Using Time-to-Digital Conversion for Resilient GNSS Receivers

GNSS is the invisible backbone of modern life, enabling precise positioning, timing and navigation for transportation, autonomous vehicles and emergency services, as well as synchronising telecommunication networks, power grids, data centres, smart agriculture and financial transactions. Its economic value is immense, supporting trillions of dollars in global commerce and critical infrastructure, including the taxis and food we track using our phones.

GNSS receivers process signals from multiple satellites to determine their position by calculating the distance between each spacecraft and the receiver. RF carriers travel at the speed of light and receivers compare their arrival times with the exact timestamp of when they were transmitted by satellites to calculate their pseudo-ranges. This method is known as trilateration and three satellites give you a 2D horizontal fix, *i.e.* latitude and longitude, whereas signals from four satellites result in a 3D location including altitude.

Once the 3D position is calculated by the receiver, several further corrections are applied to improve accuracy to compensate for atmospheric delays as the navigation carrier passes through the ionosphere and troposphere, distortion from scintillation effects, as well as multi-path reflections from buildings, trees and mountains that can block signals, reducing the number of satellites the receiver can connect with, potentially leading to errors in positioning.

By design, navigation satellites transmit 20 to 50 W carriers from MEO, that's less power than an average light bulb, which travel 20,000 km to Earth attenuated and refracted by atmospheric effects. GNSS spacecraft move at ~3.9 km/s relative to Earth's surface and this orbiting causes a Doppler shift in the received L-band signal by up to ±5 kHz, before reaching your receiver with an amplitude around -130 dBm (10^{-16} W). This is typically 100 times weaker than other RF traffic, or 20 dB below the thermal noise floor!

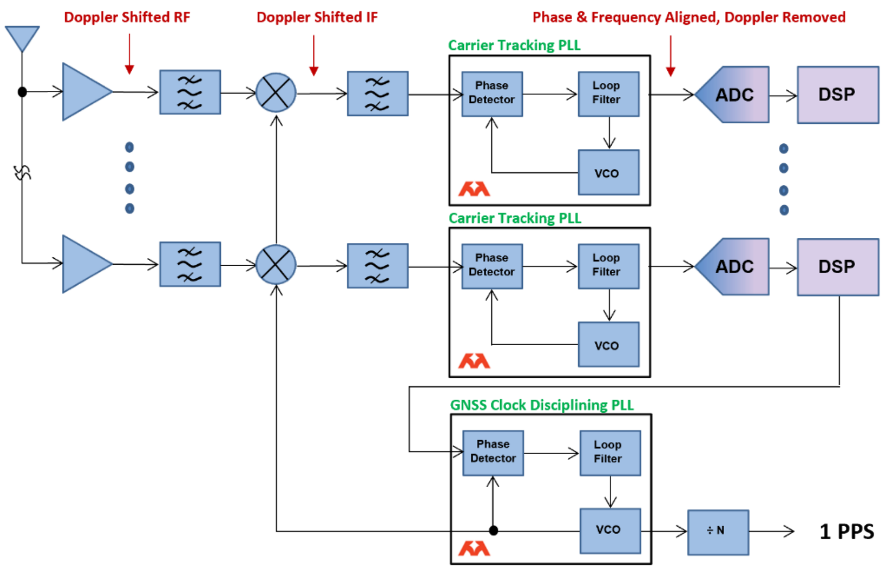

Figure 1 : Concept Block Diagram of a GNSS Receiver.

Within a GNSS receiver, PLLs are used to continuously track the incoming carriers to estimate their instantaneous phases and frequencies. Each PLL compares the phase of a down-converted IF with a locally-generated replica and any differences due to Doppler shifts or local-oscillator drift produce an error signal. A loop filter and a VCO/NCO adjust the frequency and phase of the local carrier to align with the IF prior to extracting the positional data.

