Time Tagging Technology with Picosecond Resolution for Space Applications

White Paper

TimeTag.Space (2020)
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Abbreviation List

3D – three dimensional
ASIC – Application-Specific Integrated Circuit
ADC – Analogue to Digital Conversion
°C – degree Celsius
CUTMB – Compact Universal Time Measurement Block
DSP – Digital Signal Processing
ET – Event Timer
ESA – European Space Agency
FPGA – Field-Programmable Gate Array
HELENA – Hera LiDAR Engineering Model Altimeter
LSTM – LiDAR and Altimeter specified Timing Module
LiDAR – Light/Laser Detection and Ranging
MIT – Massachusetts Institute of Technology
MSPS – Million Samples per Second
MPET – Multi-Purpose Event Timer
ns – Nanosecond(s)
ps – Picosecond(s)
ppm – parts per million
PPM – Pulse Position Modulation
R&D – Research and Development
SLR – Satellite Laser Ranging
STTT – Space Time Tagging Technology
TDC – Time to Digital Conversion
TOF – Time of Flight
UTMS – Universal Time Measurement Subsystem
UTC – Coordinated Universal Time
About the Company/Introduction

TimeTag.Space was established in summer 2019 as a spin-off of Eventech Ltd. It was launched to commercialize the high precision Space Time Tagging Technology (STTT) developed by Eventech Ltd as a spinoff of Institute of Electronics and Computer Science of Latvia. In March 2020, TimeTag.Space has signed a contract with ESA Business Incubation Centre and moved its headquarters to Graz, Austria. At present the Company operates in Riga (Latvia) and in Graz (Austria) and has 3 employees and 4 researchers.

<table>
<thead>
<tr>
<th>Company Name: TimeTag.Space</th>
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<tbody>
<tr>
<td>Legal Entity: Space.TimeTag KG</td>
</tr>
<tr>
<td>Legal address: Stremayrgasse 16, 8010 Graz, Austria</td>
</tr>
<tr>
<td>Web: <a href="http://www.timetag.space">www.timetag.space</a></td>
</tr>
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<table>
<thead>
<tr>
<th>Martins Razuks-Ebels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phone: +371 28680453</td>
</tr>
<tr>
<td>Email: <a href="mailto:martin@timetag.space">martin@timetag.space</a></td>
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**Space Time Tagging Technology** (STTT) is based on the Eventech Event Timer A033-ET for terrestrial applications. A033-ET is a computer-based instrument that measures the time of events, combining high accuracy, high measurement rate and a reasonable price in one device. When integrated into a larger system, the A033-ET timer enables the system to indirectly measure distance, speed, position, etc. Starting from 2016, when the team has signed the first contract with European Space Agency, STTT was realized as a solution for several space missions, due to its unique features and price.

Thus, **TimeTag.Space provides a financially accessible technological solution for high-accuracy event timing for space applications.**

It is possible to read about the technology’s core idea and implementation in chapter “**Space Time Tagging Technology**”. Chapter “**Space Missions and Contracts**” discusses all completed or ongoing international space projects the team is/was involved in. The broad range of potential and already proven technology applications are explored in detail in chapters: “**Satellite on-board Applications**” and “**Further Applications**”.

Take note that all information in this technology White Paper is based on consistent empirical results, as opposed to theoretical estimates (unless stated otherwise).

**TimeTag.Space’s Core Competence**

1. Picosecond precision time tagging systems with capability of handling high intensity overlapping event flows.
2. Space qualified picosecond precision time tagging systems
3. Engineering and system integration of application specific time tagging solutions under various constraints and requirements.
4. Complete functional and parametric testing of time tagging solutions in a wide temperature range.

**Space Time Tagging Technology**
According to MIT Technology Review\(^1\), the Space Industry plans to launch more than ten thousand satellites in the next decade. Therefore, many new systems will be built, where timing technologies will be required. It is essential to develop a unified timing system which will fit (with minor adjustments) a wide variety of applications (Wind, TOF, Flash LiDARS, Rotation sensors, synchronization tools, etc.). In electronics, Time to Digital Converter (TDC) is a device that provides digital representation of occurred event’s time. Interval Counting and Time Tagging Technologies are two types of TDCs

