Quartz Lock Loop (QLL) For Robust GNSS Operation in High Vibration Environments

A Topcon white paper written by Doug Langen

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About the author

Doug Langen is a professional engineer with a degree in geomatics engineering from the University of Calgary. He has worked in the GNSS industry for more than a decade contributing to research and development, application engineering, sales support and product management. He joined Topcon in 2011 as a product manager of GNSS.

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Abstract

All dynamic GNSS applications are subject to some degree of bumps, vibration and mechanical shock that can cause inaccurate measurements or complete satellite tracking failure due to impact on a receiver's quartz crystal oscillator. In September 2012 Topcon Positioning Systems (TPS) announced the release of firmware v4.0 introducing Quartz Lock Loop™ (QLL) technology on all Topcon OEM GNSS platforms. Designed by Topcon engineers for superior GNSS tracking in high-vibration environments, QLL technology is an exclusive approach to mitigating the effects of shock and vibration through patented firmware algorithms.

This paper discusses the effects of vibration, acceleration and shock on GNSS integrity, how QLL mitigates the effects for robust operation in any dynamic condition and compares performance of two industry competitors during a comprehensive vibration and shock test.

Introduction

Most high precision GNSS receivers use crystal oscillators to establish a precise timing signal, which relies on the natural resonant vibration of a quartz crystal. This conventional approach can provide suitable performance in smooth dynamics, but when exposed to severe real-word vibration and shock these simple systems can destabilize quickly, leading to inaccurate GNSS measurements or even complete satellite tracking failure.

By using advanced feedback loops, Topcon's patented QLL continuously monitors system behavior to detect and remove any fluctuations that may cause tracking problems – over a full range of vibration frequencies and magnitudes. This allows for a clean, stable timing reference signal to be preserved through strong acceleration, vibration and bumps --- for uninterrupted and reliable precise positioning.

Comprehensive testing was performed at an independent laboratory testing the performance of QLL technology alongside two competing GNSS receiver boards from two separate brands. All boards were tested at a wide variety of vibration frequencies with varying magnitudes in all orientations to simulate the conditions of real world dynamic GNSS applications. The results of the test show how GNSS performance can be quickly compromised without the use of sophisticated GNSS technology.

Crystal Oscillators in GNSS

GNSS receivers calculate position by a process called trilateration, which uses precisely determined distances to a minimum of four satellites with known locations and intersects them to determine the receiver's location. Since GNSS satellites signals travel at the speed of light, the distance or range to each satellite is determined by precisely measuring the time it takes signals transmitted by high-orbit GNSS to reach the receiver and multiplying this transit time by the speed of light. At the speed of light, a 1 microsecond error in time measurement corresponds to a 300m ranging error to each satellite, highlighting the importance of accurate time measurement. GNSS satellites use atomic clocks to achieve timing accuracies at the nanosecond scale, however, users on the ground cannot afford atomic clocks at both the expense and power levels. Consequently, most GNSS receivers use quartz crystal clocks, which rely on the natural resonant frequency of crystal to offer reliable timing stability in ideal conditions. Since quartz clocks are not as accurate as atomic clocks they must be calibrated in real time by the GNSS receiver to achieve suitable time measurement accuracy for satellite ranging and positioning. When, however, the oscillators are subjected to rapid temperature fluctuations or intense vibration or acceleration this induces spurious responses in frequency causing unpredictable timing errors. This frequency drift and unpredictable fluctuation is a common source of signal tracking degradation or failure in GNSS applications.

Quartz Lock Loop (QLL) Technology Design

Quartz crystal oscillators mounted on GNSS boards are regularly subjected to a wide variety of accelerations, vibrations and shock. Depending on the magnitudes and frequencies experienced, forces can cause the oscillations of a quartz crystal to either drift or "burst" making it difficult to maintain an accurate timing signal for GNSS measurements. Users will experience either a positioning degradation or complete failure in satellite tracking altogether.

Topcon engages in many vibration-prone applications, such as machine control, agriculture and marine, and as a result, Topcon engineers were tasked with creating a technology that would withstand the effects of quartz crystal oscillator instability in high-vibration conditions. The response: QLL technology – a software algorithm that mitigates quartz crystal limitations over a full range of vibration frequencies and magnitudes. This algorithm allows for a clean, stable timing reference signal to be preserved through strong acceleration, vibration and bumps for uninterrupted and reliable precise positioning.

QLL technology is based on dynamic feedback loops that monitor the health of the quartz crystal oscillator throughout the GNSS operation. Using broadband loops the frequency drifts and bursts are detected and removed from the timing signal to produce a clean timing reference for uninterrupted satellite tracking even in the worst vibration conditions.

Dynamics and Vibrations Testing

GNSS receivers are used on many vehicles and vessels – passenger cars, construction machinery, marine vessels, military vehicles, airborne platforms – all with their own dynamic behavior. Accelerations caused by motion, such as gravity and engine propulsion, in combination with environmental factors, such as bumpy roads, waves and turbulence, are just a fraction of the influences to a vehicles dynamics. When the design variables of a vehicle, such as center of mass, weight distribution and body flex, are added to the equation dynamics of a vehicle becomes very complex with mechanical vibration being one of the more difficult behaviours to predict and model. Consequently, systems should be designed to withstand the widest range of vibration conditions possible to minimize the chance the operational disruption.