GNSS receivers generate their own local time base using inexpensive crystal oscillators which are far less accurate than the precision atomic clocks used on-board navigation satellites. This introduces an additional error in the computed location and the signal received from a fourth satellite allows the receiver to use its pseudo-range to correct for this offset. Without this fix, even nano-second errors in time would result in metre-scale inaccuracies in positioning.

Within a receiver, the stability of the local oscillator used by the carrier-tracking loop drifts over time and a separate PLL is used to discipline this to the GNSS system clock extracted from the navigation message. Once lock is achieved, the VCO inherits the stability of the atomic clock and a 1 PPS reference is output aligned to the beginning of each second in UTC time, exporting the accuracy of GNSS clocks to synchronise external events or systems.

GNSS receivers use the pseudo ranges to calculate where you are and the 1 PPS reference ensures all your systems agree on when you are there! This quiet heartbeat synchronises the digital and physical infrastructures we depend on daily with nanosecond timing precision!

Within a GNSS receiver, low-level, L-band carriers are amplified, converted to IF or baseband, and then digitised. Correlators align locally-generated replicas of the carriers with those transmitted by GNSS satellites, followed by de-spreading of the PRN codes which collapses the 1 MHz-wide carrier back to a narrowband signal with around 43 dB of processing gain, sufficient to extract the navigation message from well below the noise floor. This data comprises the range, precise spacecraft clock data, its ephemeris, *i.e.* its specific orbit parameters, an almanac containing coarse orbits of other satellites within the constellation, as well as some status data.

Low-amplitude GNSS carries are vulnerable to interference, either unintentionally from neighbouring parts of the RF spectrum or maliciously using jamming or spoofing techniques, reducing positioning accuracy or a complete loss of navigation availability. Without a valid navigation carrier, a receiver would not be able to calculate your location or output the 1 PPS reference. GNSS receivers must be resilient to weak input levels or the absence of an incoming carrier, and continue to provide your location and the 1 PPS synchronisation signal.

GNSS receivers that use a Time-to-Digital Converter (TDC) are more resilient to weaker input powers or missing navigation carriers, and can detect spoofing to allow corrective positioning. A TDC is an electronic stopwatch which measures the elapsed interval between two events with picosecond precision, converting this into a digital value for post processing.

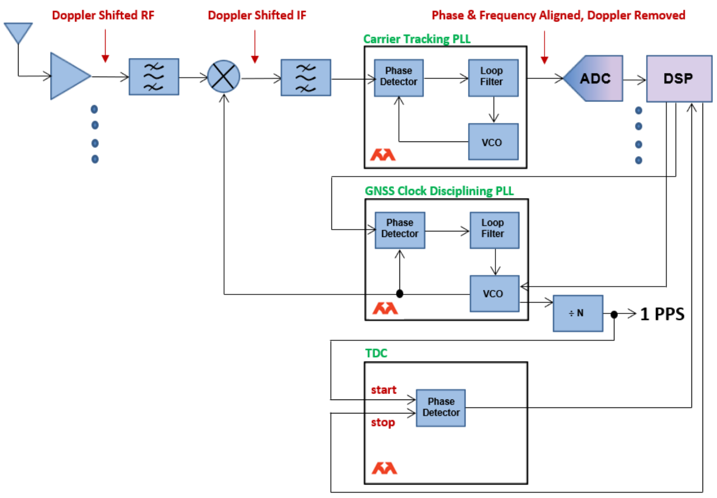

Figure 2 : Concept Block Diagram of a GNSS Receiver with TDC for 1 PPS Resilience.

During normal operation, a TDC timestamps the locked 1 PPS output as well as the local-oscillator, characterising the latter's behaviour, measuring its phase noise and drift, creating an accurate model of clock performance.

When the navigation signal becomes too weak or disappears, the receiver is unable to track the incoming carrier and discipline its local oscillator to extract the pseudo-range data. The receiver enters a 'holdover mode', the loop filter output freezes and the local oscillator drifts causing the 1 PPS output to lose alignment. The previously stored timestamps are used to extrapolate and maintain this reference by steering the local clock based on TDC feedback rather than fresh GNSS measurements. These predictions are much more accurate than relaying solely on the oscillator's free-running specification.