**Interval Counting vs Time Tagging Technology**
The standard practice of performing the time interval measurements is to use so called “time interval counters”. A typical time interval counters has two inputs, speaking in terms of laser ranging terminology, those are: inputs for Fire pulses (which are related to the moments, when the laser is fired) and for Return pulses (signals from the optical sensor related to the moments, when the return pulses of light hit the sensor). When Return or Fire pulses are registered, the time interval counter produces a digital representation of the input time interval. However, a different approach to time measurements has become popular in the last decade. The time measurement devices, which do not measure the intervals but record the epoch (points in time) of arriving events. Such approach is much more effective for a variety of applications. Devices of this type are usually called Event Timers. The output of Event Timers is typically called a time tag or time-stamp. The time tags are produced with respect to some internal time scale of the Event Timers. If the moments of events (time-tags) are produced and recorded, then any timing information can be calculated from them including the time intervals. As far as the time interval measurements are concerned, one of the main advantages of time-tagging is that the measured time intervals can overlap; this is not possible with time interval counters. The ability to do overlapped time intervals and perform long range measurements significantly improves the performance of the measurement systems in the area of modern applications such as: KHz Satellite Laser ranging, high performance LiDAR, 3D scanning, and others.

Due to high requirements of range, time resolution, and spatial resolution of timing systems’ applications, the only possible approach is the event timing (time-tagging) approach.

**Implementation**
The company’s Space Time Tagging Technology is an evolution of its terrestrial Time Tagging Technology, represented by its TOF/Time tagging devices - Eventech’s Event Timer A033-ET\(^2\), which is well known around the globe.

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It is a computer-based instrument that measures time instants when input events (represented by electrical pulses) occur. The distinguishing feature of the A033-ET is its extremely high accuracy combined with a high measurement rate.

**Diagram**

When performing a measurement, event time is registered relative to the internal time scale of the Event Timer. This time scale is defined by a system clock signal, typically 100 MHz, which triggers secondary signal sampling and increments a time counter inside an FPGA. If no external reference signal is supplied, then the system clock is provided by a free-running crystal oscillator, which corresponds to a time scale accuracy of approx. ±20 – 50 ppm, depending on the oscillator installed. If an external reference is supplied, then system clock becomes phase-locked to it. In such case, the time scale is defined by the external reference signal and systematic error of the measurements is determined by the quality of the external reference signal and temperature drift of the input delays. Random error, however, is almost completely independent of time scale accuracy and quality of the supplied reference signal, and is always 2-3 ps.

**Main parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single shot RMS resolution</td>
<td>2.5 ps</td>
</tr>
<tr>
<td>Maximum measurement rate</td>
<td>20 MSPS</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;20 W</td>
</tr>
<tr>
<td>Temperature drift of a single shot RMS resolution</td>
<td>2 ps/°C</td>
</tr>
</tbody>
</table>
Such parameters make the A033-ET one of the best event timers currently available for terrestrial applications. Combining the A033-ET with application-specific software, several different top-quality and reasonably priced event timer systems can be created. A033-ET is especially well-suited for applications related to Satellite Laser Ranging (SLR). Technology leadership is confirmed by the fact that more than 50% of the world’s Satellite Laser Ranging stations chose this device³.

Event timing in Satellite Laser Ranging (SLR), where the company dominates the market, is one of the numerous possible applications for the timing technology. Other applications, just to name few, are the following: the Jiangmen Underground Neutrino Observatory⁴ uses A033-ET timer for the control and verification of a well-known White Rabbit technology⁵ that is used for timing neutrinos.

**TimeTag.Space’s Technology Advantages**

1. **The ability to obtain complete information.** Time tags are the most complete information for researching event flows, from which it is possible to derive the relative time position of events, time intervals between events, their time correlation, etc.
2. **High accuracy of a single measurement** makes it possible to accurately study dynamic objects (such as Earth satellites).
3. **Continuous time tagging** allows exploring continuous, overlapping event flows.
4. **The ability to receive events’ time tags in the UTC time scale**, which allows to compare spatially separated events.
5. **The ability to study the flow of events in a wide range of intensities**
6. **Proprietary Monitoring and Calibration Method** allows to continuously monitor the precision of the equipment without interference with the Timer measurement processes, and to recalibrate the system when the precision is out of predefined limits.
7. **High endurance of the system**: it can continue measurements even with physical damage to a part of the electronic components.

Based on these technology’s features, possible applications arise. For example, in Satellite Laser Ranging all seven features are needed.

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⁴ Further information about the Jiangmen Underground Neutrino Observatory: [http://juno.ihep.cas.cn/](http://juno.ihep.cas.cn/)

Space Missions and Contracts

The space-grade time tagging technology development started in 2016, when TimeTag.Space’s team signed a contract with European Space Agency to adapt the A033-ET technology for use in space. As a result, a qualification model of the Multi-Purpose Event Timer (MPET) was produced. In fact, it was the first Time to Digital Convertor (TDC) with <10 ps precision available on the space market. Overall, the TimeTag.Space team has participated (or is currently taking part) in five ESA space missions/R&D projects and one commercial mission.

