Istituto Nazionale di Ricerca Metrologica (INRIM)

Report to the 21th Meeting of the CCTF

INRIM's Time and Frequency Activities.

BIPM-June 2017

Summary

Introduction

Time and Frequency activities are developed within a specific program of INRIM's Physical Metrology Division. This report aims to highlight some of the most relevant accomplishments of INRIM's group since last CCTF, rather than giving an exhaustive presentation of all the program activities.

The Time and Frequency Program is operating his ensemble of clocks and frequency standards according to the following scheme.

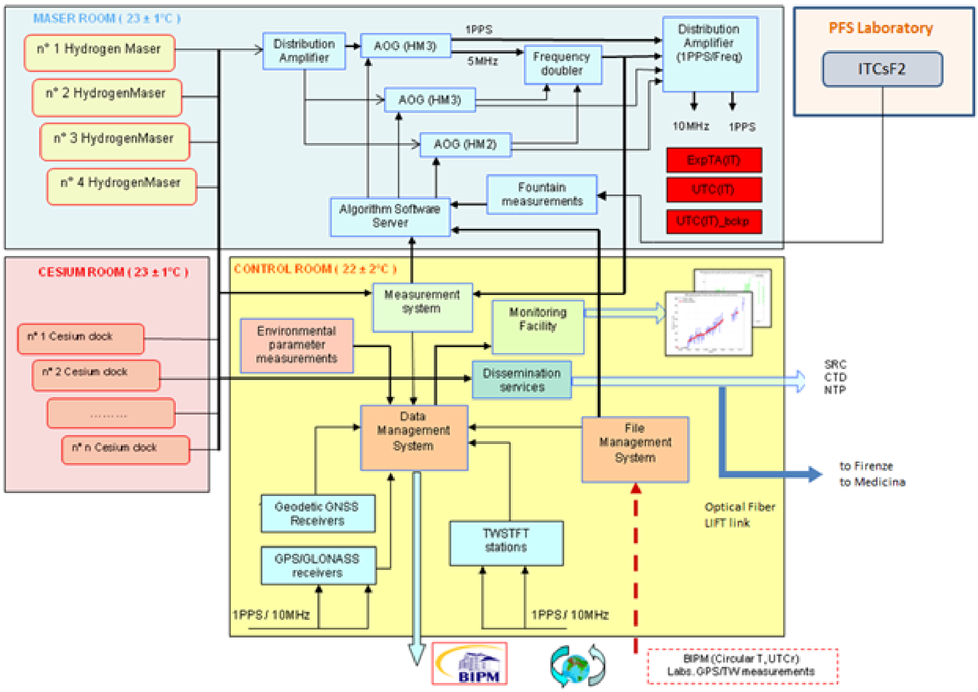

Figure 1: UTC(IT) generation and distribution.

The most relevant results achieved by INRIM during the last two years are the absolute frequency measurement of the Yb clock transition against the Cs fountain PFS, the experimental test (within an H2020 project named Demetra) of innovative time services assisted by Galileo time signals, the starting of the development of the Galileo Time Service Provider, the preliminary service to distribute time reference through optical fiber to industrial customers and the distribution of primary frequency reference to scientific users over optical fibers.

Primary frequency standard

Since 2013 INRIM is operating its cryogenic Cs fountain ITCsF2 to calibrate UTC(IT) master clock and TAI.

The accuracy budget of ITCsF2, was not changed significantly since its publication on Metrologia [Levi 2014], and is reported in the following table.

Physical effect	Bias (10^{-16})	Uncert. (10^{-16})
Zeeman effect	1087.7	0.8
Blackbody radiation	-1.45	0.12
Gravitational redshift	260.4	0.1
Microwave leakage	-1.2	1.4
DCP	-	0.2
2nd order cavity pulling	-	0.3
Background gas	-	0.5
Total Type B**		**1.7**
Atomic density (typical LD)*	-3.9	1.4
Total	**1341.6**	**2.2**

Table 1. ITCsF2 uncertainty budget during the period 57124-57139.