To provide further resilience when the incoming carrier is disrupted, some GNSS receivers have a 1 PPS input to synchronise to an external, stable 1 PPS source. These receivers can operate in 'traditional mode', *i.e.* generate a 1 PPS output when the local oscillator locks to the satellite clock extracted from the navigation data, in 'disciplined mode', aligned to the external 1 PPS input, or in 'holdover mode', which maintains continuity of operation by using the previously recorded timestamp data to steer the free-running clock. The 1 PPS output continues, now referenced to this internal clock, instead of that extracted from the satellite data. The quality of the oscillator determines the duration and how accurately the 1 PPS output can be maintained while GNSS is unavailable. Ultimately, long-term absolute time requires re-acquisition of the carrier!

Magics Technologies offers a dedicated, rad-hard TDC device to improve the resilience of GNSS receivers. The MAG-TDC00002-SC is shown below and offers an SPI slave interface to connect to FPGAs/MCUs for configuration and read-out of the elapsed time:

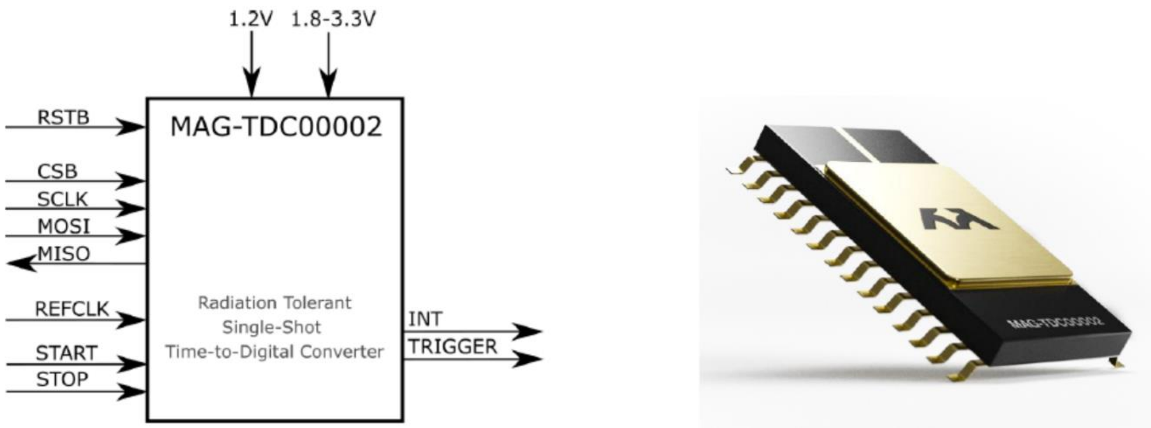

Figure 3 : Magics' TDC00002-SC, Rad-Hard TDC.

The MAG-TDC00002-SC operates from a core voltage of 1.2 V and its I/O can be powered from 1V8 to 3V3. The device consumes 20 mW (typical) and has a specified operating temperature from -40 to 125°C. The MAG-TDC00002-SC comes in a 17.9 x 10.8 mm, 28-pin, hermetic, ceramic CSOIC package as shown above.

The architecture of the MAG-TDC00002-SC and an application drawing are shown below: following power-up and initialisation (lock) of the internal PLL, the TDC enters an IDLE state. When the device is configured, a pulse is generated on the TRIGGER output and the TDC changes to a LISTEN mode. In this state, the internal 1.25 GHz counter is running and will be sampled on receipt of external start and stop signals. The values are saved to their corresponding registers and both coarse and fine measurements can be read-out via SPI to calculate time-of-flight.

The MAG-TDC00002-SC has automatic, internal self-calibration which corrects for drifts due to process, voltage, temperature and radiation degradation.