Completed

On-board Implementation of the Multi-Purpose Event Timer

MPET⁶ is implemented on space qualified components. It is aimed for on-board applications and is designed for use in extreme conditions (temperature, vibration, radiation). The typical application (military, aerospace, space) is laser ranging and its derivative applications like 3D scanning, planetary altimetry, LiDAR, range finding, satellite communication etc.

Main parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single shot resolution</td>
<td>&lt;5-6 ps</td>
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<tr>
<td>Dead time</td>
<td>&lt;60 ns</td>
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<tr>
<td>Power consumption</td>
<td>≤4W</td>
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<tr>
<td>Temperature drift of a single shot RMS resolution</td>
<td>30 ps/°C</td>
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<tr>
<td>Operating temperature range</td>
<td>-35 °C to +75 °C</td>
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Luna 27 Mission

In 2017, Neptec UK (currently MDA UK Ltd) invited TimeTag.Space to participate in ESA and Roscosmos’ Moon mission “Luna 27”. In that mission, Airbus Defence and Space was the main contractor. The task was to build TDC for the specialized landing navigation LiDAR system that was being developed by Neptec UK Ltd. The STTT was easily integrated into the Neptec LiDAR and was successfully tested⁷.

The development of the product was done through ESA’s procurement Tender system, as a result, a Universal Time Measurement Subsystem (UTMS) was created with extra control functions for the satellite TOF-based systems, which distinguishes itself by high accuracy and measurement speed. The sub-system consisted of two major parts – an Event Timer and an optical sensor with an amplifier/normalizer. Additionally, the subsystem can take several basic and application specific system control functions and features the SpaceWire communication protocol.

Commercial SPACE DRONE™ Mission

As the amount of debris in space is exponentially increasing, there is an urgent need to create satellite servicing robots to extend the operational life of constellations. Effective Space Ltd. has come to a solution developing Space Drones⁸. These are robots that fix and maintain satellites in space.

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⁶ ESA Contract No.4000115326/15/NL/Nde „On-board implementation of the multi-purpose Event Timer”
⁷ Further information about the mission: [http://www.esa.int/Our_Activities/Human_Spaceflight/Low-cost_clocks_for_landing_on_the_Moon](http://www.esa.int/Our_Activities/Human_Spaceflight/Low-cost_clocks_for_landing_on_the_Moon)
A Space Drone approaches and docks with satellites on Geostationary Earth Orbit. After docking with a target satellite, the Drone operates as an external engine providing altitude and orbit control for the spacecraft; this increases the lifespan of the satellite.

Maxar Technologies that acquired Neptec, was selected to supply sensors for the Space Drone mission. In 2018, a license to build two TimeTag.Space UTMS was sold to Neptec UK as part of space LiDARs for the mission. The Space LiDARs were originally developed for the lunar lander within “Luna 27” mission; within Space Drone mission they are used for navigation and docking in orbit and for the de-orbiting of space debris.

Current

Compact Universal Time Measurement Block
As the small satellite sector is growing rapidly, there is a modern pressing requirement to miniaturize the size of space-grade TDC as well as to lower power consumption. This could be solved by using ASIC technology. Thus, in 2019 the team signed a contract with ESA to complete a research project on potential further miniaturization of the timer.

The Goal of the proposed project is to conduct a preparatory study of how to develop and design a radiation hardened Compact Universal Time Measurement Block (CUTMB) with following main technical objectives:

1. MPET based high precision time-tagging
2. Developing a plan for embedding maximum signal switching, signal shaping and DSP functions for the event timing into ASIC to reach small size and low power consumption.

Hera Mission
This year, TimeTag.Space received positive feedback and confirmation from the Efacec space project department that a TOF system is to be developed for use on-board the Planetary Altimeter HELENA project. Thus, the team is currently working together with Efacec to provide a space-qualified Event Timer for the HELENA Laser altimeter. The later altimeter is to fly aboard the Hera spacecraft for Asteroid mapping.

TimeTag.Space’s team will provide the LiDAR and Altimeter specified Timing Module (LSTM) Engineering Model, based on the MPET, to satisfy the requirements of size and power consumption for the Project by moving the technology of interpolation and input commutation inside the FPGA, all the while preserving the high standards of the original Timer’s precision.

