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# UNLOCKING PRECISION TIMING WITH THE CW25 GDO GNSS RECEIVER

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In today's precision timing applications, stability and accuracy are critical. The Connor Winfield CW25 GDO is a flexible GNSS receiver that integrates a digital phase-locked loop (DPLL) with a numerically controlled oscillator (NCO) to offer exceptional synchronization capabilities. Its ability to leverage different master clock (MCLK) sources—ranging from an onboard temperature-compensated crystal oscillator (TCXO) to an external oven-controlled crystal oscillator (OCXO) or double OCXO (DOCXO)—allows users to optimize performance based on their specific needs.

This white paper explores the performance benefits of different MCLK configurations and loop bandwidth settings, highlighting their impact on frequency stability, phase noise, and holdover accuracy. Performance plots are provided to illustrate these distinctions, guiding users toward the best setup for their application.

### Key Benefits of the CW25 GDO

- Flexible Master Clock Input: Supports onboard TCXO or external OCXO/DOCXO.
- Customizable Loop Bandwidth: Configurable bandwidth settings for optimal trade-offs between noise filtering and response time.
- Advanced Sawtooth Error Correction: Improves phase stability using quantization error messaging.
- Enhanced Holdover Performance: Maintains precise timing even when GNSS signals are lost.

## Understanding the Role of Loop Bandwidth and MCLK Sources Comparison of Configurations

The CW25 GDO provides many configuration options but four primary configurations are illustrated here, each offering distinct advantages depending on application requirements:

1. TCXO with 50mHz Loop Bandwidth (LBW) – Fast response, high adaptability, but higher phase noise.
2. Single OCXO with 6.4mHz LBW – Balanced stability and response time.
3. Single OCXO with 1.2mHz LBW – Superior holdover performance, reduced noise.
4. DOCXO with 1.2mHz LBW – Best overall stability, lowest phase noise, ideal for critical applications.

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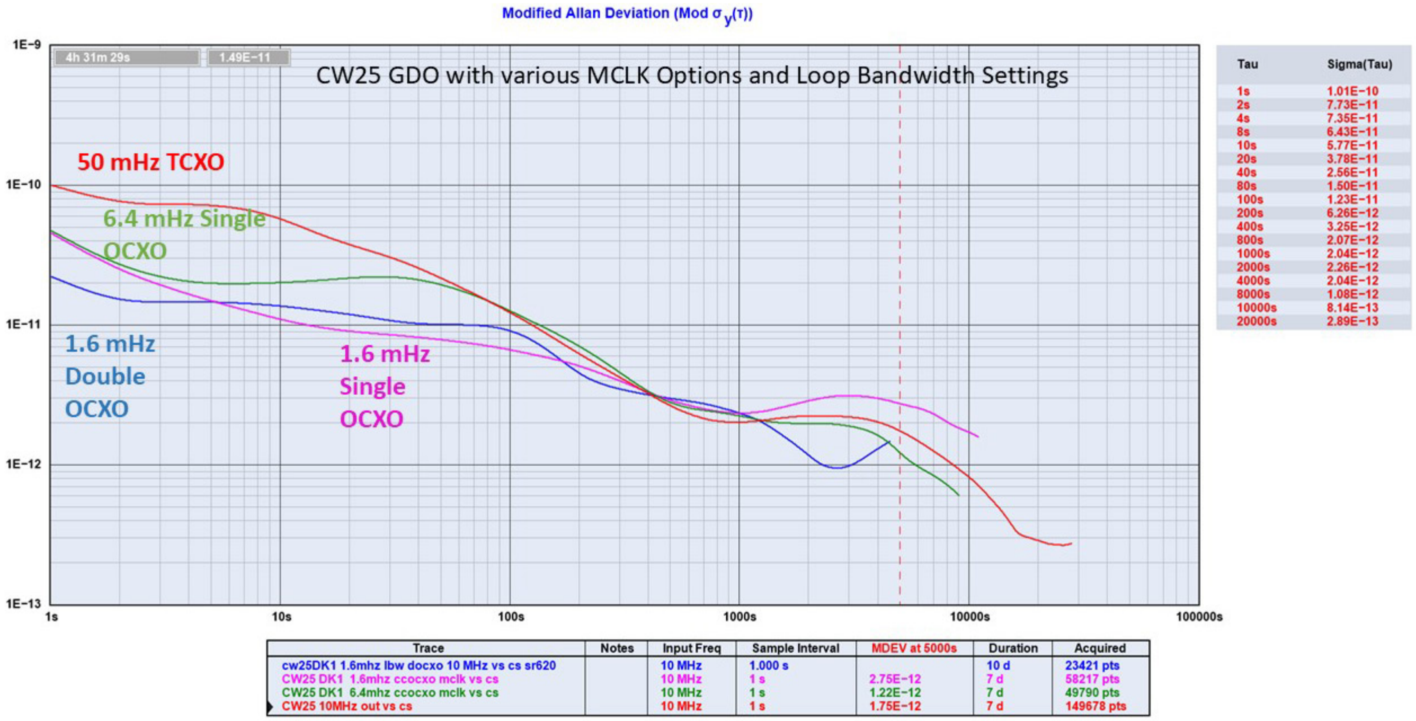
## MDEV Performance Comparison