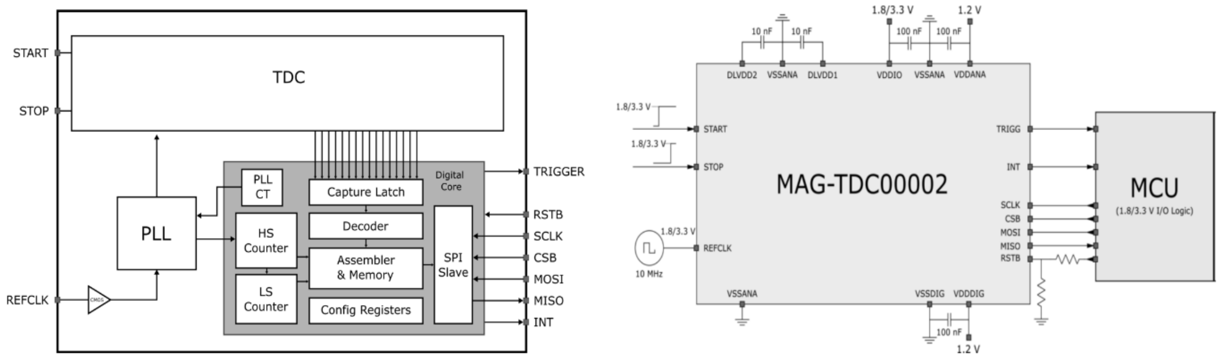

Figure 4 : Architecture and Application Drawing of MAG-TDC00002-SC.

In terms of radiation hardness, the MAG-TDC00002-SC has a specified SET/SEU tolerance of 60 MeV.cm^2/mg and a total-dose immunity > 100 kRad (Si) / 1 kGy (Si). Radiation and ESCC9000 qualification reports are available and EM, EQM and FM parts can be ordered.

To prototype and de-risk the MAG-TDC00002-SC, an evaluation kit is available comprising a base board and the TDC PCB as shown below. The latter fits on top of the former using the socket headers and the base board connects to a PC using a USB Type-C cable. The evaluation kit comes with software which communicates with the base board using SCPI commands to configure and use the MAG-TDC00002-SC as shown below:

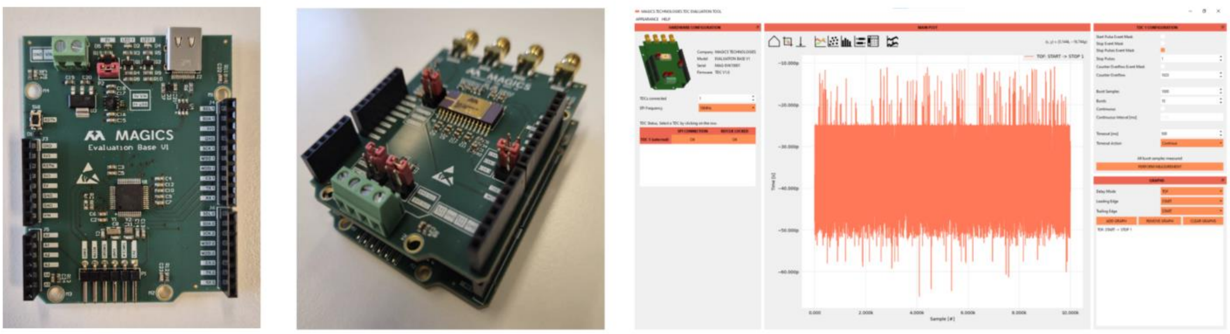

Figure 5 : MAG-TDC00002-SC Evaluation Kit and Software.

To further improve GNSS resilience, a TDC can replace the traditional phase detector within the carrier-tracking PLL to provide better receiver sensitivity for the incoming navigation signal, especially for weaker carriers, those that have been affected by multi-path fading effects or interfered with.