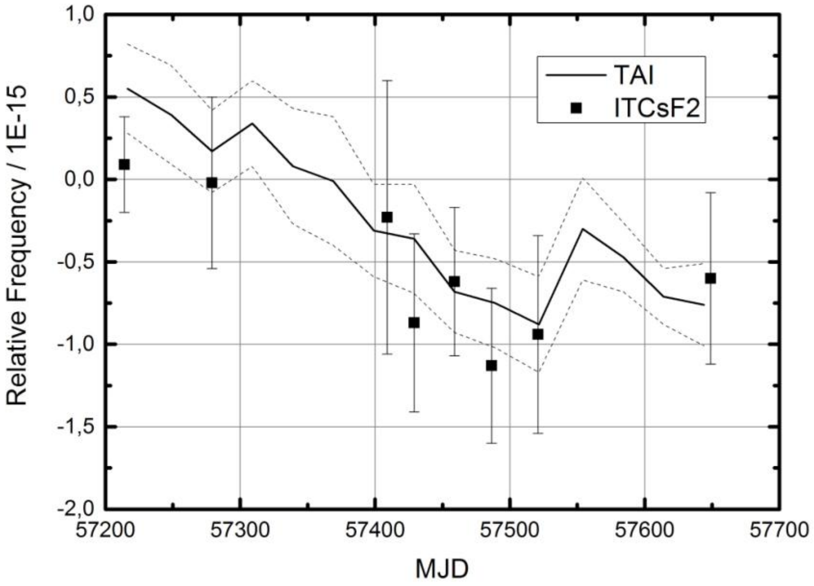

Figure 2: ITCsF2 vs TAI as reported in the BIPM circular T for the period 2015-2017.

Since 20th CCTF meeting (September 2015) ITCsF2 provided 8 TAI calibrations for a total measurement time of 200 days. The results of these calibrations are reported in figure 2. During 2016 ITCsF2 was also used to perform experimental measurements on the resonant light shift in Cs, providing an accurate measurement of the scalar and tensor light shift of the D2 transition of Cs. [Costanzo 2016]. The latter work is part of a larger study of the resonant light shift in hot and cold vapors in alkali atoms (Cs and Rb), performed in collaboration with Dr. J.C. Camparo of the Aerospace Corporation.

UTC(IT) generation

The generation of UTC(IT) time scale is currently carried out by means of an ensemble of 10 commercial atomic oscillators, namely six Cesium beam tubes (Symmetricom High Performance HP-5071A) and four Active Hydrogen Masers (#2 Symmetricom MHM-2010, #1 Kvartz CH1-75A and #1 T4Science iMaser3000). The physical realization of UTC(IT) is based on a 5 MHz signal provided by an Active Hydrogen Maser considered as Master Clock (MC), steered by a phase micro stepper (namely AOG), that automatically compensates the MC frequency offset and drift versus UTC. The steering parameters are evaluated basing on the monthly BIPM Circular T, as well as on the weekly UTC rapid solution, and the internal measures of all the INRIM clocks and frequency standards. In the following figure, the behavior of UTC(IT) is reported for the 2015-2017 period, with respect to UTC and rapid UTC.

