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Status of the INRIM-VMI Collaboration on the Use of Galactic Cosmic Rays for Time Metrology Applications

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Abstract

In this work, we present the status of the ongoing scientific collaboration between INRIM（Istituto Nazionale di Ricerca Metrologica）and VMI（International Virtual Muography Institute）on the possibility of synchronizing atomic clocks and disseminating reference atomic time scales using relativistic charged particles, muons, from cosmic rays induced Extended Air Showers（EAS）, through an approach called CTS（Cosmic Time Synchronizer）, ideated by the University of Tokyo. Based on muons, this system aims to grant timing services within the EAS shower disc with improved robustness and reliability against consolidated time synchronization systems. The CTS approach is, in principle, not affected by malicious or intentional jamming and spoofing actions, typically undermining time synchronization techniques based on the use of RF（Radio Frequency）signals, like those emitted by GPS（Global Positioning System）and other GNSS（Global Navigation Satellite Systems）satellites. This reliability makes CTS a good candidate for providing secure synchronization and dissemination of reference time in critical applications. In addition, it could complement GNSS in areas/environments not covered by its RF signals, such as indoors, underground, and underwater.

Key words：Muography, timing, synchronization, dissemination, UTC

I. INRIM, the Italian National Metrology Institute

1）General overview

INRIM, the National Metrology Institute of Italy[1)], is a public scientific research body established by the Italian government in 2004. It carries out and promotes research in metrology and develops the most advanced measurement standards, methods and related technologies, fulfilling the functions of a primary metrological institute. In this sense, INRIM creates and maintains the national standards for units of measurement. Such standards are necessary for granting the traceability and the legal value of measurements in the sectors of industry,

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commerce, scientific research, health, and environmental protection, as well as for measurement needs in the judicial field and for any other area in which the high scientific-technological content of metrological research is crucial. INRIM also enhances, disseminates, and transfers knowledge and results in measuring science and materials research to promote national technological development and improve citizens' quality of life and services. INRIM's worldwide recognized excellence ranges from materials science to quantum physics, from nanoscience to developing innovative technologies and measuring instruments. Metrology for climatic variations, energy resources/new mobility systems sustainability, food certification, and measurement techniques applied to medical physics and biomedical/biological sciences are other examples of the INRIM internationally recognized leadership.

2) The INRIM Time and Frequency Group

One of INRIM's leading and internationally recognized disciplines is time metrology. INRIM realizes UTC(IT) standard atomic time and contributes to the Universal Coordinated Time (UTC); it is a leader in the quest for more accurate timing through the realization of primary and secondary frequency standards (e.g., laser-cooled Cesium fountain and optical clocks); it has been participating for about 20 years in developing the European satellite navigation system Galileo for what time metrology is regarded; it designed and realized the fiber-based Italian Quantum Backbone for the distribution of ultra-accurate timing signals for research on quantum sensors and quantum communication, together with the provision of high added value timing services over more than 1000 km across Italy; dedicated time metrology support for fundamental physics experiments has been provided over the years, ranging from the CNGS (CERN neutrinos to Gran Sasso) measurements carried out by the Borexino collaboration, up to measurements aimed at supporting the detection of high energy extended showers (EEE, Extreme Energy Events project), culminated in the realization of a high accuracy time reference facility for Fundamental Physics experiments, called FRATERNISE.

3) The FRATERNISE facility

The FRATERNISE facility (Facility ad elevata accuRAtezza Temporale pEr espeRimeNti di fISica fondamEntale – High Timing Accuracy Facility for Fundamental Physics Experiments)$^{2)}$ (Cantoni *et al*., 2022; Cerretto *et al*., 2022a) was born because of the previously mentioned experiences of INRIM in the metrological characterization and calibration of timing devices used to verify the superluminal properties of neutrinos by the Borexino collaboration (CNGS project) (Antonello *et al*., 2012; Caccianiga *et al*., 2012; Sanchez *et al*., 2012) and in the detection of extended and ultra-high-energy cosmic showers within the EEE project (Cerretto *et al*., 2021). The FRATERNISE facility (Fig. 1) is based on a permanent measurement system installed at INRIM RadioNavigation Laboratory dedicated to the metrological characterization and calibration of timing devices for Fundamental Physics experiments and GNSS receivers used in the remote comparison of atomic clocks or time scales. In Fundamental Physics experiments (space physics, accelerator physics), time plays a crucial role, allowing the evaluation of the events timestamping (timing) and their simultaneity, thus enabling deductions about the characteristics of the observed phenomena. Furthermore, it is increasingly necessary to correlate events from experiments that occur over large distances or events measured by different experiments located in distant places investigating similar phenomena. The FRATERNISE facility aims to contribute to optimizing timing systems for these types of experiments, allowing the possibility of synchronizing them with the Italian atomic reference time scale, UTC(IT). In addition to the permanent facility, traveling units with customized functional and metrological characteristics are available to calibrate timing devices that cannot be physically transported to INRIM.