MDEV Convergence Around 1000 Seconds: The convergence of the MDEV plots for all MCLK and LBW options around 1000 seconds occurs due to the transition from short-term frequency noise to long-term drift mechanisms. At shorter timescales ( < 100s), high-frequency noise dominates, meaning that lower bandwidth settings and higher-quality oscillators (OCXO/DOCXO) perform significantly better. However, around 1000 seconds, the GNSS disciplining effect takes precedence, equalizing stability across all configurations. The loop bandwidth and oscillator quality have less impact in this region because the GNSS corrections begin to dominate frequency control.

Beyond 1000 seconds without GPS lock, the primary driver of stability becomes the oscillator's long-term drift and aging characteristics, which explains why holdover performance differs significantly when GNSS signals are unavailable. For applications requiring prolonged GNSS loss handling, a high precision DOCXO or OCXO with a 1.2mHz LBW setting remains the most stable choice.

- DOCXO with 1.2mHz LBW demonstrates the lowest Modified Allan Deviation (MDEV), ensuring the highest frequency stability over time.
- Single OCXO configurations show progressively better stability than TCXO, with the 1.2mHz LBW setting further reducing frequency fluctuations.
- TCXO exhibits the highest MDEV, but even with it's 50mHz loop bandwidth setting, it shows a significant reduction from a typical raw 1PPS undisciplined output.



| Tau | Sigma(Tau) |
|---|---|
| 1s | 1.01E-10 |
| 2s | 7.73E-11 |
| 4s | 7.35E-11 |
| 8s | 6.43E-11 |
| 10s | 5.77E-11 |
| 20s | 3.78E-11 |
| 40s | 2.56E-11 |
| 80s | 1.50E-11 |
| 100s | 1.23E-11 |
| 200s | 6.26E-12 |
| 400s | 3.25E-12 |
| 800s | 2.07E-12 |
| 1000s | 2.04E-12 |
| 2000s | 2.26E-12 |
| 4000s | 2.04E-12 |
| 8000s | 1.08E-12 |
| 10000s | 8.14E-13 |
| 20000s | 2.89E-13 |

| Trace | Notes | Input Freq | Sample Interval | MDEV at 5000s | Duration | Acquired |
|---|---|---|---|---|---|---|
| cw25DK1 1.6mhz lbw docxo 10 MHz vs cs sr620 | | 10 MHz | 1.000 s | | 10 d | 23421 pts |
| CW25 DK1 1.6mhz ccocxo mclk vs cs | | 10 MHz | 1 s | 2.75E-12 | 7 d | 58217 pts |
| CW25 DK1 6.4mhz ccocxo mclk vs cs | | 10 MHz | 1 s | 1.22E-12 | 7 d | 49790 pts |
| CW25 10MHz out vs cs | | 10 MHz | 1 s | 1.75E-12 | 7 d | 149678 pts |

