Time-to-Digital Conversion for Space Applications

A Time-to-Digital Converter (TDC) is like a stopwatch measuring the elapsed interval between two events with picosecond precision, converting this into a digital value for post processing. Many space applications require time-of-flight measurements to calculate distance, delay or velocity. For example, an ISAM spacecraft needs to determine precisely the relative location of debris before initiating rendez-vous and retrieval operations. Similarly, space-domain awareness must understand the proximity and trajectory of other orbiting objects to assess any potential threat.

A TDC receives two inputs: a start signal (or edge) to mark the beginning of the time interval to be measured, and a stop pulse. The delay between these is converted to a digital number for post processing. Different architectures are typically used to implement the logic, *e.g.* counters, delay lines or a time amplifier.

Time-to-Digital Conversion is a technique used in space-based LiDAR systems to measure the time taken for a light pulse to travel to and from an object to calculate its distance. A LiDAR emits a laser pulse towards a target, which reflects off the latter's surface returning to the sensor. The TDC starts counting when the pulse is transmitted, stops when it is detected by the receiver, and using the speed of light, distance is calculated as:

$$distance = \frac{c * t}{2}$$

where c is the speed of light and t the time-of-flight.

For example, LiDAR is used by some Earth-Observation operators to measure altitude and surface changes over time, *e.g.* to monitor vegetation height, ice-sheet or glacier thickness and melt, sea-ice elevation or relative sea level. Spaceborne LiDAR altimetry is capable of centimetre-level vertical precision and is illustrated below:

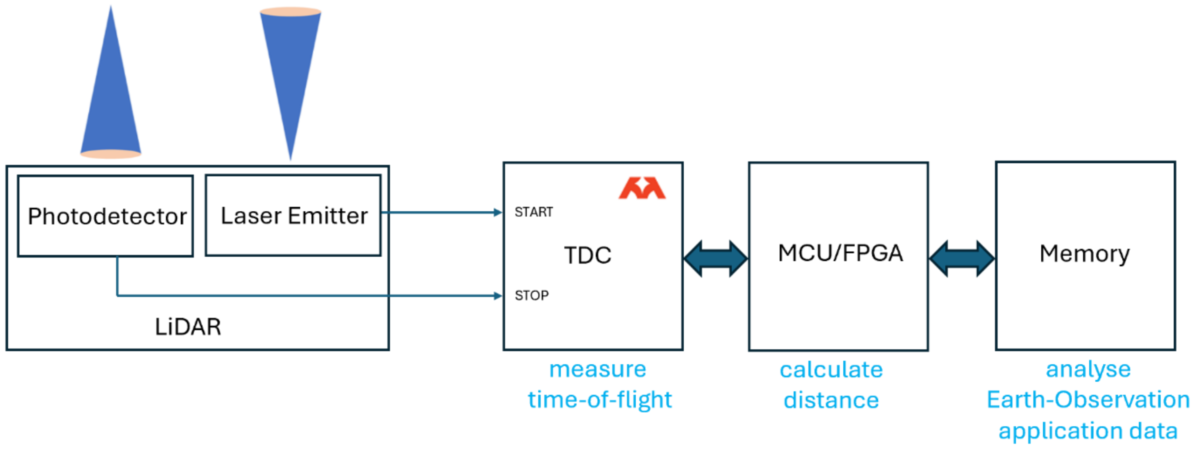


Figure 1 : The use of TDC in space-based LiDAR applications.

Similarly, a TDC is used in Mass Spectroscopy to measure how long it takes ions to travel from a source to a detector. This time-of-flight information is used to calculate the mass-to-charge ratio (m/z) of ions and since the kinetic energy given to all ions is the same, time-of-flight is directly related to their mass as follows:

$$t = k * \sqrt{\left(\frac{m}{z}\right)}$$

where t is the time of flight, k a calibration constant, m the ion mass and z the ion charge.