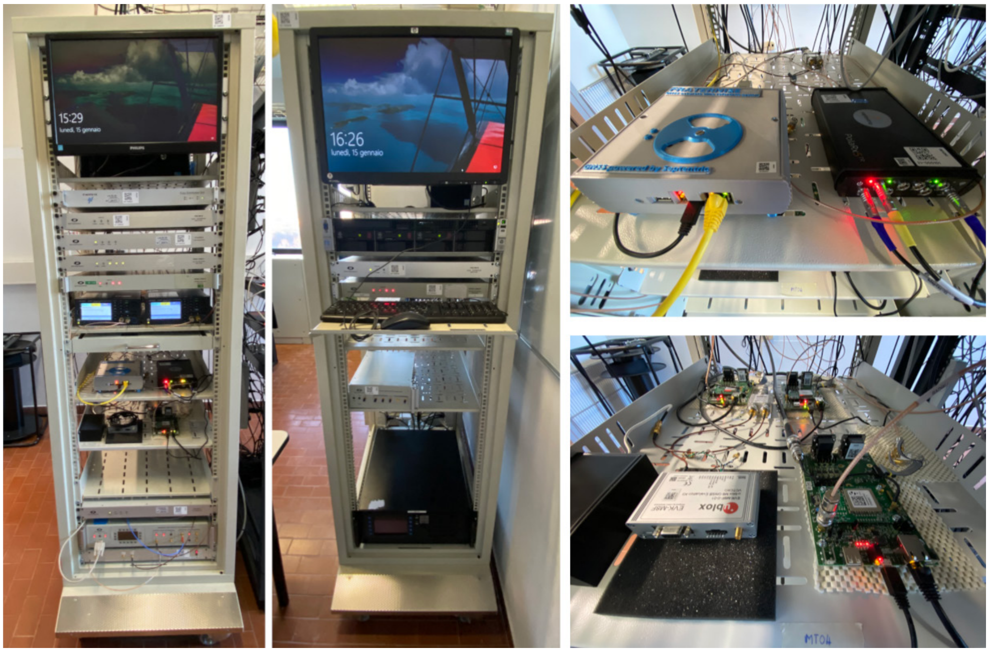

Fig. 1 FRATERNISE Facility at the INRIM RadioNavigation Laboratory. On the left is a general view of the two racks composing the Facility, while on the right are details of the facility's calibrated GNSS receivers for timing applications used for synchronizing to UTC(IT) remote fundamental physics experiments. Such receivers will be employed to evaluate the CTS time transfer capabilities when SCMs are located remotely at a final user and to test the satellite-CTS feature to extend GNSS-based timing systems in areas not covered by GNSS RF signals, like indoor, underground, and underwater environments.

II. The INRIM and VMI collaboration

1) The importance of timing in current society

Current technologies and automated infrastructures continue to progress in complexity, with increasing synchronization requirements in terms of performance, security, and reliability. In recent years, there has been a continuous increase in time requirements at the microsecond and nanosecond levels, with this precision/accuracy becoming somehow a standard level in various sectors of technology, infrastructure, finance, and, after all, everyday life, particularly with the diffusion of GPS/GNSS and the advent of 5G communications. The availability of atomic clocks and GNSS meets the above needs, although with some limitations, primarily related to cost, performance, security, and reliability. For example, high-performance atomic clocks are limited to some applications for cost reasons. In contrast, despite being generally affordable from an economic point of view with remarkable performances, the use of GNSS for timing applications could lack robustness due to possible jamming or spoofing actions, malicious or unintentional, affecting the RF signals employed by such systems. In addition, these RF-based techniques cannot be generally utilized in indoor, underground, or underwater environments. Due to these considerations, it's been some years since an important effort conducted at the international level started to find solutions to mitigate the mentioned limitations, even envisaging new techniques for timing applications. This is the case of the CTS (Cosmic Time Synchronizer) ideated by the University of Tokyo, based on using muons from EAS rather than RF signals emitted by GNSS satellites and other sources.