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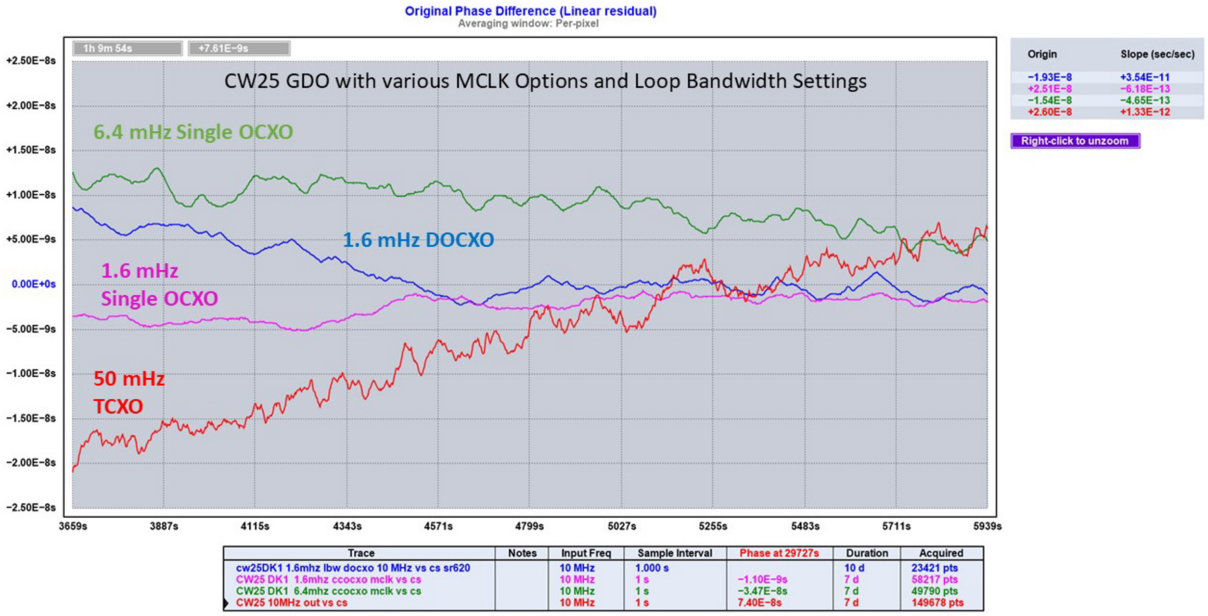
## Phase Difference Comparison

Phase Difference and Locking Performance Phase coherence is a critical aspect of timing applications. The CW25 GDO’s phase-locked loop (PLL) performance improves with lower bandwidth settings and more stable oscillators.

- TCXO with 50mHz LBW shows the highest residual phase error due to its increased sensitivity to short-term fluctuations.
- Single OCXO with 6.4mHz LBW reduces phase deviations, while the 1.2mHz LBW setting provides even tighter phase control.
- DOCXO or OCXO with 1.2mHz LBW delivers the most consistent phase stability, ensuring minimal deviation over extended periods.



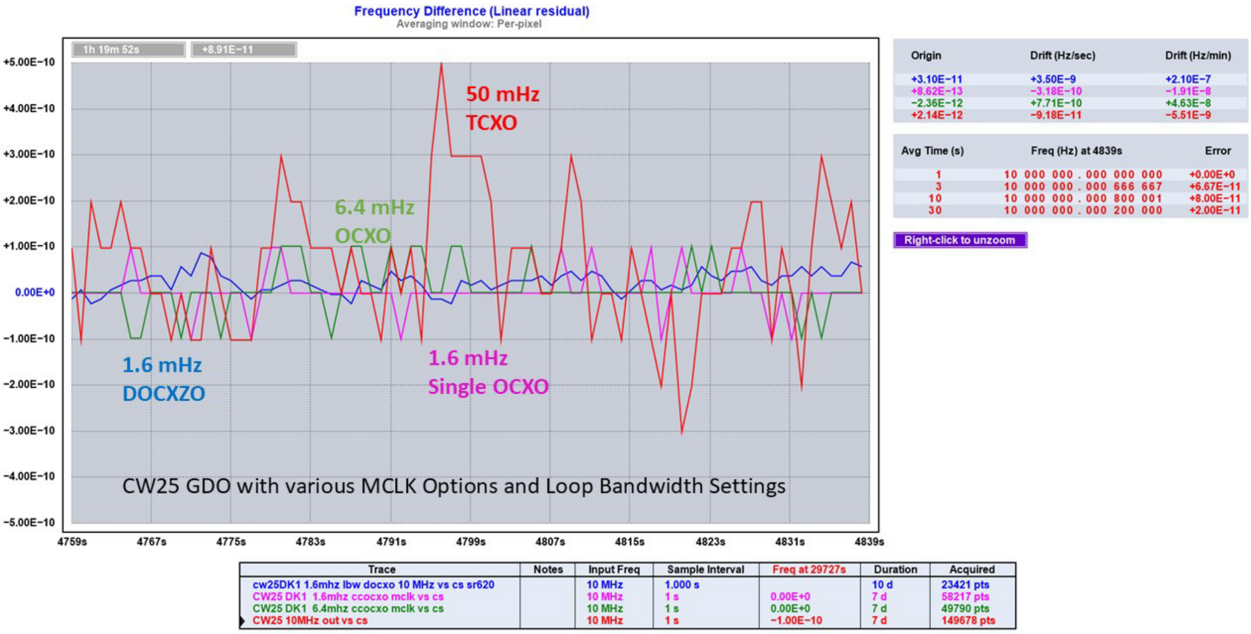
| Origin | Slope (sec/sec) |
|---|---|
| −1.93E−8 | +3.54E−11 |
| +2.51E−8 | −6.18E−13 |
| −1.54E−8 | −4.65E−13 |
| +2.60E−8 | +1.33E−12 |