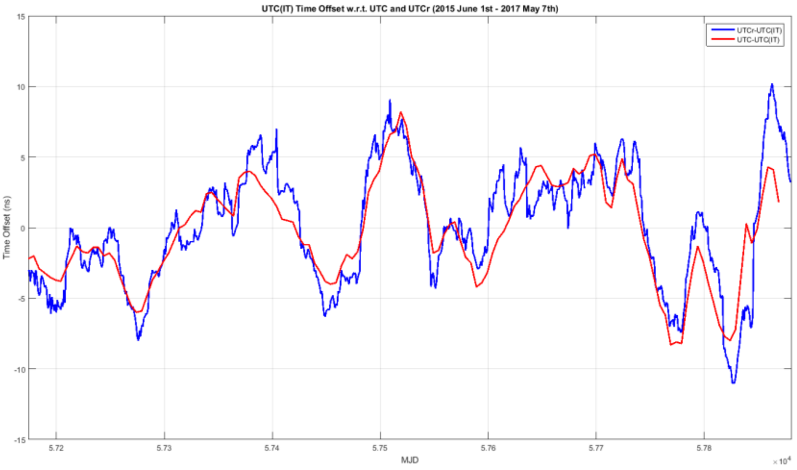

Figure 3: UTC(IT) vs UTC and UTCr time deviation, from BIPM estimates, for the 2015-2017 period.

In figure 4, the behavior of UTC(IT) vs UTCr is represented in comparison with a selection of other UTC(k) time scales for the same period (2015-2017). We can see that when UTCr is aligned to UTC there is a jump in the UTCr estimates which affects all the UTCr-UTC(k) deviations, and that can reach, in some cases, 5 ns

Figure 4 UTCr vs UTC(IT) and other UTC(k) time scales, for the 2015-2017 period

With the aim to increase the robustness and accuracy of the generation of UTC(IT), we are working on the realization of two parallel HW chains composed by different and independent H masers and micro stepper steering devices fed to a commuter (under realization) which will allow the commutation (automatic or manual) between the different chains, ensuring phase and frequency continuity. In addition, work is in progress to set up an automatic system evaluating the H maser steering corrections by three parallel independent techniques, namely versus the Cesium fountain ITCsF2, the UTC/UTCr, and the ensemble time obtained by the 10 INRIM commercial clocks, to be used as redundant and validated steering estimation, then fed to the micro steppers, on a daily basis.

The UTC(IT) time scale is continuously measured and monitored versus other UTC(k) time scales by means of time and frequency transfer techniques based on TWSTFT and GNSS. In particular INRIM operates 2 TWSTFT stations, 3 GNSS Timing receivers, and 7 GNSS dual frequency geodetic receivers for timing applications. INRIM's time scale UTC(IT) is compared every two hours with the time scales generated at ten European and two U.S. laboratories, by TWSTFT method. The two TWSTFT stations installed at INRIM are designated as IT01 and IT02. IT02 station is currently the master station used to officially contribute to UTC; this station is also used to compare UTC(IT) to the Galileo System Time generated at the two Precise Time Facilities (PTF) in the frame of the Galileo project. The second station, IT01, is currently used as back up.

The 10 INRIM GNSS (geodetic) receivers for timing applications are operated at INRIM "RadioNavigation Laboratory" (RNL), a Laboratory that is strongly complementary with respect to the INRIM Time Laboratory one, being it devoted at hosting the GNSS receiver aimed at remotely comparing atomic clocks and time scales, through geodetic devices and algorithms. This Laboratory is currently equipped with a permanent IGS/EUREF station (called IENG) connected to UTC(IT) and a GESS (Galileo Experimental Sensor Station, namely GIEN) connected to a free running H hydrogen maser. Other six GNSS (GPS+GLONASS+GALILEO+BEIDOU) geodetic receivers for timing applications, connected to atomic clocks/time scales, are operated aimed at supporting a wide range of international cooperation among NMIs and Geodetic Institution for the development of new geodetic methods for the remote comparison of atomic clocks and time scales, using the current GPS, but also the new ones, especially Galileo. These receivers are also providing data to same European projects aiming at validating the timing information transmitted by the Galileo system.