MIL-STD-810, among other test standards, was developed by the U.S. military to validate that a device is able to operate and endure the conditions that it will experience throughout its service life. Although prepared specifically for military applications, the standard is also used to test the environmental integrity of commercial products. As part of this initiative, chamber test methods were developed that replicate the effects of environments on the equipment rather than imitating the environments themselves. For vibration testing a device is mounted to an electrohydraulic or electrodynamic shake table and operational health is monitored as the unit is submitted to a wide spectrum of accelerations and vibrational magnitudes and frequencies. To classify the vibration performance of a device two types of vibration tests are performed – sinusoidal vibration testing and random vibration test.

Sinusoidal Vibration Testing

Sinusoidal vibration testing attempts to model oscillations constant in frequency, typically in the lower frequency spectrum (less than 100 Hz). This simulates vibration caused by the vehicle itself, such as engine vibration, drive train vibration aerodynamic vibration, by auxiliary equipment mounted on the vehicle (pumps, fans, drills, artillery) and by the operational environment, such driving over bumps at high speeds and scraping construction surfaces. All devices under vibration have resonant frequencies where the system tends to oscillate with greater amplitude at some frequencies than at others, and therefore, may be the most operationally harmful. Consequently, sinusoidal vibration testing involves a wide range of frequencies in a test called a sine sweep, where vibration is started at a low frequency (3 Hz) and gradually increased to an upper limit (100 Hz). As the frequency is increased multiple resonant frequencies are tested to validate that the device is able to provide operational stability throughout the sine sweep.

Random Vibration Testing

Random vibration testing models oscillations found in everyday life scenarios that are non-deterministic in nature unlike sinusoidal waveforms. This simulates “real-world” random vibrations, such as bumps experienced due to rough roads, waves and turbulence. Random vibration testing is conducted by instantaneously subjecting a device to a wide range of vibrational frequencies at short, random intervals, rather than gradually increasing vibration frequency used in sinusoidal testing.

Test Details

On October 30, 2012, sinusoidal and random vibration testing was conducted at an independent test lab to determine the performance benefits of QLL technology and to benchmark it against two GNSS industry competitors. GNSS receivers were tested at the board level to remove any hardware related biases by hard mounting each GNSS board directly to the shake table with communications lines and satellite signal cables connected directly to each board (figure 1). To test the orientation susceptibility, each board was tested in all three axes for all random and sinusoidal test configurations. Testing each orientation of a GNSS receiver indicates the suitability and mounting flexibility in a high dynamic application. Both electrohydraulic and electrodynamic shaker systems were used to test both low and high-frequency vibration.

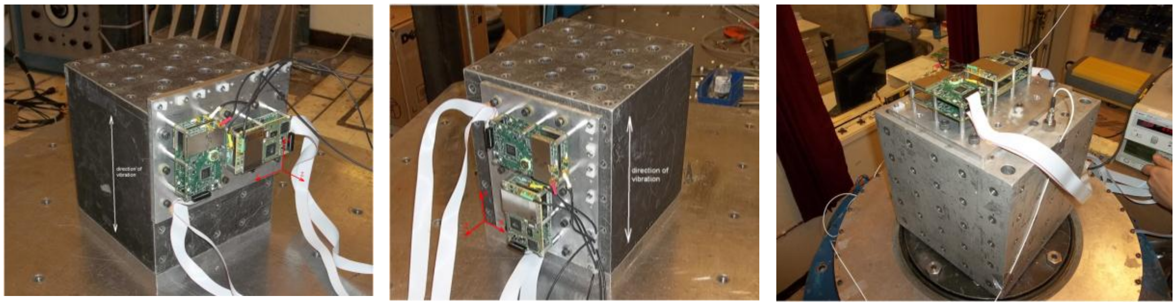

Figure 1: Electrohydraulic and electrodynamic test setups in all three orientations (X, Y and Z respectively).

Nineteen tests were conducted in total to test a variety of vibrational accelerations and frequencies to determine each GNSS boards vibration resistance to vibration to the point of failure. Accelerations ranged from 2g to 23g with frequency ranges of 3 Hz to 2000 Hz.

Raw data was logged from all GNSS receivers throughout the test to monitor signal quality, quantity of satellites tracked and positioning accuracy. The passing criteria for each test were not only whether or not position accuracy has been compromised, but also whether or not satellite signal tracking failure occurred.

Results

Table 1, below, summarizes the details and results of each test conducted:

Table 1: Sinusoidal vibration test details and results.