2) The Cosmic Time Synchronizer (CTS)

The muon-based synchronization technique CTS (Cosmic Time Synchronizer)—which relies on muons derived from relativistic cosmic ray showers—was proposed by the University of Tokyo at the beginning of the second decade of the 2000s (Tanaka, 2022) and can potentially be envisaged as a complementary or alternative solution to existing methods, depending on the requirements of the final user (Fig. 2).

As mentioned, GNSS is probably the most diffused and among the most performing systems for timing applications. It can be used mainly outdoors but not in areas not covered by RF signals. Also, there are some critical applications, like the financial sector, where GNSS is not recommended to be operated standalone but with alternatives or replaced by more robust systems. Possible jamming and spoofing actions could impair the system's operation, leading to serious problems and considerable economic losses. CTS, based on muon detections, could potentially overcome both limitations. When a Cosmic Ray (CR) enters the atmosphere, hadronic collisions occur with air nuclei, creating a shower of secondary particles known as Extended Air Showers (EAS). The primary components of these showers are hadronic, electromagnetic, and muonic, along with other phenomena such as fluorescent and Cherenkov effects and neutrino production from particle decays. Each EAS delivers approximately 10^6 secondary particles to the ground over an average area of a few square kilometers, with around 2% of these being relativistic muons, the most penetrating component of the shower, capable of traversing air and ground. Due to these properties, muons can generate images of the interiors of large structures like volcanoes or pyramids within a specialized field known as Muographic Imagery. In an EAS, individual muons can be treated as "simultaneous" events for detectors within tens of nanoseconds. Furthermore, the differences in arrival times between two or more detectors are highly stable over time, primarily influenced by white Gaussian noise. This stability makes them particularly suitable for timing-related applications (T) within an emerging field of study called Muochrony, analogous to the more established area of Muographic Imagery and another developing technology known as Muometry, which focuses on muonic Positioning and Navigation (PN). Muographic Imagery, Muometry (i.e., PN), and Muochrony (i.e., T) form the foundational pillars of the muonic scientific discipline referred to as Muography. The low interaction cross-section of EAS muons enables CTS to facilitate cost-effective, long-term wireless synchronization of atomic clocks and the dissemination of reference time scales within the EAS shower disc area, with enhanced resistance to jamming and spoofing. Suitable for indoor, underground, and underwater applications (considering the increased detector network granularity needed as the water equivalent depth traversed by muons in underground settings increases), CTS could be a viable option for providing secure synchronization and reference time dissemination in critical applications, as well as complementing GNSS in areas or environments lacking RF signal coverage.

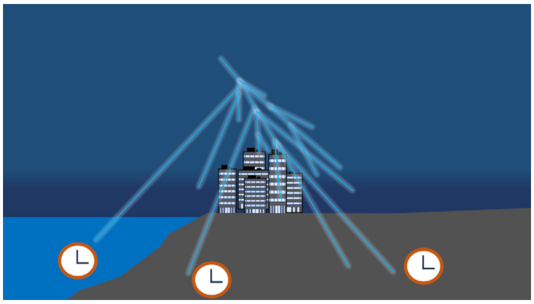

Fig. 2 CTS rationale showing the possibility of synchronizing clocks indoor, underground and underwater.

A CTS network system consists of at least two CTS sensors: one acting as Master connected to a time reference, which could be either a standalone atomic clock, a GPS Disciplined Oscillator (GPS DO), or a UTC(k) timescale; the other(s) acting as Slave(s) and equipped with the local clocks to be synchronized (e.g., Rubidium atomic clocks, OCXO, etc.). Each

CTS sensor performs a local measurement, providing each detected muon with a timestamp according to the sensor time reference. Hence, the muons detected at the Master will be time-tagged to the system's reference clock, while those detected at the Slave(s) will be time-tagged according to the clock to be synchronized. Then, by comparing the Master and Slave(s) timestamp data, EAS coincidences can be estimated, representing the time difference between the Master and Slave(s) clocks that can be synchronized every time a coincidence is found. Given that muons are not susceptible to radio magnetic interference and no critical timing information traffic between Master and Slave(s) occurs, CTS could be considered, in principle, a secure technique for time synchronization, immune to jamming and spoofing actions, whether done unintentionally or on purpose. A small-scale CTS sensor network was developed and tested for the first time at the University of Tokyo in 2022. The obtained results (Tanaka *et al*., 2023a), although preliminary, were auspicious, demonstrating synchronization capabilities at the level of tens of nanoseconds (i.e., 30 ns, SD, 1σ) in terms of precision over 60 meters in an indoor environment (with reinforced concrete masonry elements of 30 cm), simulating a real-world scenario where the use of GNSS systems is not possible.