Optical frequency standards

In 2016, INRIM completed a laser cooled ^{171}Yb optical frequency standard, based on the doubly forbidden transition $^1S_0 \leftrightarrow ^3P_0$ clock transition (wavelength 578.4 nm) observed in an optical lattice tuned at the Stark shift-free wavelength (759 nm). Yb atoms are cooled in a double stage magneto-optical trap exploiting the Yb transitions $^1S_0 \leftrightarrow ^1P_1$ at 398.9 nm the $^1S_0 \leftrightarrow ^3P_1$ at 555.6 nm, then they are transferred in the lattice: some 1E4 atoms are currently loaded in the lattice at the end of the cooling cycle; the life-time of the trap is measured to be above 1 s. A single Rabi pulse at 578 nm is used to excite the clock transition. The detection stage consists in measuring the transition probability through the florescence of the $S_0 \leftrightarrow ^1P_1$ transition at 398.9 nm and a renormalization process that exploits the transition $^3P_0 \leftrightarrow ^3D_1$ at 1389 nm. The operation scheme is depicted in the Figure 5.

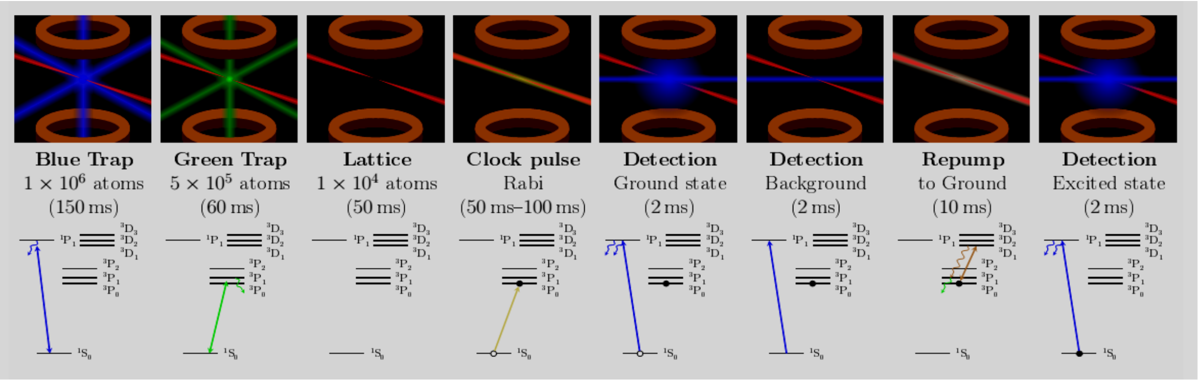

Figure 5: Yb clock cycle and atomic levels

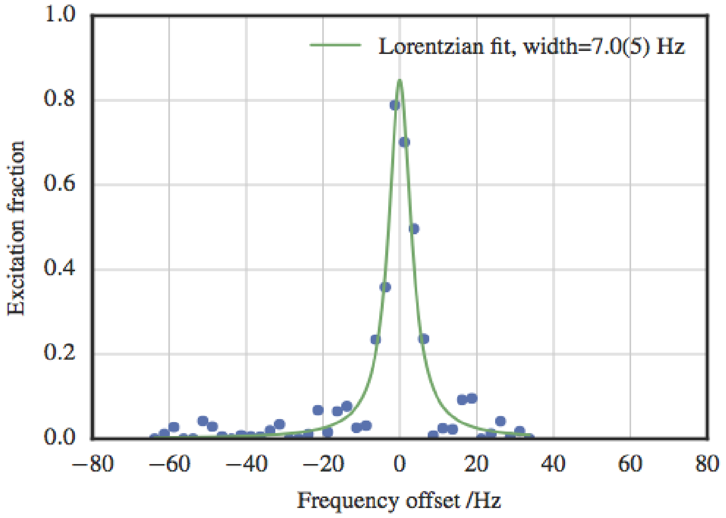

Figure 6: Yb clock transition spectroscopy

In Figure 6, the spectroscopic line of the clock transition is reported. The measured linewidth at half maximum is 7 Hz. The clock is typically operated alternating a spin-polarized atomic sample in the two $m_J = \pm 1/2$ state. The published accuracy of the standard is 1.6×10^{-16} [Pizzocaro, 2017], mainly limited by the short term instability of the clock laser. The evaluation is detailed in Table 2.

