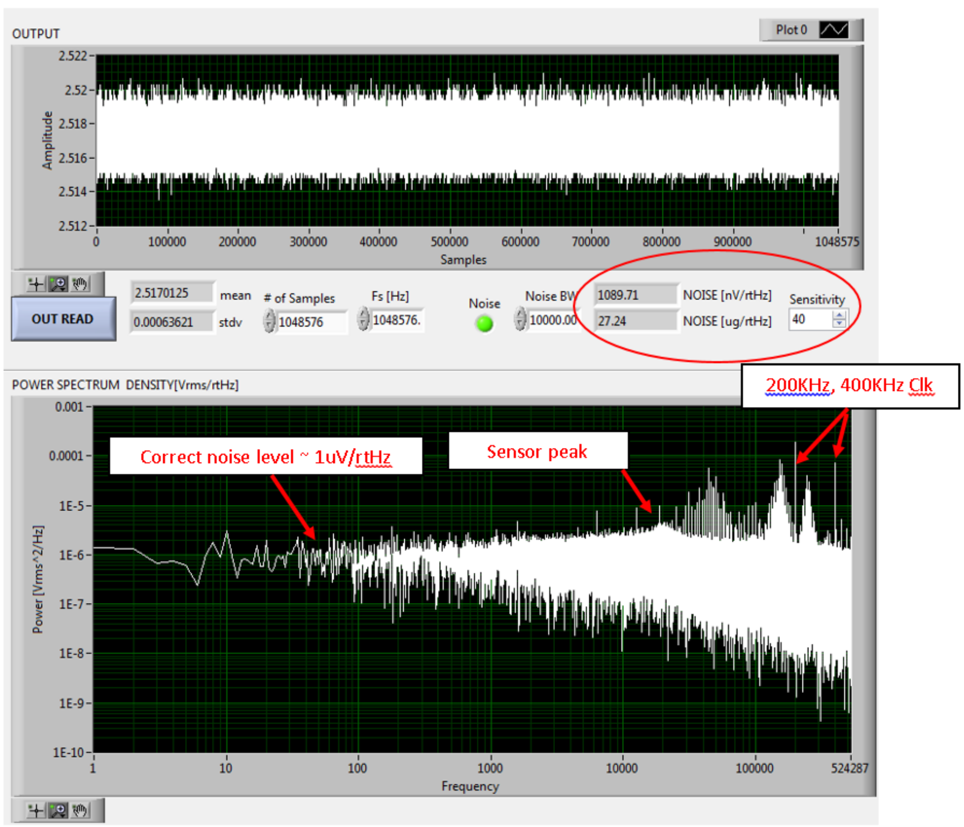


In the above measurement, the sensor peak is buried in the noise.