| Trace | Notes | Input Freq | Sample Interval | Phase at 29727s | Duration | Acquired |
|---|---|---|---|---|---|---|
| cw25DK1 1.6mhz lbw docxo 10 MHz vs cs sr620 | | 10 MHz | 1.000 s | | 10 d | 23421 pts |
| CW25 DK1 1.6mhz ccocxo mclk vs cs | | 10 MHz | 1 s | −1.10E−9s | 7 d | 58217 pts |
| CW25 DK1 6.4mhz ccocxo mclk vs cs | | 10 MHz | 1 s | −3.47E−8s | 7 d | 49790 pts |
| ▶ CW25 10MHz out vs cs | | 10 MHz | 1 s | 7.40E−8s | 7 d | 149678 pts |

## Frequency Difference Comparison

Effect of Loop Bandwidth on Short-Term Frequency Fluctuations and Its Relationship to Frequency Difference Measurements.

- Short-term frequency fluctuations are best observed in the sub-ppb range, as derived from Time Lab calculations.
- Lower bandwidth settings (1.2mHz LBW) exhibit reduced frequency fluctuations, leading to improved short-term frequency stability.
- DOCXO provides the least variation in short-term frequency, making it ideal for applications requiring ultra-low noise performance.
- TCXO with 50mHz LBW exhibits more variation, showing higher short-term instability due to increased sensitivity to noise and environmental factors.



| Origin | Drift (Hz/sec) | Drift (Hz/min) |
|---|---|---|
| +3.10E−11 | +3.50E−9 | +2.10E−7 |
| +8.62E−13 | −3.18E−10 | −1.91E−8 |
| −2.36E−12 | +7.71E−10 | +4.63E−8 |
| +2.14E−12 | −9.18E−11 | −5.51E−9 |

| Avg Time (s) | Freq (Hz) at 4839s | Error |
|---|---|---|
| 1 | 10 000 000 . 000 000 000 | +0.00E+0 |
| 3 | 10 000 000 . 000 666 667 | +6.67E−11 |
| 10 | 10 000 000 . 000 800 001 | +8.00E−11 |
| 30 | 10 000 000 . 000 200 000 | +2.00E−11 |

| Trace | Notes | Input Freq | Sample Interval | Freq at 29727s | Duration | Acquired |
|---|---|---|---|---|---|---|
| cw25DK1 1.6mhz lbw docxo 10 MHz vs cs sr620 | | 10 MHz | 1.000 s | | 10 d | 23421 pts |
| CW25 DK1 1.6mhz ccocxo mclk vs cs | | 10 MHz | 1 s | 0.00E+0 | 7 d | 58217 pts |
| CW25 DK1 6.4mhz ccocxo mclk vs cs | | 10 MHz | 1 s | 0.00E+0 | 7 d | 49790 pts |
| ▶ CW25 10MHz out vs cs | | 10 MHz | 1 s | −1.00E−10 | 7 d | 149678 pts |

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## Why Phase and Frequency Difference Measurements Reduce Proportionally to Loop Bandwidth setting reductions

The observed reduction in phase and frequency and difference measurements as loop bandwidth decreases is a direct consequence of how the phase-locked loop (PLL) filters noise and responds to frequency fluctuations:

- Filtering of High-Frequency Noise: A lower loop bandwidth acts as a low-pass filter, significantly attenuating high-frequency variations that contribute to short-term frequency fluctuations. This results in a smoother frequency output, minimizing deviations in the frequency difference measurements.
- Reduced Response to GNSS Jitter: A wider bandwidth setting allows the PLL to react more quickly to GNSS timing variations, leading to more frequent but smaller frequency corrections. Conversely, a narrower bandwidth setting slows down these corrections, preventing the PLL from introducing rapid variations in response to GNSS fluctuations.
- Increased Dependence on the Local Oscillator: At lower bandwidths, the PLL relies more on the intrinsic stability of the master clock (MCLK), especially in the presence of high-quality OCXO and DOCXO sources. Since these oscillators have inherently lower frequency noise, the frequency difference measurements show much smaller variations compared to a system with a TCXO and higher bandwidth.