Space-based Mass Spectroscopy has many applications to identify and quantify chemical composition by measuring the mass-to-charge ratio of ions. For example, Earth Observation and Space Weather monitor the make-up of the Earth's ionosphere and magnetosphere, including solar wind particles. Space science analyses the chemical structure of planetary atmospheres, lunar and asteroid surface composition, as well as soil or ice samples to detect organic molecules and potential signs of life. Time-of-flight mass spectroscopy is illustrated below:

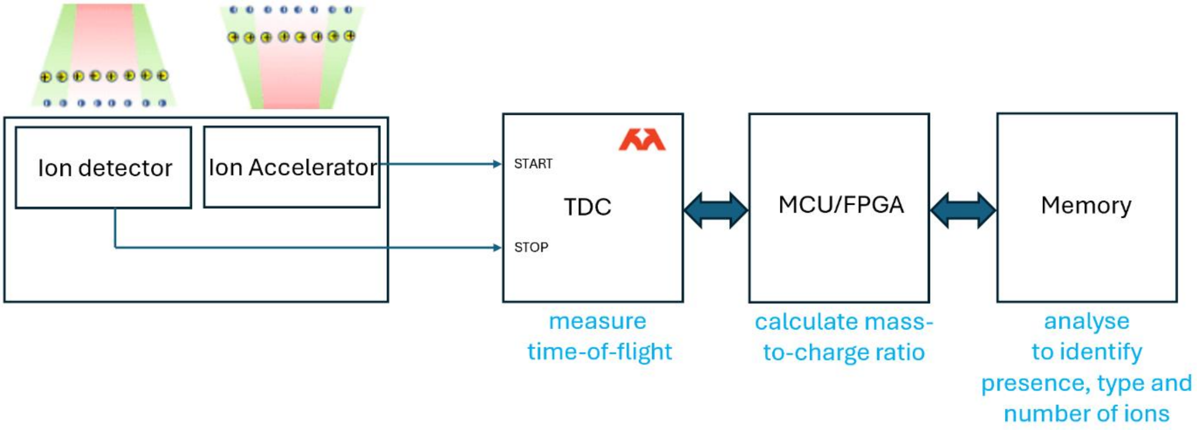


Figure 2 : The use of TDC in time-of-flight mass spectroscopy.

Optical communication is increasingly being used to transmit data wirelessly between orbiting satellites, *e.g.* intersatellite links, or from the ground to a spacecraft. High-throughput payloads are now using fibre to send data within sub-systems to overcome the bandwidth, loss, mass and EMI limitations of traditional copper communications.

TDCs are used to detect when photons arrive, for timing-jitter analysis to prevent degradation of system performance, clock recovery and synchronisation for aligning and decoding incoming data streams as illustrated below.