2. Not using a low pass filter at the output, with high sampling rate

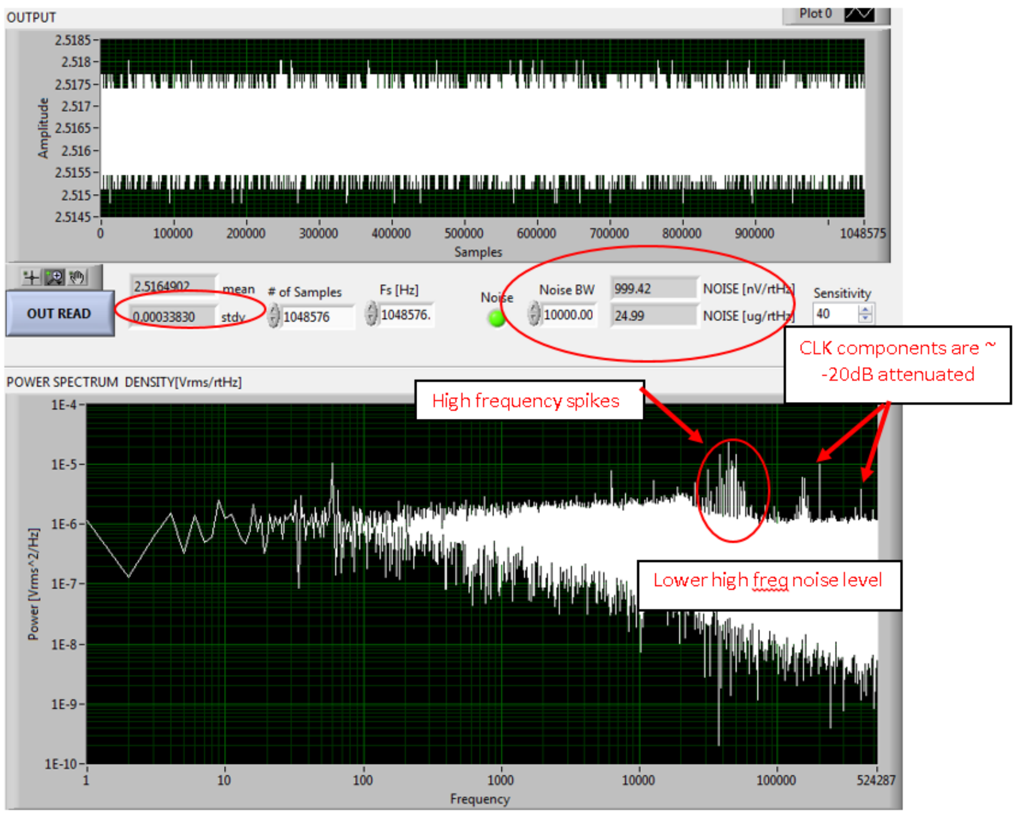
Fast sampling at 1MHz allows the sensor clock at 200kHz into the signal bandwidth. If one monitors the RMS noise (636µV), and assumes 21kHz as the signal bandwidth, then the noise density calculated is **636 µV/√(21000Hz) = 4.3µV/√Hz = 107µg/√Hz**, which is an incorrect method of estimating noise density due to the reasons described on the previous page (not accounting for the noise bandwidth, and contribution to the noise from the clock signal).

The PSD gives an accurate picture of the true noise level. From the PSD chart for this measurement, for 10 kHz noise bandwidth, one obtains the correct noise density of **1.089µV/√Hz = 27µg/√Hz**. Thus, although the ADXL1002 noise density is within expectations, absence of output filter results in higher noise measurement.