Compared to a conventional PLL which uses an analogue detector to measure phase error coarsely at some fraction of the reference clock, a TDC's picosecond resolution allows it to detect and correct much smaller phase changes, improving the accuracy of the pseudo-range calculations and keeping the receiver locked for longer with less phase noise and jitter.

Furthermore, analogue phase detectors have a dead zone, *i.e.* a small range of phase differences where its output doesn't respond, effectively becoming blind to small errors, adding jitter to the PLL output because the loop can no longer make fine adjustments reducing its accuracy. TDCs do not suffer from this sensitivity issue, measure timing continuously across its full range, maintaining linear tracking even with weak or noisy inputs.

The feedback loops of analogue PLLs are also susceptible to temperature, radiation, noise and non-linearities that can drift the loop out of lock when the incoming GNSS carrier is weak, whereas an all-digital design offers a more stable and robust controller.

Similar to extrapolating and maintaining a 1 PPS output if the GNSS carrier is jammed or experiences an outage, the use of a TDC allows the signal dynamics of the incoming navigation signal to be logged during normal operation. If the input disappears, the stored information can be used to predict its phase and frequency behaviour to improve the holdover response and continue providing navigation services.

To further improve GNSS resilience, the use of a higher precision TDC within a PLL can detect subtle shifts in code or carrier phase, as well as minute changes to a 1 PPS input, due to malicious spoofing. Typically, these exceed what is physically plausible from a satellite's motion or atmospheric effects, and can be compared for consistency with other carriers from multiple constellations, preventing tampering of location and/or time.

Magics Technologies offers a space-grade PLL that uses a high-resolution TDC as its phase detector to improve the resilience of GNSS receivers. The MAG-PLL000X2-SP can receive an input from 10 to 100MHz, either from an on-chip oscillator or an external reference, and provides four digital (LVDS, CML, LVCMOS and LVPECL) outputs from 1 MHz up to 1 GHz, as well as two RF drivers up to 5 GHz. The typical integrated phase jitter is 170 fs and the device offers SPI slave and two-wire interfaces (TWI) to connect to FPGAs/MCUs for configuration or to read status information.

The MAG-PLL000X2-SP can be powered from a single 1V8 to 3V3 supply, consumes 220 mW (typical) or 330 mW when outputting 5 GHz, and has a specified operating temperature from -40 to 125°C. Each output supports multiple, independent voltage levels to comply with the target device receiving the clock or carrier signal. The part comes in a 7 x 7 mm BGA plastic package and is available for procurement in 30 and 100 kRad(Si) total-dose, radiation-hardness levels:

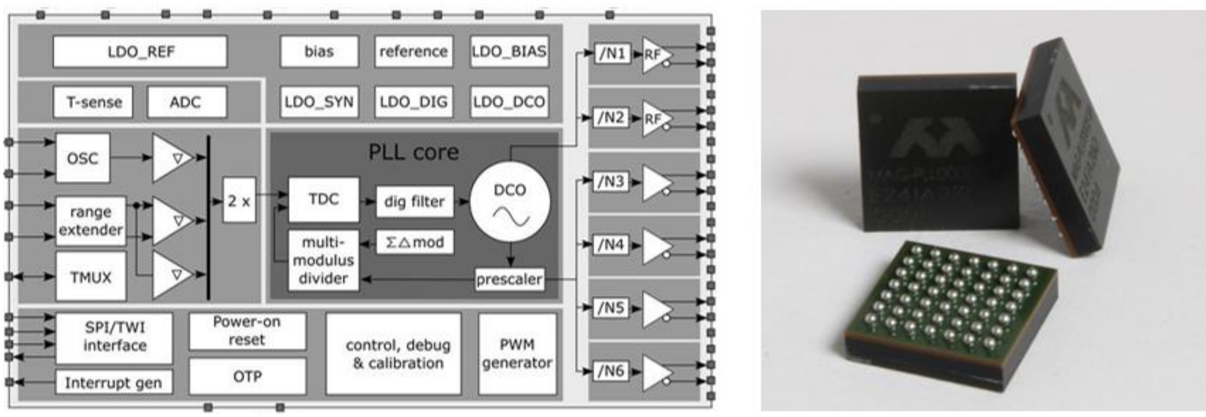

Figure 6 : Magics' MAG-PLL000X2-SP, Rad-Hard, All-Digital PLL with TDC.