Thus, as the loop bandwidth is reduced, the system shifts from a rapid correction mechanism (which increases frequency variation) to a more stable, oscillator-dependent system (which minimizes short-term frequency fluctuations). This explains why lower bandwidth settings produce proportionally smaller frequency difference measurements and why DOCXO configurations with narrow LBW settings exhibit the best frequency stability.

## Understanding the Role of Loop Bandwidth and MCLK Sources

### Local Oscillator Requirements for Low Bandwidth Settings

The ability to successfully implement a low loop bandwidth setting, such as 1mHz, depends heavily on the quality of the master clock (MCLK). The local oscillator must meet stringent stability and noise performance requirements to ensure optimal phase lock loop (PLL) operation. Key considerations include:

- Phase Noise Performance: A high-quality OCXO or DOCXO with low phase noise ensures the PLL can operate effectively without excessive correction noise. A TCXO, with its higher phase noise, is unsuitable for very low bandwidth settings.
- Short-Term Stability: The Allan Deviation (ADEV) of the oscillator must be sufficiently low to prevent excessive phase fluctuations. Typical minimum requirements for 1mHz loop bandwidth include:
  OCXO: ADEV in the range of $5 \times 10^{12}$ at 1s.
  DOCXO: ADEV in the range of $2 \times 10^{12}$ at 1s.
- Thermal Stability: Temperature-induced frequency variations must be minimal. DOCXOs, with their tighter thermal compensation, perform best in this scenario.
- Aging Characteristics: Over extended periods, frequency drift must remain within acceptable limits. A high-quality DOCXO exhibits minimal drift, making it ideal for applications requiring long-term frequency accuracy.

The lower the loop bandwidth, the more the system depends on the stability of the MCLK rather than external GNSS corrections. Thus, a high-performance OCXO or DOCXO is essential for achieving reliable performance at 1mHz loop bandwidth, while TCXOs and lower-grade OCXOs are unsuitable due to their higher noise and drift characteristics.

## Understanding the Role of Quantization Error Correction

Advanced Sawtooth Error Compensation and PLL Stability is one of the CW25 GDO's standout features is its ability to correct for sawtooth errors using quantization error messaging and phase compensation control. By predicting the location of the next GNSS PPS pulse and adjusting the phase accordingly, the receiver enhances its PLL performance:

- Minimizing Phase Jitter: Active compensation smooths phase tracking, reducing noise artifacts.
- Enhancing Locking Performance: Predictive adjustments keep the PLL tightly locked.
- Reducing Frequency Drift: Improves holdover stability by maintaining a consistent frequency reference.

## Holdover Performance and Long-Term Stability without GPS Lock

Holdover performance is determined primarily by the thermal stability and Allan Deviation (ADEV) of the chosen MCLK source. When GNSS signals are lost, the long-term frequency drift characteristics of the oscillator become the dominant factor in maintaining accurate timing. The key holdover performance metrics for the CW25 GDO configurations are:

- TCXO: Stability of 50 ppb (5×10), ADEV of $1\times10^{1}$, making it the least stable choice for extended holdover.
- Single OCXO: Stability of 5 ppb (5×10), ADEV of $1\times10^{11}$, providing moderate long-term stability.
- Compensated OCXO: Stability of .3 ppb (3×1010), ADEV of 6×1012, providing excellent long-term stability.
- DOCXO: Stability of 0.2 ppb ($2\times10^{1}$), ADEV of $2\times10^{12}$, ensuring the best long-term frequency stability and minimal drift.

For applications requiring even further extended GNSS signal loss resilience, due to its minimal frequency drift over time, a chip scale atomic clock with a sub 1 mHz LBW is also an MLCK option choice with the CW25 GDO.

### Choosing the Right Configuration for Your Needs

- For fast GNSS tracking  TCXO with 50mHz LBW.
- For balanced stability and response  Single OCXO with 6.4mHz LBW.
- For high-precision applications  Single OCXO with 1.2mHz LBW.
- For ultimate stability and minimal drift  DOCXO or CCOCXO with 1.2mHz LBW.

## Conclusion

The CW25 GDO's configurable loop bandwidth and support for various MCLK sources allow users to optimize performance based on their timing requirements. By leveraging advanced sawtooth error correction and low-bandwidth filtering, the receiver ensures superior phase stability and frequency accuracy, making it an excellent choice for precision timing applications.

The included performance plots illustrate these benefits, providing a clear roadmap for selecting the best CW25 GDO configuration for your needs.

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