Intrinsic GNSS Metrological Time Traceability to UTC

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***Abstract*—In many documents describing Global Navigation Satellite System (GNSS) features at user level, the wording "traceability to UTC" appears, UTC being the Coordinated Universal Time computed monthly by the Bureau International des Poids et Mesures (BIPM). This should be read as "metrological traceability to UTC", but it implies numerous requirements. We propose to discuss what would be an intrinsic time traceability to UTC by using a GNSS signal according to metrological rules. After a reminder of what these metrological rules are, we describe and analyze in a generic approach the relationship to UTC of a user time scale through GNSS. We provide a more detailed analysis of two examples from European GNSS. First with the European Geostationary Navigation Overlay Service (EGNOS), whose relationship to UTC is based on an Earth station located in Observatoire de Paris (OP) and connected to UTC(OP), the local realization of UTC. Second with Galileo, whose relationship to UTC is based on time transfer between the Galileo Precise Time Facilities (PTF), where Galileo System Time (GST) is generated, and five European National Metrology Institutes (NMI) or Designated Institutes (DI) providing UTC(k), the local realizations of UTC.**

Keywords—GNSS; Traceability to UTC; Metrological traceability

I. Introduction

In many documents or websites describing Global Navigation Satellite System (GNSS) features at user level, the wording "traceability to UTC" appears, UTC being the Coordinated Universal Time computed monthly by the Bureau International des Poids et Mesures (BIPM) and published in Circular T [1]. In the time metrology world, this should be read as "metrological traceability to UTC", but this implies numerous requirements. In this paper, we propose to discuss what would be required to provide an intrinsic GNSS metrological traceability to UTC at user level. UTC not being available in real-time, this implies access to a realization of UTC according to metrological rules without using any other data but the user GNSS local measurements.

We propose first a comprehensive reminder of all the formal requirements to be fulfilled to achieve a metrological traceability to the international system of units (SI). When applied to time metrology, some specific elements are required to obtain traceability to UTC. We then describe in a generic approach the way a GNSS relates its time scale to UTC, and how a user can determine from the GNSS signal the relationship between his own time scale and UTC. The next step is to discuss a qualitative analysis of what would be required to ensure intrinsic time traceability to UTC in this generic approach according to the metrological rules.

Furthermore, we provide an analysis of two examples from European GNSS. First with the European Geostationary Navigation Overlay Service (EGNOS), whose relationship to UTC is based on an Earth station located in Observatoire de Paris (OP) and connected to the local realization of UTC UTC(OP) [2,3]. Second with Galileo, whose relationship to UTC is based on time transfer between the Galileo Precise Time Facilities (PTF), where Galileo System Time (GST) is generated, and five European National Metrology Institutes (NMI) or Designated Institutes (DI) providing local realizations UTC(k) of UTC [4]. These five partners are: the OP laboratory Systèmes de référence Temps-Espace (SYRTE) designated by the French NMI Laboratoire National de Métrologie et d'Essais (LNE); the Italian Istituto Nazionale di Riserca Metrologica (INRIM); the German Physikalisch Technische Bundesanstalt (PTB); the Spanish laboratory Real Oservatorio de la Armada (ROA); and the Research Institute of Sweden (RISE).

II. Reminders

A. The Generic Metrological Traceability Rules

The International vocabulary of metrology (VIM) reference document provides a definition of "metrological traceability" to a given reference [5]: it is the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty". Here, the "reference" can be a measurement unit through its practical realization, and the computation of a chain of calibrations might require a calibration hierarchy [5, Section 2.40]. In the case when more than one input quantity is included in the measurement model, each of the input quantity values should itself be metrologically traceable.

The International Telecommunication Union – Radiocommunication sector (ITU-R) adopted the following definition [6]: "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through

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an unbroken chain of comparisons all having stated uncertainties".

The International Laboratory Accreditation Conference (ILAC) adopted the same definition as in the VIM and refers to both the VIM and the ISO/IEC 17025 standard [7]. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) gave additional information on establishing and demonstrating metrological traceability [8], while referring to CIPM-MRA, ILAC and the joint BIPM, the International Organization of Legal Metrology (OIML), ILAC and ISO declaration on metrological traceability. The additional recommendations from these bodies are that the required calibrations should be carried out by National Metrology Institutes (NMI) or Designated Institutes (DI) participating in the CIPM-MRA and having their Calibration and measurement capabilities (CMC) published in the relevant area of the Key comparison database (KCDB) maintained by the BIPM [9]. In any case, results of the measurements made in an accredited laboratory guarantee traceability to the SI.