3) CTS metrological characterization at INRIM

Starting from the promising results achieved at the University of Tokyo Laboratories, a collaboration between INRIM and the VMI/MUOGRAPHIX-the University of Tokyo was established through the signature of a LOI (Letter of Interest) by the president and director of both institutions. This agreement foresees joint research activities benefiting from the field of expertise/excellence of each institute, namely Time Metrology at INRIM and Muography at VMI/MUOGRAPHIX-The University of Tokyo. Alongside this convergence of intentions to develop joint research activities, the LOI planned a first concrete experimental activity, namely the metrological characterization of the CTS system at INRIM, to evaluate the system's ultimate performance, with the perspective to be employed for time metrology applications. A CTS setup composed of four 30 cm × 30 cm scintillators and related measurement equipment was shipped to INRIM, installed at the INRIM RadioNavigation Laboratory, and integrated into the FRATERNISE facility in late October 2023 (Cerretto *et al*., 2022b, 2024a) (Fig. 3). In this sense, CTS is the first test case of FRATERNISE since its completion, representing a significant added value in customizing it for real applications. FRATERNISE provides UTC(IT) time scale and other commercial frequency standards time and frequency signals for CTS, allowing to perform the required metrological characterization and test aimed at confirming it as a novel tool for the dissemination of reference time scale for final users. Also, FRATERNISE will allow CTS to be metrologically confirmed when tested outside INRIM in an "end-to-end" configuration (i.e., Master installed at INRIM and Slave(s) installed remotely at a final user) employing the calibrated GNSS receivers for timing applications comprising the facility itself.

As the first installation currently under characterization, CTS detectors were placed across the RadioNavigation laboratory within a radius of 5 m. With this measurement system, different tests and metrological characterization activities were planned. At first, the Master (MCS) and the three Slave(s) (SCMs) sensors were connected, through FRATERNISE, to UTC(IT), as realized at the INRIM Time Laboratory, to start a measurement campaign to preliminary evaluate the CTS system noise. After this measurement campaign, the Master was kept connected to the UTC(IT) signal (considered a reference). At the same time, the Slave(s) were linked to Active Hydrogen Maser (AHM) signals provided by FRATERNISE. With this configuration, the capabilities of CTS in estimating the relative frequency offset (and drift) of the AHM to UTC(IT) have started to be evaluated, also in comparison with other

Fig. 3 CTS setup at INRIM RadioNavigation Laboratory. On the left is a view of the rack hosting the CTS power supply system, MCS and SCMs TDCs, and ancillary measurement systems. The details of the 30 cm × 30 cm plastic scintillators, PMT (Photo Multiplier Tubes), and HV (High Voltage) units are on the right.

state-of-the-art time metrology measurements systems operated at the INRIM Time and RadioNavigation Laboratories. Based on these results, the first tests to discipline the AHM to UTC(IT) and disseminate a UTC(IT) replica (i.e., UTC(IT)_CTS) remotely with the short-term characteristics of the AHM and the medium-long term one of UTC(IT) have been started. Although preliminary, the results achieved are encouraging (Cerretto *et al.*, 2024b), showing CTS can generate a UTC(IT) replica remotely within 5 m below the two nanoseconds to UTC(IT) in terms of precision. From these results, further studies have started, based on moving one of the three SCMs 30 m far away and considering as SCM reference the time and frequency signals provided by a FRATERNISE commercial Rubidium clock.