Wind LiDAR
Recently TimeTag.Space was awarded an ESA contract to assess the original concept of a correlation wind LiDAR for space applications.

The main goal of this project is to assess the potential of the STTT to operate as a processor in several space sensors spanning from Earth observation to Science and telecom/navigation. The objectives of this study are:

● to establish new/advanced sensor concepts exploiting the ET Timer Module;

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9 ESA Contract No. 4000125526
10 Proposal in response to ESA’s AO/1-9953/19/NL/SC
• to carry out overall preliminary designs, of appropriate sensor/ET processor combination;
• to carry out a development plan for the sensor(s);
• to perform a preliminary end-to-end performance budget for the overall sensors, including Timers;
• to identify, for each sensor or class of sensor, the performance specifications required for the appropriate ET Timer Module to perform as the processor;

The preliminary list of pre-identified sensors covers:
• Imaging Lidar
• Correlation Wind Lidar
• Autocorrelation sensors & techniques

For the wind LiDAR, the application of these technologies/techniques shall prove, for the 1st time, the possibility of operation of a non-Doppler Wind Lidar System from space.

This project will conduct a detailed evaluation of the new sensors’ concepts, including, whenever possible, representative field demonstrations to show the potential for spaceborne operation.

**Satellite on-board Applications**

The capabilities offered by picosecond-precision Time Tagging, alias Event Timer, allow for significant improvement of measurements already being performed by other techniques as well as open possibilities for novel measurements in R&D domains. For example, Optical Gravimetry, Optical Time Domain Reflectometry, and Optical Gyroscope for Rotation Measurements. Those will be discussed in the proceeding chapter.

Meanwhile, functions needed for any successful satellite missions are discussed in this chapter. The STTT can be manufactured into a space grade timing device for embedding into several systems/subsystems to provide all these functions simultaneously operating on-board a satellite:

1. One-shot distance measurement:
   a. laser altimetry
   b. laser imaging
2. Clock distribution & synchronization in free space;
3. Laser communication by pulse-position modulation;
4. Quantum communication.

**One Shot Distance Measurement**

There is a common approach to measure distance in research and industry called Time of Flight (TOF) measurements. Also, from TOF measurements, it is possible to establish time standards, to measure speed, or to study particles or medium properties. In the Laser Ranging application, TOF is the time needed for laser from a laser gun (observer) to reach the targeted object and return. From this information, the distance is derived. To do so a pulse laser and a laser pulse sensor (or sensors) are needed. Time Tagging technology measures the time interval between the Fire and the Return pulses. The better the time interval measurements accuracy the more accurate the obtained distances are. For example, to reach one-centimeter accuracy requires 66 ps time interval measurement accuracy. Also, the high precision of a single shot measurement allows to study dynamic objects. The required accuracy depends on the application.
Laser Ranging

**Satellite Laser Ranging (SLR)** is currently the most accurate method for geocentric location identification of a satellite. Short pulses of laser are fired from the SLR station at a satellite that is equipped with retroreflectors, which return the initial pulses back to the station on the ground. For this application, Eventech know-how is packaged into an Event Timer, which is used to measure the time between the outgoing and incoming laser pulse, which in turn enables instantaneous calculation of the distance to the satellite with millimeter accuracy. Aggregation of this data allows for accurate satellite orbit description, which is used for fundamental research in cartography and geodesy.

**The Eventech Event Timer is integrated into more than 50% of the world’s SLR stations.**

Lunar Laser Ranging can be mentioned as one of the applications executed at existing SLR stations. It is used to measure the distance between Earth and the Moon, utilizing the same principle as SLR, where laser beams from the Earth are reflected by retroreflectors on the Moon’s surface.

Laser Altimetry & Imaging

Laser Altimetry is the direct extension of the highly developed Ranging technique, involving laser mapping of specific target areas, as for landing sites or land (resources) mapping & management, etc.

Combination of an Array-detector with a Scanning or Flash Lidar is an important perspective application for STTT: the picosecond accuracy/resolution combined with a small (= ns) dead time allows for photon time tagging with high signal-to-noise ratio. The company is currently developing an imaging lidar for envisaged space applications. This will be the first demonstration of picosecond time tagging in an imaging lidar.

Backscattering Lidar & Correlation Wind Lidar

TimeTag.Space’s team is also exploring the application of picosecond accuracy time tagging with an array detector for backscattering & wind lidar applications (CWL). Another current R&D activity aims to demonstrate time tagging with atmospheric wind measurements. This technique uses a micro-lidar with azimuth/elevation scanning with an array detector with multi-channel picosecond time tagging. Wind-induced aerosol motions in the troposphere are being detected via cross-correlation of point-cloud histograms.