Test	Axis	Acceleration, g	Frequency, Hz (lower)	Frequency, Hz (upper)	Topcon	Receiver A	Receiver B
1.1	X	2	5	30	Pass	Pass	Pass
1.2	X	4	3	30	Pass	Pass	Fail
1.3	X	6	3	30	Pass	Pass	Fail
1.4	X	6	3	100	Pass	Pass	Fail
1.5	X	8	3	50	Pass	Pass	Fail
1.6	X	10	3	30	Pass	Pass	Fail
1.7	Y	8	3	50	Pass	Fail	Pass
1.8	Y	10	3	30	Pass	Fail	Pass
1.9	Z	8	3	50	Pass	Pass	Pass
1.10	Z	10	3	30	Pass	Pass	Fail

Table 2: Random vibration test details and results.

Test	Axis	Acceleration, g RMS	Frequency, Hz (lower)	Frequency, Hz (upper)	Topcon	Receiver A	Receiver B
2.11	X	7.7	20	2000	Pass	Pass	Pass
2.12	X	19.4	20	2000	Pass	Pass	Fail
2.13	X	23	20	2000	Pass	Pass	Fail
2.14	Y	7.7	20	2000	Pass	Pass	Fail
2.15	Y	19.4	20	2000	Pass	Pass	Fail
2.16	Y	23	20	2000	Pass	Pass	Fail
2.17	Z	7.7	20	2000	Pass	Pass	Pass
2.18	Z	19.4	20	2000	Pass	Pass	Fail
2.19	Z	23	20	2000	Pass	Fail	Fail

It should be noted that the Topcon receiver with QLL passed all tests through both the sinusoidal and random tests. These results are expanded upon in the position and tracking domains illustrated in the figures below.

Sinusoidal Vibration Testing at Specification (4g)

A common sinusoidal vibration specification for GNSS receivers is a resistance to 4g of acceleration without any operational disturbances. The results of test 1.2 are shown below, which is a 4g sinusoidal vibration test in the X axis.

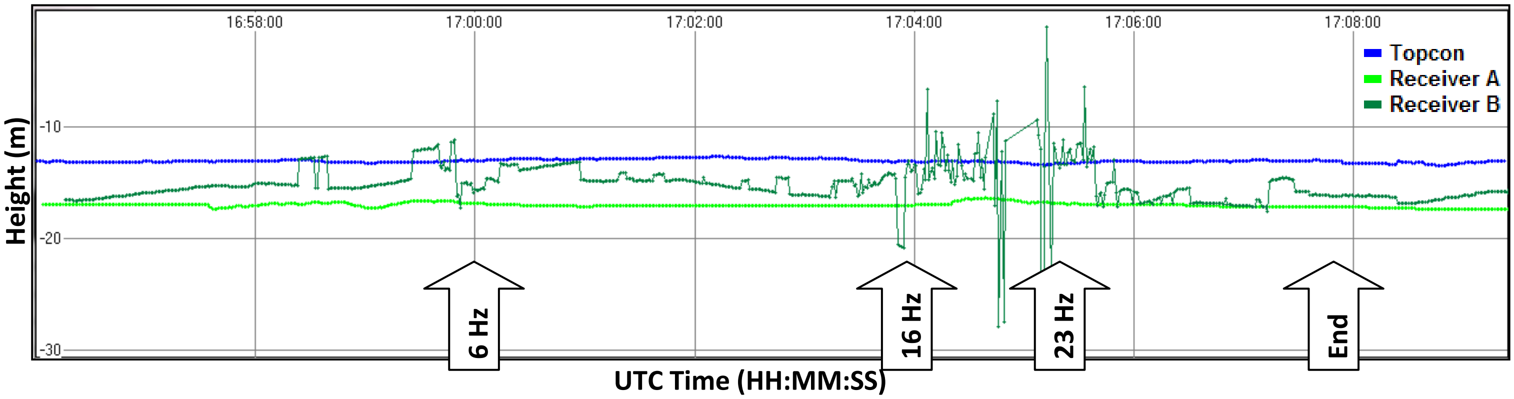

Figure 2: Height position stability during sinusoidal vibration test at 4g (3-30 Hz) on the X-axis.