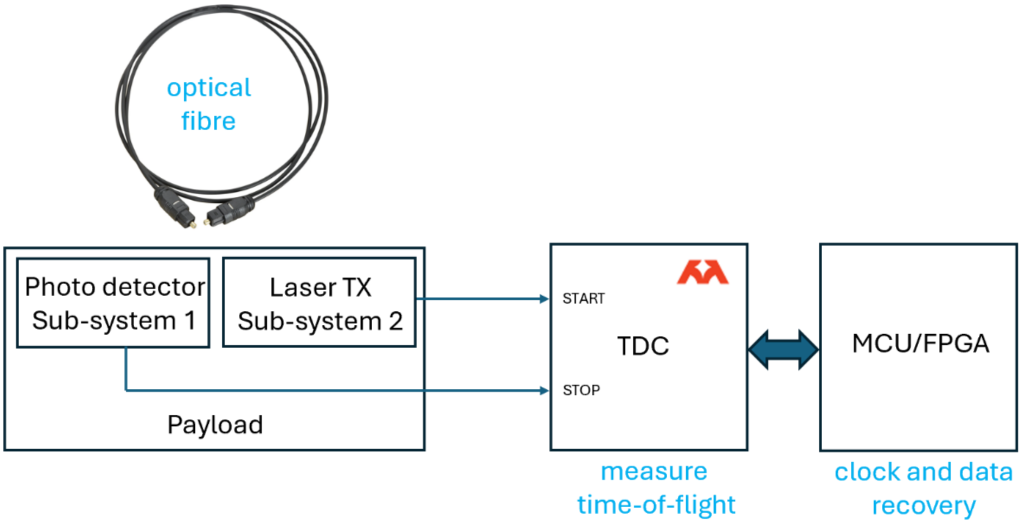


Figure 3 : The use of TDC and fibre-based optical communications within a payload.

TDC is also used to calculate absolute time with the help of satellite navigation for applications such as quantum key distribution over long distances. Both the transmitter and the receiver use GNSS-disciplined oscillators to synchronise their local system clocks to a global time reference, *e.g.* UTC or GPS time. A precise timestamp can be calculated as:

$$Tevent = TGNSS_{epoch} + (N * Tclk) + tfine$$

where $TGNSS_{epoch}$ is the absolute time of the last GNSS PPS signal, *e.g.* 14:23:08 UTC, N is the number of clock cycles since the PPS, $Tclk$ is the clock period and t_{fine} is the sub-nanosecond fine time from interpolation. For example, if the TDC counts 8,700 clock cycles with a period of 1 ns and t_{fine} = 0.217 ns, the resulting timestamp can be calculated as:

$$Tevent = 14:23:08 + 8.700217\,us = 14:23:08.000008700217\,UTC$$

The system concept based on optical communications is illustrated below:

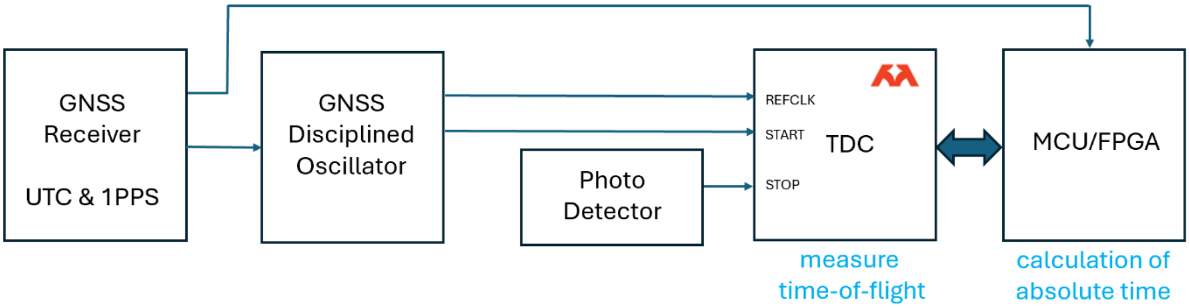


Figure 4 : The use of TDC to calculate absolute time for quantum key distribution.

Magics Technologies NV has just released a rad-hard TDC for space applications: the MAG-TDC00002-Sx is shown below and can measure time delays with picosecond precision, converting this to a digital value for post processing. The device offers an SPI slave interface to connect to FPGAs/MCUs for configuration and read-out of the elapsed time:

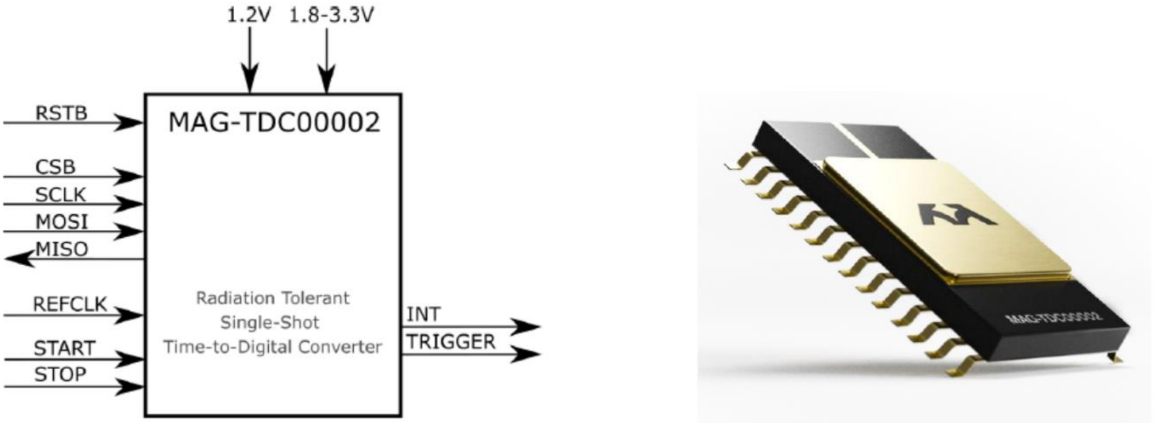


Figure 5 : Magics' TDC00002-Sx, Rad-Hard TDC.

The MAG-TDC00002-Sx 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-Sx comes in a 17.9 x 10.8 mm, 28-pin, hermetic, ceramic COIC package as shown above.

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

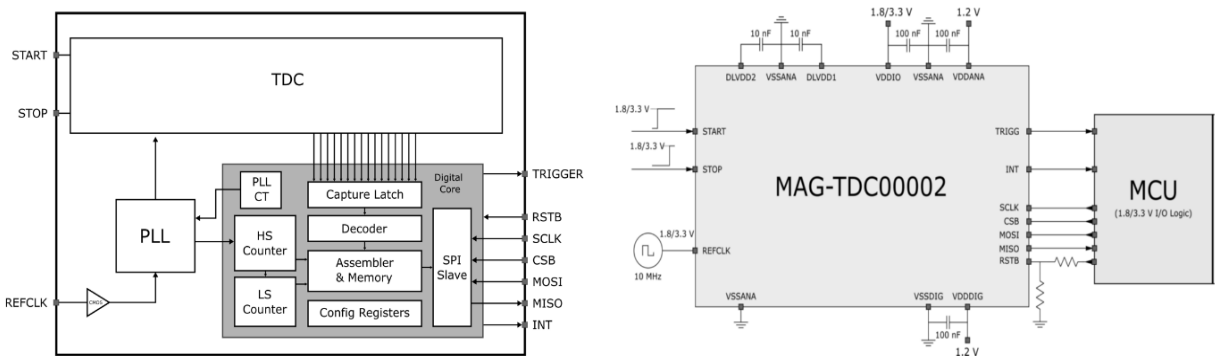


Figure 6 : Architecture and Application Drawing of MAG-TDC00002-Sx.

As an example, a time-of-flight measurement between a single start and stop event resulted in the following MAG-TDC00002-Sx register data:

```
START BIN DEL = 121
STOP BIN DEL0 = 28
START BIN CAL PERIOD = 110
STOP BIN CAL PERIOD0 = 110
START BIN CAL OFFSET = 8
STOP BIN CAL OFFSET = 9
START CNT VAL L = 4
START CNT VAL H = 0
STOP CNT VAL L0 = 14
STOP CNT VAL H0 = 0
```

The calculation of time-of-flight is:

$$LSBstart = \frac{Tclk}{START\ BIN\ CAL\ PERIOD - START\ BIN\ CAL\ OFFSET} = \frac{800 * 10^{-12}}{110 - 8} = 7.843\ ps$$

$$LSBstop = \frac{Tclk}{STOP\ BIN\ CAL\ PERIODn - STOP\ BIN\ CAL\ OFFSETn} = \frac{800 * 10^{-12}}{110 - 9} = 7.921\ ps$$

$$COUNTn = STOP\ CNTn - START\ CNTn = 14 - 4 = 10$$

$$Time\_of\_Flight = (LSBstart * START\ BIN\ DEL) - (LSBstop * STOP\ BIN\ DELn) + (COUNTn * Tclk)$$

$$Time\_of\_Flight = (7.843\ ps * 121) - (7.921\ ps * 28) + (10 * 800\ ps) = 8.727\ ns$$