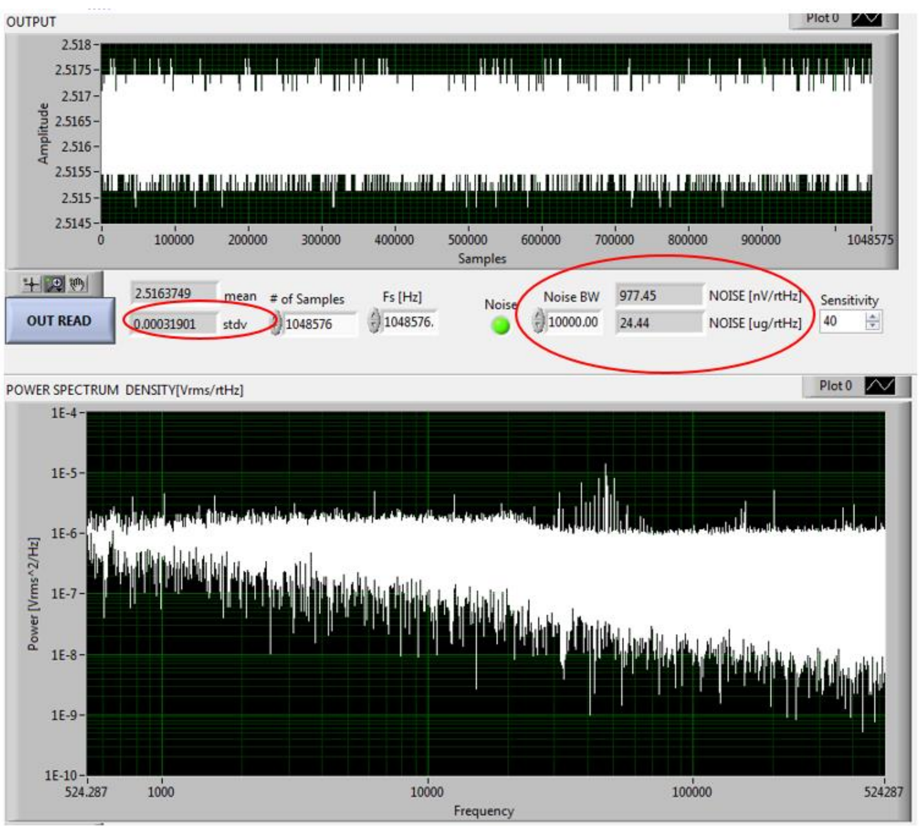


3. Using a single pole low pass filter at the output

Using a single pole RC filter at 24kHz will attenuate the contribution from high frequency noise sources. This measurement uses 1MHz sampling rate. The noise density matches expectations and with a 10 kHz noise bandwidth, the measured noise density from PSD is **0.999µV/√Hz = 24.99µg/√Hz**. The RMS noise of the time domain signal however is 338µV, and assuming 24kHz as the signal bandwidth, then the calculated noise density is **338 µV/√(24000Hz) = 2.18µV/√Hz = 54.54µg/√Hz**. The discrepancy here is on account of insufficient attenuation of the clock signal and high frequency noise sources inside the noise bandwidth of the output amplifier.



As another example, consider a 11 kHz low pass filter at the output. The ADXL1002 has 3-dB sensitivity bandwidth of 11 kHz, and hence in this example this frequency is chosen as the bandwidth by introducing a single pole RC filter. This condition is similar to most applications for the ADXL1002. This reduces the RMS noise to 319µV, but assuming 11 kHz as the bandwidth, this will translate to a calculated noise density of **3µV/√Hz = 75µg/√Hz**. This calculated number is higher than expected as the single pole filter does not sufficiently attenuate the clock signal and high frequency noise sources. The PSD indicates that the noise in 10 kHz bandwidth is **0.977µV/√Hz = 24.44µg/√Hz**.



Conclusion

- **Low sampling rate should never be considered for the ADXL1002, as doing so will introduce higher noise due to aliasing. The sampling rate should be larger than 2X the ENB of the amplifier i.e. 220 kHz.**
- **The RMS noise from a wide band measurement should not be used to estimate the noise density of the ADXL1002, assuming the sensor resonant frequency as the bandwidth. All the noise sources must be properly accounted for, and the noise density should be measured from the PSD.**
- **A combination of fast sampling and appropriate low pass filter results in the best noise performance. A higher order filter will result in better noise performance by sufficiently attenuating the sensor clock and higher frequency noise sources.**

Summary of experiments:

<table>
<tr><th>Filter</th><th>Sampling rate</th><th>RMS noise (µV)</th><th>Calculated noise density from RMS noise (µg/√Hz)</th><th>Noise density from PSD – 10kHz bandwidth (µg/√Hz)</th><th>Comments</th></tr>
<tr><td>4th order Butterworth at 20kHz</td><td>1MHz</td><td>173</td><td>30.5</td><td>28.35</td><td rowspan="2">Sufficient attenuation of high frequency noise from higher order digital filter → RMS noise matches expectation</td></tr>
<tr><td>4th order Butterworth at 10kHz</td><td>1MHz</td><td>109</td><td>27.2</td><td>25.78</td></tr>
<tr><td>None</td><td>65kHz</td><td>636</td><td>107</td><td>96</td><td>Aliasing of high frequency noise</td></tr>
<tr><td>None</td><td>1MHz</td><td>636</td><td>107</td><td>27</td><td>Absence of filter results in integration of noise over wider bandwidth</td></tr>
<tr><td>24kHz RC</td><td>1MHz</td><td>338</td><td>54.54</td><td>24.99</td><td rowspan="2">RMS noise higher than expected due to insufficient attenuation of high frequency noise</td></tr>
<tr><td>11kHz RC</td><td>1MHz</td><td>319</td><td>75</td><td>24.44</td></tr>
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