B. *The Mutual Recognition Arrangement*

The participants in the CIPM MRA are NMI, DI and International Organizations [10]. This implies that these bodies have built a Quality management system (QMS) around their declared CMCs, which is assessed by dedicated formal review and agreed at the Regional metrology organization (RMO) level. Fig.1 provides a world map of the current RMO. In addition, each NMI/DI has to declare its CMCs, which are peer reviewed and approved before being included in the BIPM KCDB.

Fig.1. World map of RMO. From left to right: Inter-American Metrology System (SIM) for the Americas, European Association of Metrology Institutes (EURAMET) for Europe, Intra-Africa Metrology System (AFRIMET) for Africa, Gulf Association for Metrology (GULFMET) for Middle-East, Euro-Asian Cooperation of National Metrological Institutions (COOMET) for Eastern Europe, and Asia Pacific Metrology Program (APMP) for Asian Pacific region [Source: BIPM].

C. *The Time Metrology Domain*

There is only one CCTF key comparison in the time metrology domain: CCTF-K001.UTC [11]. The key comparison reference value is the Coordinated Universal Time (UTC), which is a deferred-time paper time scale computed monthly by BIPM from an ensemble of about 400 atomic standards disseminated over the world. The UTC(k) generated by timing centres are realizations of the reference. In this frame, the metrological traceability to UTC is ensured for UTC(k) time scales generated by NMIs or DIs participating in the CIPM MRA, having degrees of equivalence UTC – UTC(k) published in the BIPM KCDB, and/or having CMCs published in the BIPM KCDB. Generally, these institutes have developed a QMS according to the ISO/IEC 17025 standard, a framework guaranteeing the traceability of measurements to the SI.

III. Generic Approach for GNSS Time Traceability

A. *Generic Model Between UTC and a User Time Scale*

When considering the GNSS signal, we propose to distinguish the so-called "unbroken chain" into three different parts. The first part takes place in the GNSS ground segment. This is where the common GNSS time scale (GTS) is generated from an ensemble of clocks which are located on the ground, possibly also including satellite clocks, whose offsets to this GTS are needed for the functioning of the GNSS. It is also here that the offset between this GTS and an appropriate prediction of UTC is computed. These are some of the parameters which are part of the navigation message prepared on the ground and uploaded to satellites. The second part we consider is related to the GNSS space segment. Indeed the offset of each satellite clock against GTS must be part of the navigation message. The proper transmission of the navigation message on the GNSS carrier frequencies is required. The third part concerns the user segment, where the correct operation of the GNSS station should be validated, including when required a suitable connection to a local time scale or oscillator.

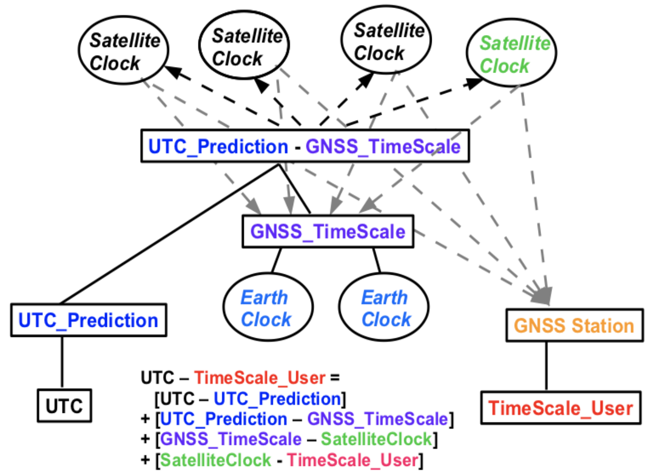

Fig.2. Generic description of the different offsets to be considered in the computation of the relationship between a user time scale and UTC. The GNSS control segment must relate the GTS to a prediction of UTC, and the offset between both is part of the navigation message uploaded to the satellites. The offset between each satellite clock and GTS is also monitored and transmitted to users. At user level, the GNSS station dates the epoch of arrival of the satellite signal with respect to the local time scale. The navigation message provides the parameters required to compute all lines of this equation up to the UTC_Prediction used by the system. The offset to UTC is granted by the NMI generating the prediction of UTC.