Effect	Bias $\times 10^{17}$	Unc. $\times 10^{17}$
Lattice polarizability	-4	8
Nonlinear lattice shifts	-12	10
Density shift	-2	6
Zeeman shift	-27	4
BBR room	-	2.5
BBR oven	235.3	0.8
Probe light shift	-2.1	3.5
Doppler shift	1	5
Background gas shift	-	1.5
Static stark shift	-	1
Servo error	-	1
Tunnelling	-	0.4
Line pulling	-	0.4
AOM switching	-	0.4
Fiber links	-	0.1
Total		16

Table 2. Uncertainty budget during the period 57124-57139

The absolute frequency of the Yb clock transition has been measured with respect to INRIM cryogenic fountain ITCsF2 and the value is:

$$\nu(\mathrm{Yb}) = 518\,295\,836\,590\,863.59(31)\ \mathrm{Hz},$$

that corresponds to a relative uncertainty of 5.9×10^{-16} limited mainly by the statistical uncertainty. In spring 2016, we compared INRIM Yb clock to a transportable Sr optical frequency standard from PTB [Grotti, 2017 submitted], reporting the frequency ratio between the two clock transition:

$$\nu(\mathrm{Yb})/\nu(\mathrm{Sr}) = 1.207\,507\,039\,343\,338\,41(34)$$

Optical fiber links

INRIM's has developed a large Italian optical fiber link infrastructure to disseminate time and frequency signals to highly qualified and demanding scientific and industrial users.

Figure 7: Italian optical fiber link.
The connections Torino-Modane and Torino-Bologna-Firenze are fully operative;
the link toward Roma, Napoli, Fucino and Matera is currently under development.

Two main tracks were developed and are now fully operative: the first one (150 km in hybrid DWDM-CWDM architecture) connects INRIM to LSM (Laboratorie Souterrain de Modane), a French laboratory located in the Frejus tunnel at the French-Italian border, that will be also used to connect INRIM to SYRTE. The second one (650 km in dark fiber and marginally hybrid-DWDM architecture) connects INRIM to the INAF radio-telescope in Medicina (near Bologna) and the scientific campus of Firenze University where is located the LENS (European Laboratory for Nonlinear Spectroscopy) and where important atomic and molecular spectroscopic experiments are operated. The extensions toward Rome, the Fucino space navigation centre and the geodetic space center of Matera is under development (being Firenze Roma almost operative).

INRIM demonstrated the dissemination of frequency signals with accuracy in the $5\text{x}10^{-19}$ range over 1300 km [9], doubling the INRIM-LENS. The instability of this link is shown in Figure 7.

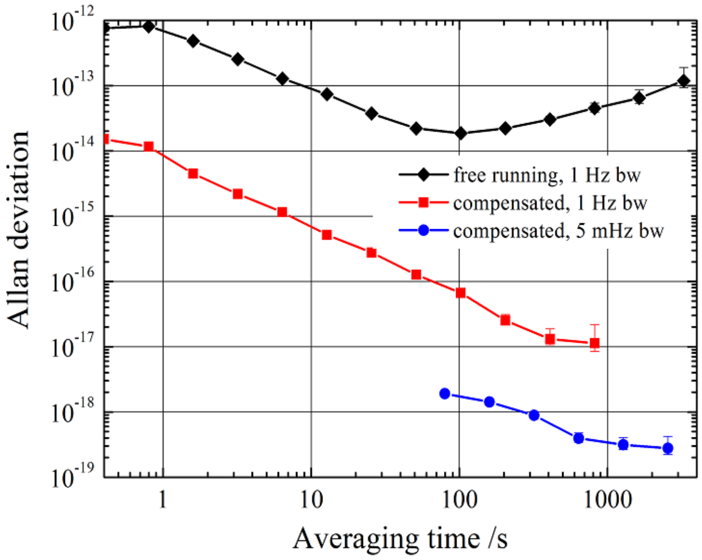

Figure 8 – Instability of the INRIM-LENS link.