Clock Distribution & Synchronization in Free Space (e.g. among Satellites)

For Optical and RF Telecom satellites, the STTT can relax the Ground Stations requirements in terms of density and coverage by providing in Orbit picosecond precision clock distribution for timing and synchronization. An internal study is looking at the Trade-offs for this type of application.

The capability of the Event Timer for time transfer through optical fibers has already been proven. Our partners - scientists from the VNIIFTRI Institute of the Russian Academy of Metrology11 - have used our Event Timer in time transfer tasks and delay measurements in optical fibers and have shown promising results. The extreme accuracy of the Event Timer is crucial for measuring transfer delays in optical fibers, which is very important while developing new optical materials and new data transfer techniques. According to our partner, the most

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beneficial features of our Event Timer for TOF tasks are the extremely high accuracy and multi-stop functionality.12

**Laser Communication by Pulse Position Modulation**

The Pulse Position Modulation (PPM) is one of the approaches to data transmission. In optical communication, the PPM allows to transfer data with low energy consumption. In this method, N bits of information are encoded by transmitting a single laser pulse with one of $2^N$ time delays relative to the previous one. With average delay of T seconds, the transmission speed is $N/T$ bits per second on average. Reduced dead time of the system allows for shorter minimum delay and consequently shorter T, and increased precision allows encoding data with less difference between time delays, which means either more bits encoded with the same T, or shorter T for the same number of bits per pulse.

The Laser Communication by PPM requires precise STTT and can be used as inter satellite communication solution.

**Quantum Communication**

Due to the timer’s unique performance characteristics, it is possible to use it as an asset for many quantum optical measurements via Coincidence Correlation or Time tagging. Again, interferometric optical schemes as used for other envisaged application can be used: here specifically with the Hanbury Brown Twiss interferometer. Unique measurements capabilities can be applied here for:

- QKD (key distribution)
- QDS (digital signature)
- QE (entanglement)
- QT (teleportation)
- QIP (information processing)
- Photon Antibunching (identifying single-photon-emitter)

**Further Applications**

The following result are success cases for terrestrial Timer applications. It is possible to employ the applications in the Outer Space environment using STTT.

**Optical Gravimetry**

Event Timers can be successfully used for Gravity field measurements: embedded after the detector in an optical Mach Zehnder Configuration, they can allow fine displacements to be measured with high accuracy and resolution. Absolute gravimetry is a method used to measure gravitational acceleration, for specific positions as well as the detection of gravity changes with time at a given location. For high accuracy demands, the geometric position of a gravity point must be defined very accurately. Absolute gravity measurements are performed by an optical laser interferometer that measures the free-fall acceleration of a retroreflector in a vacuum. The measurement is directly referenced to atomic standards of length and time. These systems have been

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undergoing miniaturization in recent years, and The Terrestrial Timer is used as an excellent, high-accuracy time-measurement solution for this purpose.\textsuperscript{13}

The Terrestrial Event Timer is being used by the scientists from the Institute of Geodesy and Geophysics (Chinese Academy of Science) in Wuhan.

**Optical Time Domain Reflectometry**

The Terrestrial Event Timer with its picosecond accuracy and low dead time is the ideal instrument to perform Optical Time Delay Reflectometry for Fiber links in high-speed communication networks or for characterization of fiber loss in Optical Pyros for launchers. TimeTag.Space’s team is aware of the difficulty of this technique and we are ready to discuss specific requirements and design implementations\textsuperscript{14}.

**Optical Gyroscope for Rotation Measurements**

As for Gravimetry, a picosecond-accuracy Terrestrial timer, utilizing a similar optical scheme with a Mach Zehnder interferometer with embedded fiber variable delay, can be used as Gyroscope sensor. A TimeTag.Space internal assessment work is ongoing to assess the performance capabilities and design options between photonic integration or discrete optics.

**Others**

Another applications worth mentioning are

- Synchronization Tasks (Supercomputers, Tera Grid tech, etc.)
- Archaeology
- Oil & Gas (sediment analysis)
- Avionics
- Positron Emission Tomography
- Flow Cytometry
- Spectrometry
- Nuclear Spectroscopy
- Railway Scanning
- High frequency trading
- Machine-to-Machine communications
- Particle Image Velocimetry


\textsuperscript{14} “High-accuracy optical time delay measurement in fibre link”, Chinese Optics Letters, June 2019