Fig. 2 shows a description of these different parts, where the relationship between the prediction of UTC used by the GNSS and UTC is also added. A simple model for the computation of the offset between UTC and a user time scale might be as follows, with self-explaining notations.

UTC – TimeScale_User = [UTC – UTC_Prediction]

+ [UTC_Prediction – GTS]

+ [GTS – SatelliteClock]

+ [SatelliteClock – TimeScale_User]

B. Analysis of the Unbroken Chain of Calibrations

The NMI generating the realization of UTC which is used for computing a prediction of UTC has to provide the metrological traceability to UTC. The UTC – UTC_Prediction offset must be based on one (or more) NMIs participating to the CIPM MRA, with RMO assessed QMS and peer reviewed CMC, having degrees of equivalence UTC – UTC(k) published in the BIPM KCDB.

The offset between GTS and such a prediction of UTC is computed by the GNSS operator, either by including such a UTC_Prediction in the ensemble time scale computation of GTS, or by achieving proper time transfer between the GNSS ground station where GTS is generated and the laboratory generating the prediction of UTC. In both cases, an uncertainty given by an adequate calibration should be estimated. In addition, the GNSS operator also monitors the offset between each satellite clock and GTS. This can be either obtained by including the satellite clocks in the GTS ensemble time scale, or it can be measured by other GNSS operator means. Here too, an uncertainty of this offset must be estimated. The unbroken chain of calibrations must be documented. Note that the Signal in Space (SiS) transmission is where the responsibility of the GNSS operator stops from metrological traceability point of view.

And finally, the user must operate a proper GNSS station, able to collect GNSS data, first by measurement of the epoch of arrival of the satellite signal with respect to the user local time scale, which might be internal or external to the station, and second by properly decoding the navigation message which contains not only the time parameters relating the satellite clock to GTS and GTS to UTC_Prediction, but also all other parameters which have to be taken into account in this kind of measurement based on a pseudo-range time offset: satellite ephemeris, ionospheric and tropospheric models and parameters, epoch of signal transmission in the satellite clock time scale, etc. Here too, the impact of all these parameters on the delay measurements should be estimated together with the relevant uncertainty.

On the GNSS operator side, an assessment of the documented unbroken chain of calibrations must be achieved by RMO or NMI/DI representatives or by an accredited body, with confidentiality granted. The ability of the user station to carry out all required computations should also be proven. It can either be the responsibility of the GNSS station manufacturer to prove the unbroken chain, provided the metrological measurements are resulting from an assessment of an accreditation. Or it might be the responsibility of the user to validate the unbroken chain for this part of the measurements.

IV. EGNOS

Fig. 3 shows a diagram of the timing aspects of the EGNOS system implementation. EGNOS Network Time (ENT) is an ensemble time scale based on atomic standards located in Earth stations called Ranging and Integrity Monitoring Stations (RIMS), disseminated all over Europe and abroad, which are continuously compared to each other by Global Positioning System (GPS) time transfer in an automated way [3]. One of these RIMS, the RIMS-PAR, is located in OP. It is not used for the computation of the EGNOS navigation parameters, it is only aiming at relating ENT to UTC through UTC(OP). The RIMS-PAR source signal is UTC(OP), which is then included in the ENT generation, allowing the computation of ENT – UTC(OP) as an output. This parameter is part of the navigation message of the EGNOS signal which is broadcast to dedicated telecommunication satellites, and transmitted to users over a ground area centered on Europe. A user station, whose receiver is qualified for EGNOS signals, must collect the EGNOS signals and decode the EGNOS navigation message to relate its local time scale to UTC(OP) via ENT.

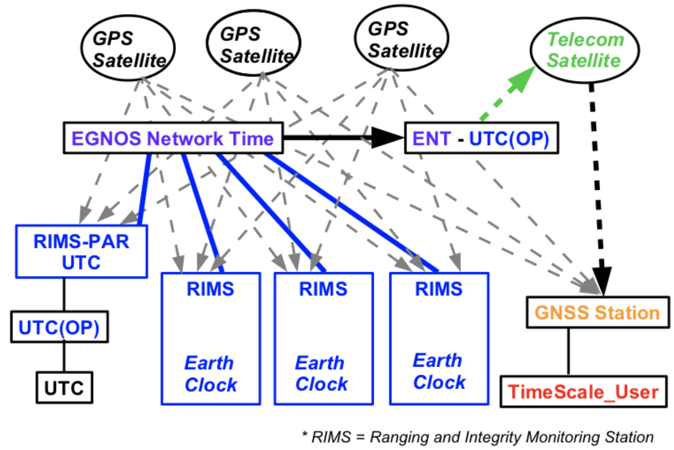

Fig.3. Block diagram of the timing aspects of the EGNOS system. ENT is a common ensemble time scale based on atomic clocks located inside each RIMS, RIMS-PAR allowing to relate ENT to UTC(OP) hence to UTC. The parameter ENT – UTC(OP) is part of the EGNOS navigation message transmitted to users, which an EGNOS qualified station can collect and decode to relate its own time scale to UTC(OP).