Research activities were aimed to study different experimental schemes of the optical fiber link that can improve the stability of the frequency comparison and reduce the noise figure of the link itself. In particular two distinct techniques were theoretically and experimentally studied: the two way link and the post-process delay-change. [6,12]. Studies were also performed on the use of different type of bidirectional optical amplifiers (Raman and Brillouin) conducting field experiments and tests on real links. In particular was proved the possibility to use Raman amplification in a link, in DWDM architecture, with the simultaneous presence of internet data traffic.

The link INRIM-LSM was realized within the frame of EMRP-ITOC project, and provided a relativistic geodesy proof of principle in real field, comparing the frequency of a resident clock at INRIM with a transportable Sr clock in two different locations. In the experiment the clock sensitivity to the gravitational field was used to demonstrate that optical clocks are mature quantum sensors for relativity test and gravity sensors.

The link connecting INRIM to INAF is devoted to provide an absolute frequency reference to VLBI antenna that will result in improved measurement accuracy , and when optical clock will be available, also a much lower noise local oscillator opening to radio-astronomy new observation windows. In [Clivati, 2017] the first geodetic VLBI experiment using a remote H-Maser disseminated by a coherent optical fiber link is demonstrated. At LENS a number of high accuracy atomic and molecular experiments are performed that benefit from the accurate frequency reference delivered by INRIM. In [Clivati, 2017] a new measurement of ^{173}Yb clock transition frequency has been achieved, improving of four order of magnitude the previous value. In [Livi 2016] is reported an experiment of quantum simulation that has been enabled by the stabilization of the local laser via the fiber link.

The southern extension of the link will connect the Galileo Time Facility located in Fucino, providing to Galileo Time the possibility to have a direct comparison with UTC(IT) and a primary frequency standards. The link will then reach Matera where is located ASI's Space Geodesy Center.

Time dissemination

The current dissemination services freely provided from INRIM to the public is based mainly on the NTP (Network Time Protocol) system, having the Italian radio-television broadcaster (RAI) decided to stop the transmission of certified time signals at the end of 2016.

Time and frequency dissemination techniques as well as innovative timing servicers were tested in the frame of an Horizon 2020 project named DEMETRA (DEMonstrator of EGNSS services based on Time Reference Architecture), funded by the European Union. The project aimed to develop and test a demonstrator able to generate, distribute, and monitor several time services based on the European Global Navigation Satellite System (GNSS) and introducing important new features such as certified time stamping, improved accuracy, or integrity, redundancy and resilience, not yet provided by GNSS systems. The project started in January 2015, the demonstrator was assembled at INRIM premises by the end of February 2016, and it was tested with two validation test campaigns.

The Time Services were tested for 3 months in a Closed Loop configuration with the User Terminal located in the same premises of the Time Service Generator, therefore immediately verifying the capacity to transmit at user level the requested signals and information. Then the User Terminal were moved remotely at user location and they were continuously monitored by means of Key Performance Indicators based on appropriate measures, to test the real advantages and feasibility of the proposed time services in a user environment.

The aim of the project was also to meet different users community either by Demetra organized workshop or by attending international meeting, exhibitions, and forum with the aim to introduce Demetra services and to gather feedback from the users and stimulate new ideas. The Demetra activity were described and the experimentation results available on www.demetratime.eu which has received more than 4000 visitors. The project, ended in Dec 2016, gave some insights on the feasibility of innovative time services and prepared the terrain for different follow up activities from possible patents, to scientific collaborations, industrial developments and marketing opportunities.