In terms of radiation hardness, the MAG-PLL000X2-SP has a specified SEL/SEU tolerance of 62.5 MeV.cm^2/mg and a total-dose immunity > 100 kRad (Si) / 1 kGy (Si). Radiation reports are available and EM parts can be ordered at the end of Q4 2025, with EQM and FM parts expected in Q1 2026 and the end of next year respectively.

To prototype and de-risk the MAG-PLL00002, an evaluation kit is available comprising a base board and the PLL PCB as shown below. The latter fits on top of the former using the socket headers and the base board connects to a PC using a USB Type-C cable. The evaluation kit is fitted with a 48 MHz crystal for use with the PLL's internal oscillator, or an external reference, either single-ended or differential, can be attached using the SMA connectors. Termination options for this clock as well as the desired supply voltage can be configured on the PCB.

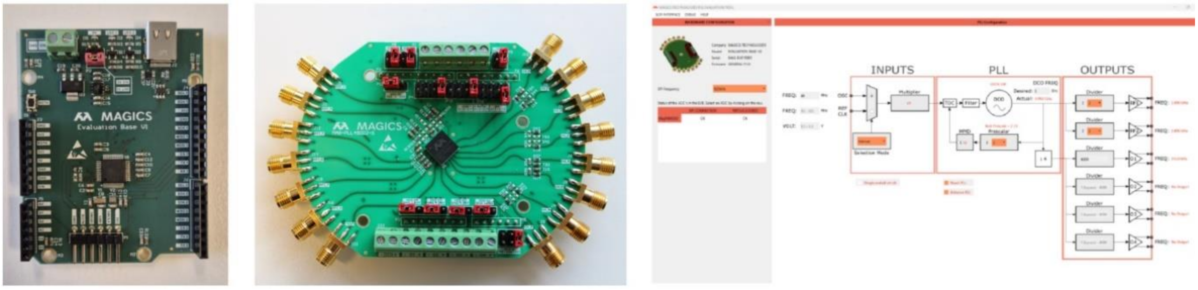

Figure 7 : MAG-PLL00002-SC Evaluation Kit and Software.

Product pages for the MAG-TDC00002 and the MAG-PLL00002-SC can be viewed by clicking these links and datasheets can be requested. Both devices are European and ITAR-free which is advantageous if you have import/export constraints!

GNSS is the invisible backbone of modern life, enabling critical positioning, timing and navigation on Earth. It is equally important when used in space with satellites in all orbits using GNSS for PNT, *e.g.* autonomous management of constellations as well as the synchronisation of on-board systems and communication links.

A TDC's higher precision can improve the resilience of GNSS receivers to maintain a stable, locked 1 PPS output to synchronise external events and systems even when the incoming navigation carriers disappear. This precise reference is the critical heartbeat used to time telecommunication networks, power grids, data centres, smart agriculture and financial transactions.

When used as a high-precision phase detector within the PLL of the carrier tracking loop, a TDC allows a receiver to lock and process a weaker carrier, and continue providing location.

The use of a TDC also allows detection of the subtle malicious tampering caused by spoofing and corrective action can be taken, *e.g.* ignoring a suspect carrier from the pseudo-range calculation.

Dr. Rajan Bedi is the CEO and founder of Spacechips, which designs and builds a range of advanced, award-winning, AI-enabled, ultra-high-throughput re-configurable transponders, SDRs, Edge-based processors and Data Centres for telecommunication, Earth-Observation, ISAM, SIGINT and satellites. The company also offers Space-Electronics Design-Consultancy, Avionics Testing, Technical-Marketing, Business-Intelligence and Training Services. (www.spacechips.co.uk).