The LNE-SYRTE in OP is fully compliant with the metrology requirements leading to the presence of UTC – UTC(OP) degree of equivalence in the BIPM KCDB. Therefore the EGNOS operator needs to document and to validate an unbroken chain of calibration composed of first the output ENT – UTC(OP) of the ensemble time scale and second the transmission of this parameter inside the navigation message available on the EGNOS carrier. This should be formally assessed by an NMI representative or by a relevant accredited body. It should include a validation of the generation of the signal transmitted to users and of the navigation message content. We note that [3] states the requirement that the offset between ENT and UTC should be less than 50 ns (5 σ). However the information provided in [3] is mostly technical, hence not sufficient to fully qualify the metrological traceability of ENT to UTC: a formal assessment of the unbroken chain of calibrations according to the metrological rules should be obtained.

V. GALILEO

Fig. 4 shows a diagram of the timing aspects of the Galileo system implementation. The Galileo reference time scale, Galileo System Time (GST), is generated in the two Precise Time Facilities (PTF) of the Galileo Control Centers (GCC) with full redundancy. Time transfer by Two-Way Satellite Time and Frequency Transfer (TWSTFT) and by GPS Common-Views (CV) is implemented between GST and five UTC(k)s made available by the following NMIs or DIs: LNE-SYRTE in OP, where UTC(OP) is generated, INRIM, where UTC(IT) is generated, PTB, where UTC(PTB) is generated, ROA, where UTC(ROA) is generated, and RISE, where UTC(SP) is generated [4]. All five institutes are fully compliant with the metrology requirements leading to the inclusion of all five UTC(k) in the BIPM KCDB. From these time transfer data, a mean offset between GST and a prediction of UTC is computed by the Time Service Provider (TSP), this offset becoming part of the Galileo signal navigation message. The monitoring of the satellite clocks is also done by the GCCs, and the offset between GST and each satellite clock is also part of the Galileo signal navigation message uploaded to each satellite to be transmitted to users. At user level, the GNSS station measures the epoch of arrival of the satellite signal with respect to the user local time scale, which might be internal or external to the station, and decodes the navigation message which contains not only the time parameters relating the satellite clock to GST and GST to UTC_Prediction, but also all other parameters which have to be taken into account in this pseudo-range time offset measurement: precise satellite ephemeris, ionospheric and tropospheric models and parameters, epoch of signal transmission in the satellite clock time scale, etc.

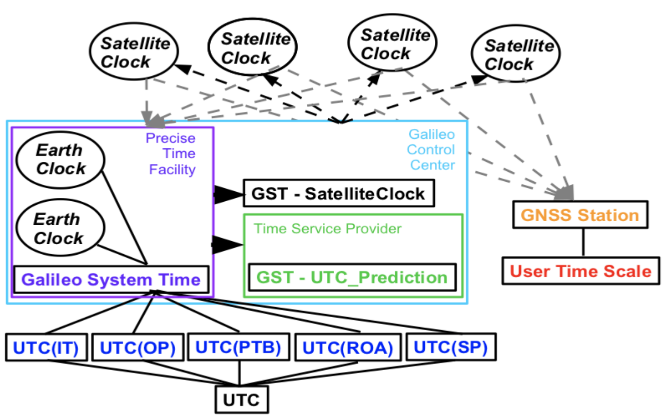

Fig.4. Block diagram of the timing aspects of the Galileo system. A fully redundant GST is generated in each PTF, and compared to five UTC(k) by time transfer. From these comparisons, an offset between GST and a prediction of UTC is computed, and this parameter is part of the navigation message uploaded to satellites, together with the offset between GST and each satellite clock. The user GNSS station allows for dating the epoch of arrival of the satellite signal with respect to its local time scale and for collecting Galileo data, in order to relate its local time scale to the satellite clock, then the satellite clock to GST, and to the Galileo prediction of UTC.