In terms of radiation hardness, the MAG-TDC00002-Sx has a specified SET/SEU tolerance of 60 MeV.cm^2/mg and a total-dose immunity > 100 kRad (Si) / 1 kGy (Si). Radiation reports and ESCC9000 qualification are expected in Q3 of this year, and EM and EQM parts can be ordered today.

The product page for the MAG-TDC00002-Sx can be viewed here and a device datasheet can be requested. The device is European and ITAR-free which is advantageous if you have import/export concerns!

To prototype and de-risk the MAG-TDC00002-Sx, an evaluation kit is available comprising a base board and a 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:

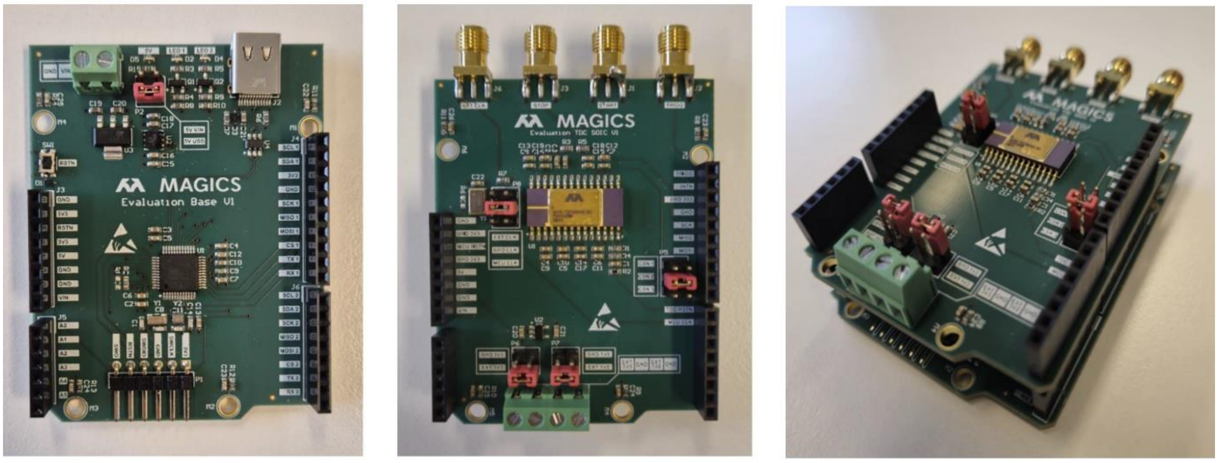
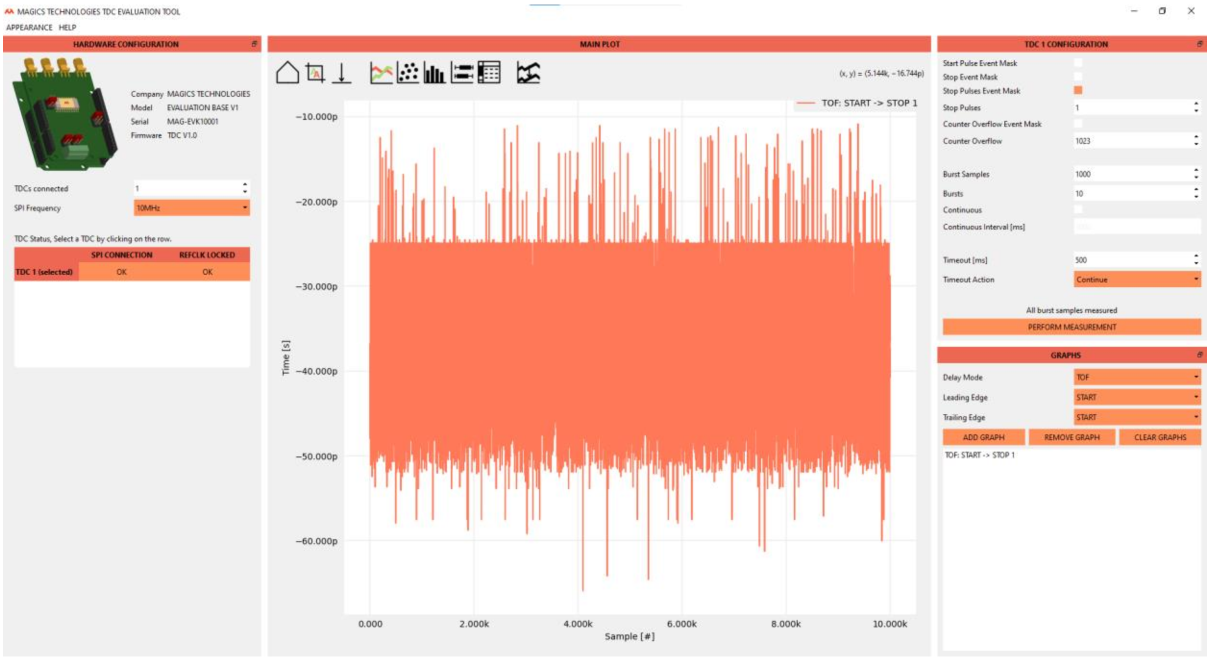