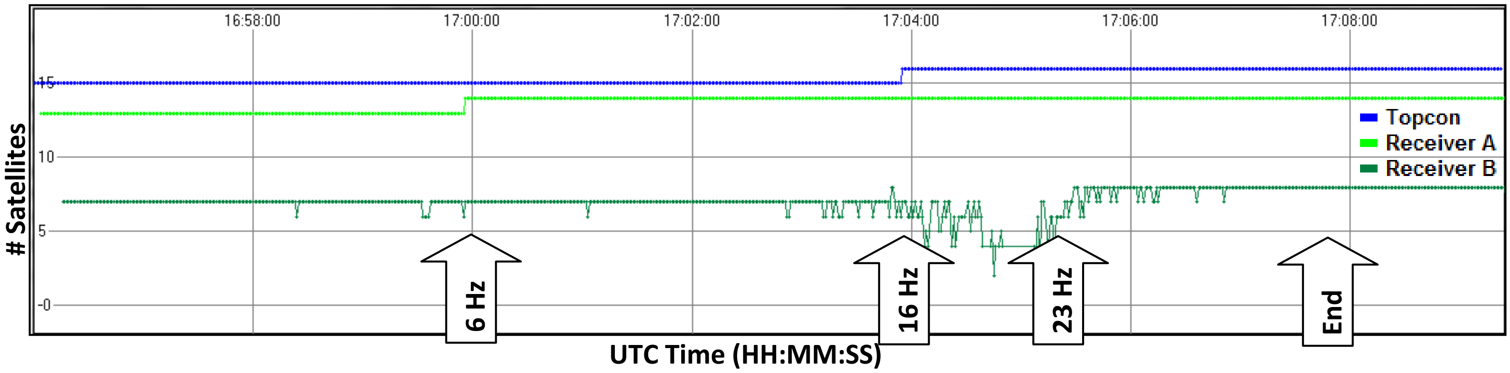

Figure 3: Satellite tracking stability during sinusoidal vibration test at 4g (3-30 Hz) on the X-axis.

As figures 2 and 3 show, Topcon and Receiver A were unaffected by the 4g sinusoidal vibration, while Receiver B had significant position stability problems starting at 6 Hz due to frequent tracking failures to multiple satellites during the test.

Sinusoidal Vibration Testing at Test Lab Limits (10g)

Testing was repeated on the X-axis until the breaking point of each receiver was successfully determined, or when the limits of the test lab shake table were reached. Acceleration magnitudes were incrementally increased until either scenario occurred – QLL technology exceeded the limit of the test lab.

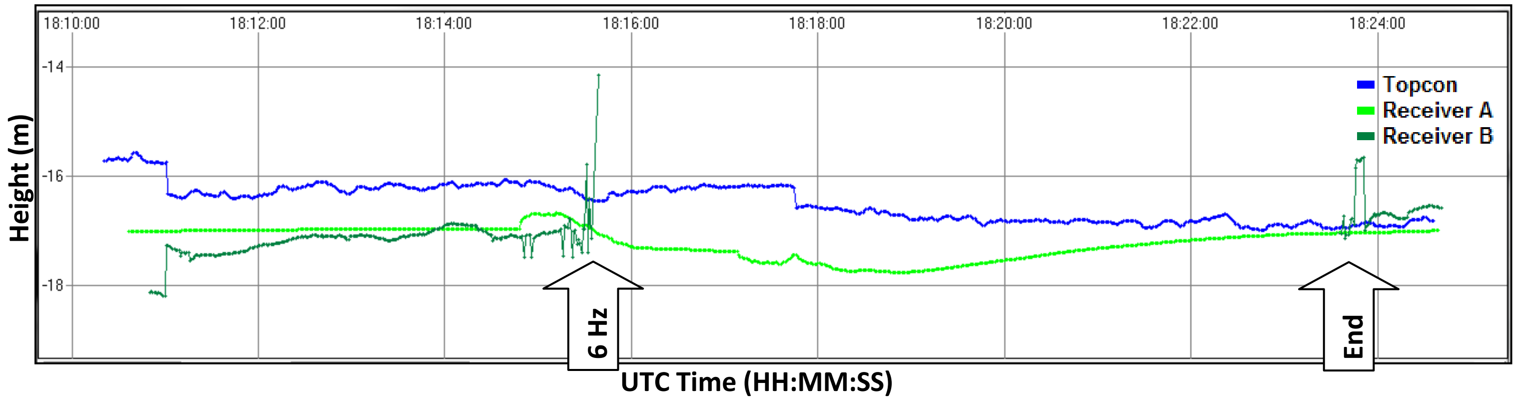

Figure 4: Height position stability during sinusoidal vibration test at 10g (3-30 Hz) on the X-axis.

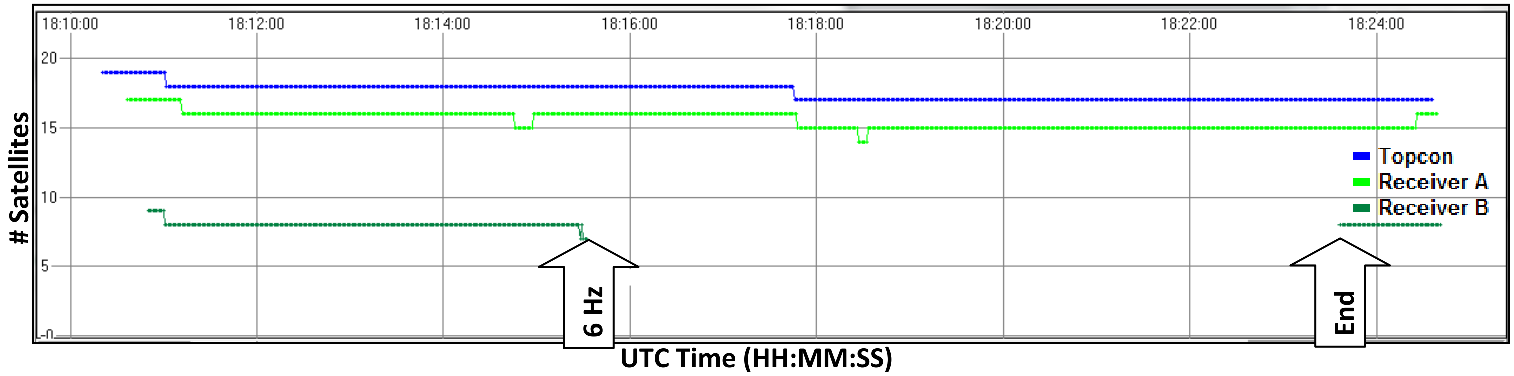

Figure 5: Satellite tracking stability during sinusoidal vibration test at 10g (3-30 Hz) on the X-axis.