The first step for providing metrological traceability to UTC through Galileo signal should be to document the unbroken chain of calibrations in the computation of the offset between GST and the prediction of UTC which is part of the Galileo signal navigation message. A similar documentation should be provided for the offset between GST and each satellite clock, but also for other parameters used for the computation of the pseudo-range measurements at user level. This unbroken chain of calibrations should be validated by a formal assessment by an NMI representative or by an accredited body. Here too, the responsibility of the Galileo operator from metrological traceability point of view stops where the SiS is transmitted.

At user level, the GNSS station is supposed to measure the epoch of arrival of the Galileo signal with respect to its local time scale, either internal or external. Its ability to collect and properly decode the Galileo navigation message should be proven within a given uncertainty. A proper document describing the unbroken chain of calibrations should be released by the manufacturer, and assessed by an accredited body. When a local time scale outside the GNSS station is the reference, either an external accredited body or the user themselves should also assess and prove the metrological relationship between the GNSS data and the local time scale reference point.

VI. CONCLUSION

GNSS intrinsic metrological traceability to UTC has not been fully addressed yet. It can only be achieved by following the required metrological rules. GNSS operators are in charge of all steps between the relevant prediction of UTC, provided by one or more NMI ensuring the metrological traceability to UTC, up to the SiS transmitted by each satellite. Here, the unbroken chain of calibrations can be proven and assessed by an NMI following BIPM, OIML, ILAC, ISO and IEC recommendations, or by an accredited body. At user level, other requirements depend on GNSS station manufacturers, because the unbroken chain of calibrations must be assessed here too, and on ties with the local time scale, either internal or external to the station.

We consider that EGNOS already has most of the ingredients necessary for achieving metrological traceability to UTC via UTC(OP). UTC(OP) is provided by LNE-SYRTE, which fulfills all the metrological requirements as UTC – UTC(OP) is included in KCDB, UTC(OP) is included in ENT computation, and the offset between ENT and UTC(OP) is part of the EGNOS navigation message. What is missing is a formal assessment of this computation with an estimated uncertainty, and of the proper generation and transmission of the EGNOS signal to users, which should be achieved by an accredited body with confidentiality granted. The prediction of UTC used by Galileo is based on five UTC(k)s which all fulfill the metrological requirements and are included in KCDB. However there is more work to be done in terms of technical documentation of the unbroken chain together with the proper assessment of the relevant calibrations with estimated uncertainties. In both cases, the user local station should also be properly assessed.

What is described in this paper is an approach to achieving traceability of the time information broadcast by a GNSS system, providing two examples for EGNOS and Galileo, in such a way that no performance quantities outside the GNSS signal requirements have to be validated. Of course, a similar analysis might be achieved for other GNSS like either GPS, or GLONASS, BeiDou, etc. This is complementary to approaches which make use of additional data, such as direct measurement of the SiS GTS by an NMI/DI. The metrological access to UTC via GNSS signals is nevertheless considered today as a hot topic, and the CCTF has established a Task Group from CCTF Working Groups on GNSS and on MRA. The expected output of this Task Group will be a White Paper on the subject, to be released in 2022.

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Acronym List

BIPM: Bureau International des Poids et Mesures

CIPM: Comité International des Poids et Mesures

CMC: Calibration and Measurement Capabilities

EGNOS: European Geostationary Navigation Overlay Service

GLONASS: Russian GNSS

GNSS: Global Navigation Satellite System

GPS: USA GNSS

IEC: International Electrotechnical Committee

ILAC: International Laboratory Accreditation Cooperation

INRIM: Istituto Nazionale di Riserca Metrologica, Italian NMI

ISO: International Standard Organization

KCDB: Key Comparison Database

LNE: Laboratoire National de Métrologie et d'Essais, French NMI

LNE-SYRTE: French Designated Institute for time and frequency metrology

MRA: Mutual Recognition Arrangement

NMI: National Metrology Institute

OIML: Organisation Internationale de Métrologie Légale

OP: Observatoire de Paris

PTB: Physikalisch Technisches Bundesanstalt, German NMI

RISE: Research Institute of Sweden, Sweden NMI

RIMS: Ranging and Integrity Monitoring Station

ROA: Real Oservatorio de la Armada, Spanish Designated Institute for time metrology

SYRTE: Système de Références Temps-Espace, OP laboratory

UTC: Coordinated Universal Time

UTC(k): Real-time realization of UTC by laboratory or institution or country k