Figure 9 – Demonstrator assembled and integrated in the DEMETRA Laboratory at INRIM, Italy

Preliminary services to provide time distribution along optical fibers have been implemented using the technique known as White Rabbit. In the figure hereafter reported the stability of the timing signal measured over several days is plotted, showing excellent performances well below 1 ns.

Within the H2020-Demetra project, we have established the dissemination of UTC(IT) using an optical fiber transfer, with the protocol known as White Rabbit, introduced by CERN and derived from the IEEE 1588v2 standard. We have now a permanent fiber link to disseminate UTC(IT) by optical fiber to the financial district in Milano (140 km away from Torino), where there is the location of the Italian stock exchange and the servers of the main financial stakeholders. Figure 10 shows a typical data run. The accuracy of the transfer has been measured with a GPS-PPP technique, limited by the GPS accuracy.

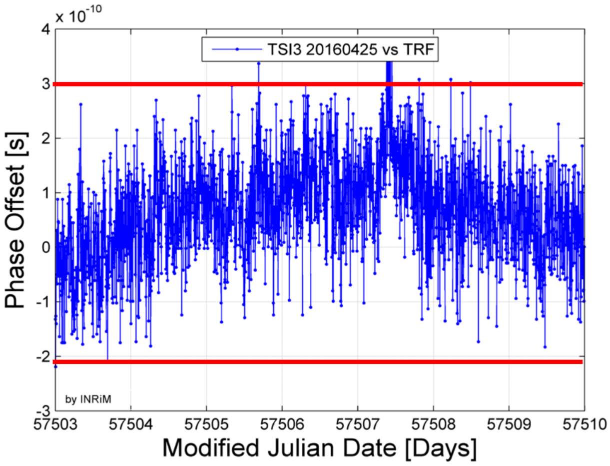

Figure 10 – Time offset between UTC(IT) and the user terminal after about the dedicated time transfer fiber link using the White Rabbit protocol. The link is dedicated to financial users.

INRIM contribution to Galileo GNSS

INRIM is deeply committed in the development of the European Global Navigation Satellite System Galileo in collaboration with other NMIs and industrial companies. In the last 15 years, INRIM was involved in nearly 30 projects.

The activities are mainly following two main streams:

1. Participation to the definition, realization, and validation of the Galileo timing system.

INRIM has been responsible of the validation of the Galileo space clocks and the whole timing system from the first experimental phases. Currently INRIM contributes to the MARTE project (Monitoring, Alerting, Reporting, and Troubleshooting) funded by ESA in collaboration with Thales Alenia Space Italy, for the characterization of the onboard clocks of the Galileo constellation and on the validation of the UTC and GGTO dissemination by the Galileo signal, in collaboration with ORB.

INRIM is also contributing to the validation of the timing parameters of the EGNOS system, in collaboration with the French Space Agency CNES, and currently collaborating to the Time and Geodetic Validation Facility lead by the Spanish GMV.

At the end of 2016 the contract for the development of the Galileo Time Service Provider was awarded to INRIM, in co-prime leadership with Thales Alenia Space France, by the EU GNSS Agency, in the frame of the Galileo System Operation contract. INRIM, in collaboration with PTB, OP, ROA, SP, and ORB, European industrial and academic institutions, will develop the Galileo facility aiming to provide the necessary information to maintain the Galileo time in close agreement with UTC and ensuring the UTC dissemination service at the highest level of accuracy.

2. Development and test of timing services based on the Galileo signals.

INRIM has started additionally activities developing and testing time services based on the Galileo signals.

In the frame of an ESA contract, from Sept 2015 till March 2016, the capability of time transfer of the Galileo signals, particularly based on the new Galileo transmission frequency and modulation, was tested under the coordination of ORB

The Horizon 2020 Demetra project described above, coordinated by INRIM, with 13 European partners, aimed to demonstrate the feasibility of delivering GNSS improved timing services to end users. The project aimed also to stimulate the discussion in Europe on the necessity to synchronize the critical infrastructures basing on common standardized time services, also based on the European GNSS.

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