Again, figures 4 and 5 illustrate that Topcon and Receiver A were unaffected by the 10g sinusoidal vibration, while Receiver B had a complete tracking and positioning failure starting at 6 Hz. Both sinusoidal vibration tests at 6g (tests 1.3 and 1.4) and testing at 8g (test 1.5) also showed that Competitor B experienced complete tracking and positioning failure at around 6 Hz and persisting until 30Hz of vibration.

When sinusoidal vibration testing changed orientation from the X-axis to the Y-axis, Receiver A experienced disturbances:

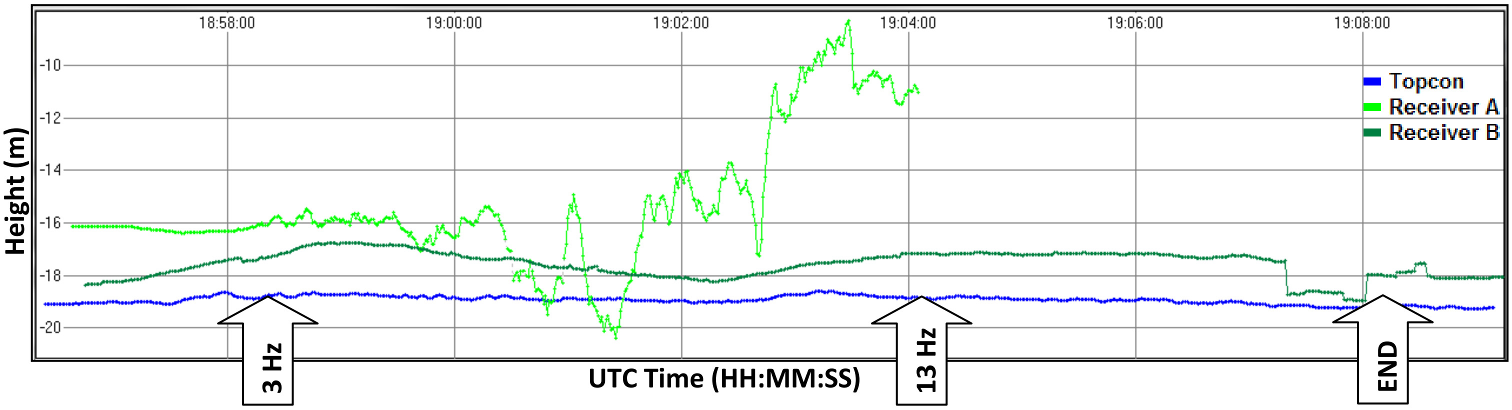

Figure 6: Height position stability during sinusoidal vibration test at 10g (3-30 Hz) on the Y-axis.

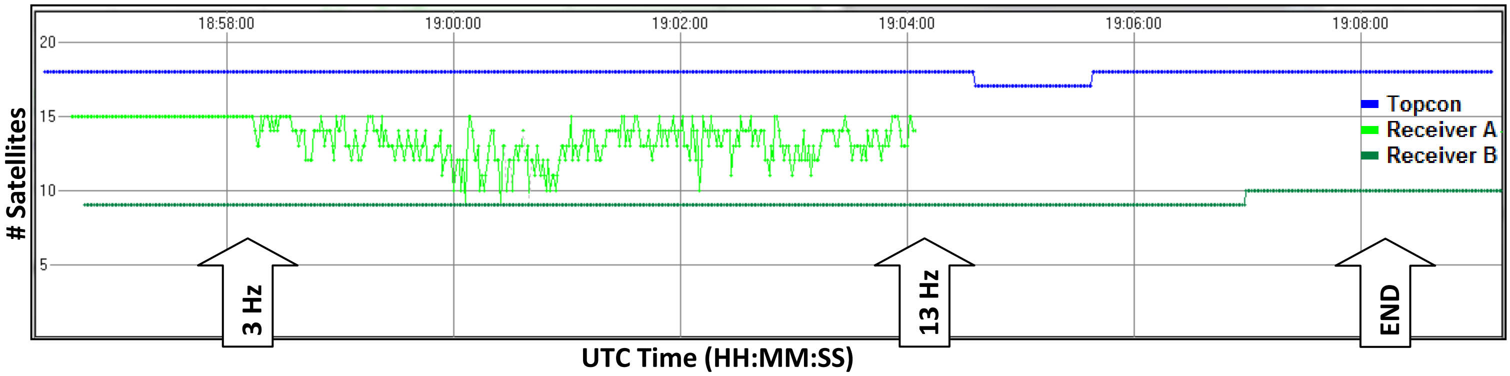

Figure 7: Satellite tracking stability during sinusoidal vibration test at 10g (3-30 Hz) on the Y-axis.