Figure 7 : MAG-TDC00002-Sx Evaluation Kit.

The evaluation kit comes with software which communicates with the base board using SCPI commands to configure and use the MAG-TDC00002-Sx as shown below:



Company MAGICS TECHNOLOGIES
Model EVALUATION BASE V1
Serial MAG-EVK10001
Firmware TDC V1.0

TDCs connected: 1
SPI Frequency: 10MHz

TDC Status, Select a TDC by clicking on the row.

	SPI CONNECTION	REFCLK LOCKED
TDC 1 (selected)	OK	OK

Start Pulse Event Mask ☐
Stop Event Mask ☐
Stop Pulses Event Mask ☑
Stop Pulses: 1
Counter Overflow Event Mask ☐
Counter Overflow: 1023
Burst Samples: 1000
Bursts: 10
Continuous ☐
Continuous Interval [ms]
Timeout [ms]: 500
Timeout Action: Continue

All burst samples measured

Delay Mode: TOF
Leading Edge: START
Trailing Edge: START

TOF: START -> STOP 1

Figure 8 : Screenshot of MAG-TDC00002-Sx Evaluation Kit Software.

If you are a manufacturer of Earth-Observation LiDAR instruments, space-science mass spectrometers, ISAM/space-domain awareness proximity detectors or high-throughput optical communications transceivers, Magics' MAG-TDC00002-Sx offers you a high-precision, small, low-power, rad-hard TDC to calculate time-of-flight to enable your space application.

If you need to calculate absolute time for applications such as secure quantum key exchange via satellite, Magics' MAG-TDC00002-Sx offers you a rad-tolerant solution.

ITAR-free EM and EQM parts are available today with full qualification and flight-grade components procurable from Q3 this year.

Further information about Magics' MAG-TDC00002-Sx will be shared in a webinar to be broadcast on 22nd May and you can register using this link.

Dr. Rajan Bedi is the CEO and founder of Spacechips, which designs and builds a range of advanced, AI-enabled, re-configurable, L to K-band, ultra high-throughput transponders, SDRs, Edge-based on-board processors and Mass-Memory Units for telecommunication, Earth-Observation, ISAM, SIGINT, navigation, 5G, internet and M2M/IoT satellites. The company also offers Space-Electronics Design-Consultancy, Avionics Testing, Technical-Marketing, Business-Intelligence and Training Services. (www.spacechips.co.uk).