III. Conclusion and perspectives

Timing is becoming increasingly important in science, technology, and society, demanding better characteristics—even at microsecond and nanosecond levels—in a global effort to improve also reliability and performance to avoid or mitigate the effects of jamming and spoofing actions, which typically affect timing systems based on the use of RF signals, like those emitted by GPS/GNSS satellites. In this context, new timing systems coping with such requirements are becoming of increasing interest. The University of Tokyo has devised and developed a new timing system based on the use of muons coming from EAS, rather than the standard RF signals, in the perspective to be a good candidate for providing time synchronization for critical applications with improved characteristics in terms of reliability and robustness. Also, CTS can be envisaged as a solution to complement GNSS-based time synchronization/dissemination techniques in areas not covered by GNSS RF signals, like indoors, underground, and underwater environments. After a preliminary evaluation at the University of Tokyo Laboratories, a CTS system was installed at the INRIM RadioNavigation Laboratory in the frame of a LOI established between the Italian Institute of Metrology and VMI/MUOGRAPHIX-the University of Tokyo. In such a context, scientific research and rigorous metrological characterization of the CTS system are undergoing at INRIM to define the ultimate performances and its possible future use for time metrology applications, namely the remote synchronization of atomic clocks and dissemination of reference time scales. A first evaluation of the CTS system noise and tests to discipline an AHM to UTC（IT） employing CTS measurements have been performed. Starting with the encouraging results achieved, further research and tests will be carried out at INRIM on CTS, evaluating the disciplining capabilities with Slave detectors placed in more distant areas of the INRIM campus（Tanaka *et al*., 2023b; Tanaka, 2024） and adopting other clocks as reference rather than the AHM（i.e., Rubidium atomic clocks, Chip Scale Atomic Clocks, etc.）. Improvements in the disciplining algorithm will also be faced, considering the deterministic and stochastic characteristics of the clocks to be disciplined. Also, rigorous uncertainty budget estimation and calibration techniques will be required to use CTS in contexts of time metrology. The possibility of combining CTS and GPS（GNSS） will be evaluated to extend GNSS coverage in areas non-reached by its signals, typically indoors, underground, and underwater. Besides this satellite-cosmo approach（i.e., GNSS combined with CTS）, other techniques will have to be identified and tested（Pollastri, 2024） to send a reference and UTC-traceable time scale to the CTS system if not available locally, with improved characteristics in terms of jamming/spoofing resistance, to GNSS. From a technological point of view, the development of customized master and slave detectors will have to be faced depending on the requirements of the final user, who must be aware of the local coverage of the CTS technique. Also, prototypal versions of a compact muonic Disciplined Oscillator（μ-DO）（in analogy to the most common GPS-DO） are being projected and developed by INRIM, with improved characteristics in terms of detection and electronics.

In conclusion, an important, innovative, and challenging collaborative research initiative has been established. The primary challenge, which emerged mainly at the project's outset, involved integrating two distinct scientific disciplines—Time Metrology and Particle Physics—around a common research theme. This integration presented difficulties due to varying areas of expertise, different scientific languages, and diverse working methods. However, what initially appeared to be a limitation soon evolved into a significant strength of the collaboration among INRIM, VMI, and MUOGRAPHIX-The University of Tokyo. The differences that once posed challenges were transformed into added value, thanks to the efforts of Prof. Hiroyuki Tanaka's team and the INRIM VMI team, who identified a shared and common goal. This goal was pursued with passion, dedication, mutual support, and a desire for growth, all aimed at making an innovative and meaningful contribution to science and society.

From a technological perspective, although Muography and Time Metrology are two distinct and seemingly unrelated scientific approaches, they have surprisingly merged fruitfully, giving rise to a new discipline known as Muochrony. This field combines the ability to detect muons with the capability to discipline an oscillator using classical Time Metrology techniques. No significant challenge has been faced in setting up the measurement apparatus and conducting the experiment, demonstrating these two techniques' strong compatibility in creating something novel and unexpectedly innovative.

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Notes

1） INRIM: https://www.inrim.it/it/en［Cited 2024/9/4］.

2） FRATERNISE: https://fraternise.inrim.it/fraternise-english［Cited 2024/9/4］.

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時間計測応用における銀河宇宙線利用に関する INRIM-VMI 共同研究の進捗状況

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本研究は，宇宙線起源の相対論的荷電粒子であるミュオンを利用した原子時計の同期および基準時刻の伝播手法に関する，INRIM（イタリア国立計量研究所）および VMI（国際バーチャル・ミュオグラフィ研究所）による継続的な学術的連携の進展状況を報告する。東京大学により提案された Cosmic Time Synchronizer（CTS）方式は，宇宙線誘起の広がった空気シャワー（Extended Air Showers: EAS）中に生成されるミュオン等を基盤とし，既存の時刻同期システムと比較して高い堅牢性および信頼性を備えた時刻同期サービスの実現を目指している。CTS 方式は，GPS（全地球測位システム）やその他の GNSS（全地球航法衛星システム）において用いられる無線周波（RF）信号に対する妨害（ジャミング）やなりすまし（スプーフィング）といった意図的干渉の影響を原理的に受けにくいという特長を有する。このような高い信頼性により，CTS はクリティカルな応用分野における安全な時刻同期および基準時刻の配信手段として有望視されている。さらに，CTS は GNSS の RF 信号が届きにくい屋内，地下，水中などの環境においても，既存技術を補完する時刻同期手法としての活用が期待されている。

キーワード：ミュオグラフィ，時刻，時刻同期，時刻配信，協定世界時

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