In this test, Topcon and Receiver B were unaffected by the 10g sinusoidal vibration at all frequencies, while Receiver A had significant position and tracking stability problems starting at 3 Hz. At 13 Hz competitor A completely lost satellite tracking and didn’t restore it till the end of the test. Testing performed in the Y-axis at 8g showed that competitor A had similar disruptions starting at 3 Hz and enduring until vibration frequency reached 20 Hz.

Random Vibration Testing at Specification (7.7g RMS)

A common random vibration specification for GNSS receivers is a resistance to 7.7g RMS of acceleration without any operational disturbances. The results of test 2.14 are shown below, which is a 7.7g RMS random vibration test in the Y-axis.

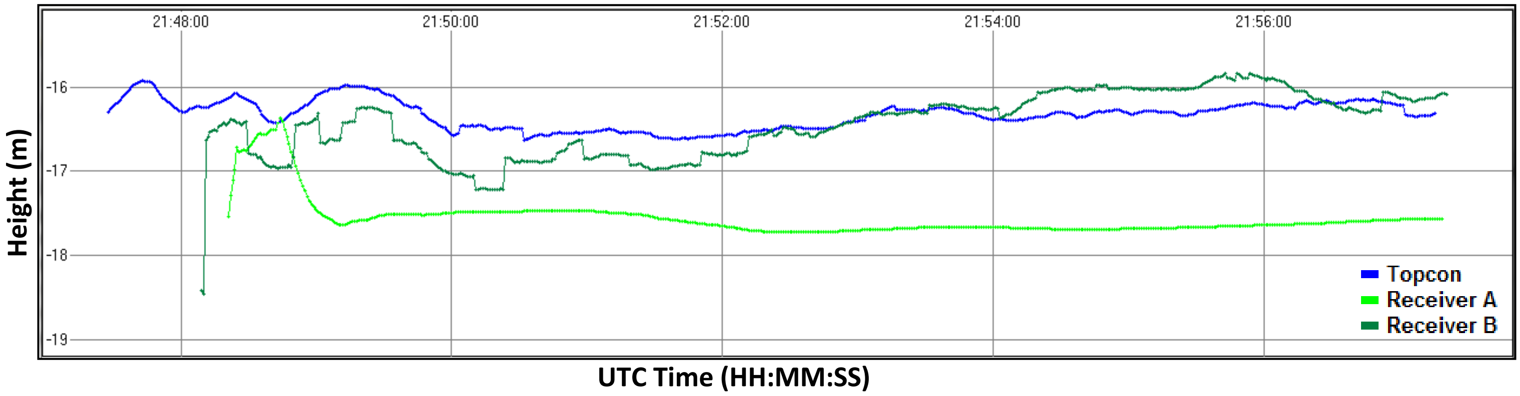

Figure 8: Height position stability during random vibration test at 7.7g RMS (20-2000 Hz) on the Y-axis.

Even though no satellite signals appeared to be dropped throughout the test, random vibration proved to have a negative effect on the positioning stability of Receiver B.

Random Vibration Testing at 19.4g RMS

When random vibration intensity was increased to 19.4g RMS Receiver B experienced instability in positioning in all axis orientations, while Topcon and Receiver A operate without flaws:

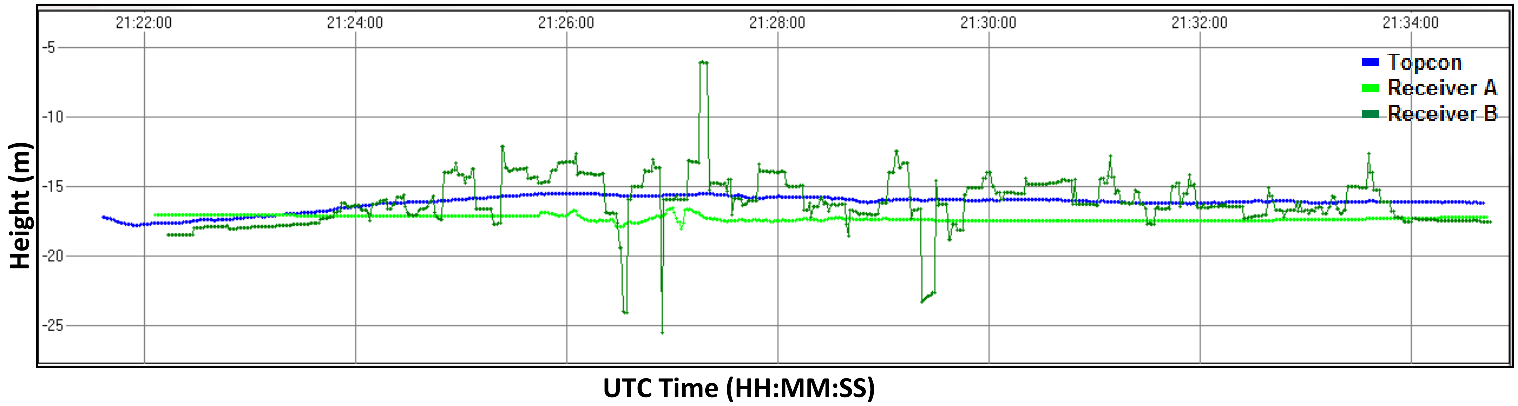

Figure 9: Height position stability during random vibration test at 19.4g RMS (20-2000 Hz) on the X-axis.

Random Vibration Testing at Test Lab Limits (23g RMS)

Similar to sinusoidal vibration testing, random had to be performed until the limits of the test lab were reached since QLL technology did not reach its breaking point. At 23g RMS Receiver B showed severe problems in positioning and tracking stability on all three axes (example for X-axis see below):

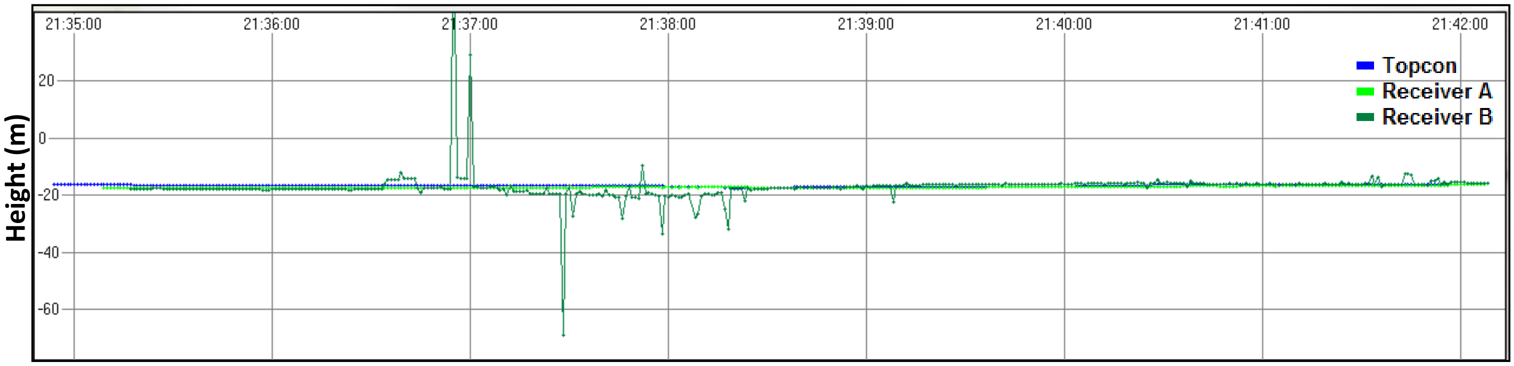

Figure 10: Height position stability during random vibration test at 23g (20-2000 Hz) on the X-axis.

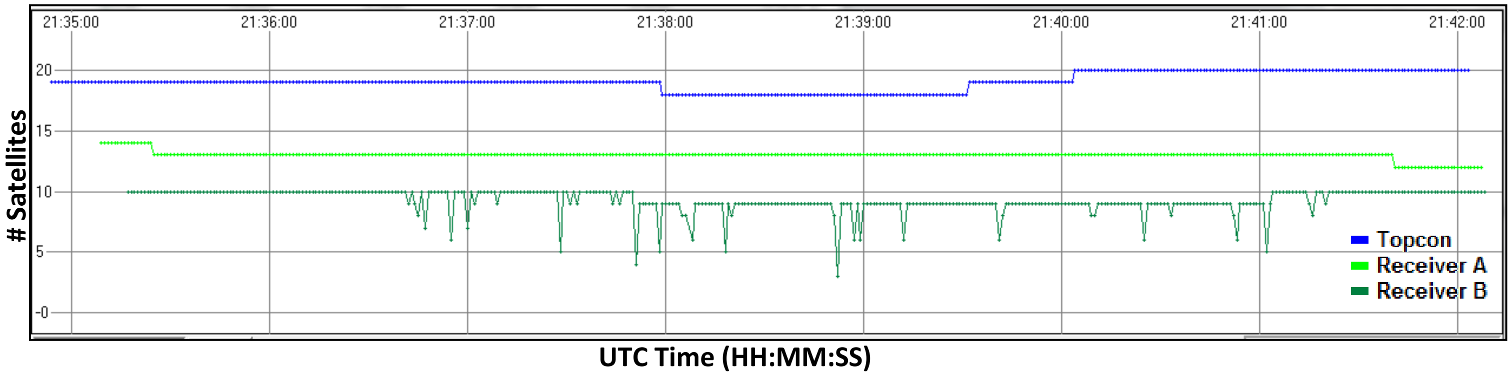

Figure 11: Satellite tracking stability during random vibration test at 23g (20-2000 Hz) on the X-axis.

The Topcon receiver with QLL enabled operated without any problems at 23g RMS on all three axes. Competitor A experiences stability problems at 23gRMS when vibration axis was Z:

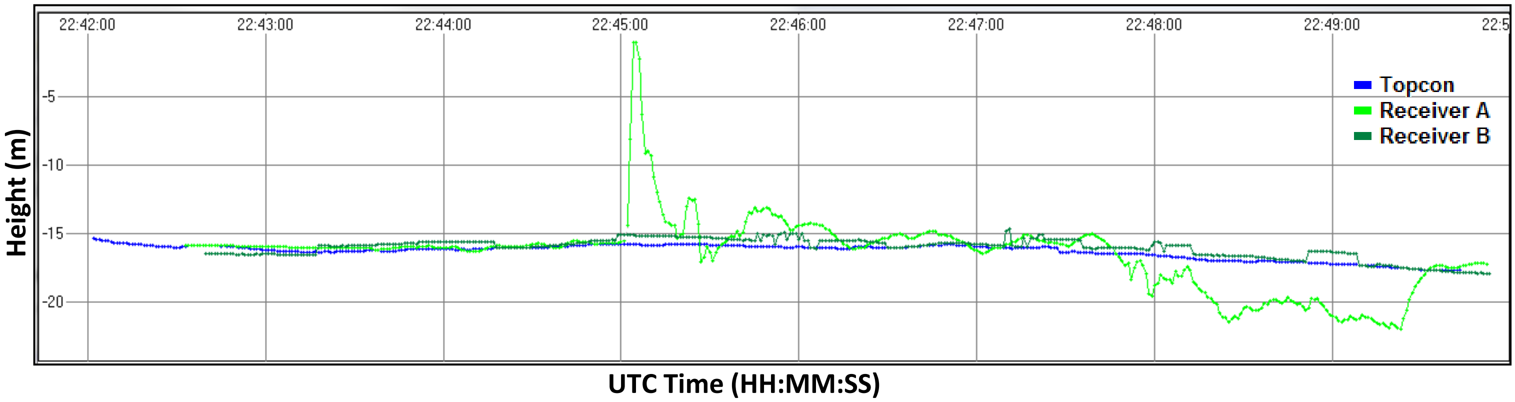

Figure 12: Height position stability during random vibration test at 23g (20-2000 Hz) on the Z-axis.

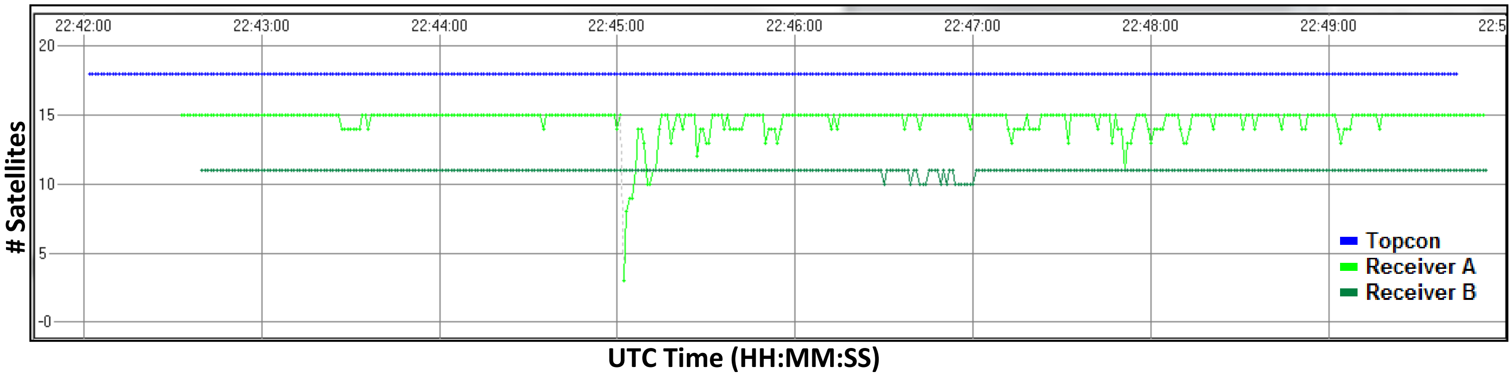

Figure 13: Satellite tracking stability during random vibration test at 23g (20-2000 Hz) on the Z-axis.

Conclusion

GNSS application areas are growing and GNSS technology will consistently be subjected to vibration and shock as adoption continue to grow and expand into other areas and niche markets. The susceptibility of crystal oscillators to vibration and shock can be a limiting factor in operation of GNSS receivers in demanding dynamic environments if the GNSS manufacturer does not have the suitable technology to overcome dynamic barriers. Through comprehensive sinusoidal and random vibration testing, QLL technology has proven to allow Topcon receivers to provide stable satellite tracking and positioning in a wide spectrum of vibration frequencies, at intense magnitudes and in any orientation. However, testing two different GNSS receiver products shows vulnerabilities at many vibration frequencies and magnitudes with orientation dependent sensitivity. For dynamic GNSS applications with operational expectations that cannot be compromised during any degree of vibration, QLL technology ensures the best in satellite navigation accuracy and availability in the industry.

This statement holds great value to customers using Topcon turnkey systems or integrating Topcon OEM GNSS receivers: QLL Technology assures the most robust GNSS positioning performance on the market in dynamic real world applications.