UTC and Galileo Time Services: a Report from the Galileosat Working Group on the Galileo Time Interface

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on behalf of the Working Group

BIOGRAPHY

Patrizia Tavella received the degree in Physics from the University of Torino and PhD degree in Metrology (1992) from the Politecnico of Torino, Italy. She is now with the Istituto Elettrotecnico Nazionale, Torino, Italy. Her main interests are mathematical and statistical models mostly applied to atomic time scale algorithms and to the uncertainty evaluation of atomic clock measurements, also in collaboration with the BIPM, Sevres, France.

John Laverty is Head of the Time & Ultrafast Team at the National Physical Laboratory. The Team's responsibilities include the maintenance of the UK national time standard, the development of primary frequency standards, dissemination of time and frequency standards through the MSF 60 kHz transmissions, knowledge transfer activities, and the development of satellite-based time transfer methods. Before joining NPL in April 1996, John worked in the Operational Instrumentation Division of the Meteorological Office. He holds a Ph.D. in experimental physics from Imperial College, London and a BA in Natural Sciences from the University of Cambridge.

Jörg H. Hahn received his M.Sc. in Physics and Mathematics from the Belorussian State University, Minsk in 1993 and his Ph.D. in Engineering Sciences from the University FAF, Munich in 1999. In the past years he worked with DLR Oberpaffenhofen in the navigation section where he specialised in clock synchronisation aspects before he joint ESA/ESTEC's Galileo Project Division as a Navigation Systems Engineer in April 2000. Here he is involved in all the related activities of the system engineering section of the Galileo Project Office.

ABSTRACT

This paper describes the work of a group of 13 European timing specialists who reviewed the baseline design for Galileo's timing system between July 2000 and February 2001.

Note: the content of this paper was also presented at the European Frequency and Time Forum (EFTF) held in Neuchatel, Switzerland, in March 2001

BACKGROUND

Galileo is a Global Satellite Navigation System to be designed, built and operated by European industry and institutions. The Galileo Programme completed its Definition Phase during 2000 and early 2001, during which a number of studies were undertaken to investigate user requirements and design issues in detail. One of the main studies, organised by the European Space Agency (ESA), was the GalileoSat Programme for the design, development and in-orbit validation of the Galileo space and related ground segment. With the GalileoSat Definition Phase study underway, ESA invited the leading European organisations involved in time-keeping to participate in a new Working Group to review particular timing aspects of the GalileoSat design. Nearly fifty representatives attended a meeting at ESTEC on 29 June 2000, with a core of thirteen representatives agreeing to actively participate in the new GalileoSat Working Group on the Galileo Time Interface (abbreviated to "WG" for short).

The working group

The baseline for the timing aspects of GalileoSat design had already been fixed at the time the WG was formed on 29 June 2000 [1]. In this context, the objectives set for the WG were to review the baseline definition, and to make recommendations to the GalileoSat Programme, through ESA, on the timing aspects of the system. The WG members are listed in the Box below. Most of the work was carried out by correspondence, with some additional meetings at ESTEC to allow participants to debate the issues more freely. Those meetings enabled ESA and the relevant experts from the Galileo Industries to provide news and comments from the GalileoSat developments. The WG presented its initial observations and recommendations to ESA on 14 September 2000. The Working Group activities were then extended to the end of February 2001, and this paper presents a summary of the WG's findings [2].

Members of the Working Group

John Laverty (NPL/Chair), Patrizia Tavella (IEN/Co-Chair), Andreas Bauch (PTB), Michel Brunet (CNES), Jon Clarke (NPL), John Davis (NPL), Gregor Dudle (METAS), Jan Johannsen (SP), Gerrit de Jong (VSL), Gerard Petit (BIPM), Wolfgang Schäfer (Timetech), Pierre Uhrich (BNM-LPTF), and Jörg Hahn (ESA).

GalileoSat Baseline Design

The brief description of the GalileoSat Baseline Design given here is based on information provided to the WG during the GalileoSat Definition Phase. However, it should be noted that the GalileoSat design was evolving during the lifetime of this WG, and hence this description is intended as a guide to the main timing elements anticipated in the system. It is not a definitive statement on GalileoSat's architecture.

The Orbit Determination and Time Synchronisation (OD&TS) architecture is expected to consist of :

- 30 x Galileo Space Vehicles, each with 2 passive hydrogen masers (PHM) and 2 rubidium atomic frequency standards (RAFS)
- 12 Orbitography and Synchronisation Stations (OSS) (+3 for redundancy, 1 at each PTS, 1 at UTC(k) lab)
- 2 Orbitography and Synchronisation Processing Facilities (OSPF)
- 2 Precise Timing Stations (PTS)
- UTC interface

The Precise Timing Stations (PTS) each include two active hydrogen masers and twelve high-performance caesium clocks. The Orbitography and Synchronisation Stations (OSS) are based on rubidium clocks, measure one-way pseudo-ranges and transmit that data to the Orbitography and Synchronisation Processing Facility (OSPF). An OSS is co-located in each PTS and in at least one UTC(k) laboratory. The Orbitography and Synchronisation Processing Facilities collect pseudo-range measurements from the OSS and calculate orbits and synchronisation parameters. The OSPF calculates Galileo System Time (GST) as part of the OD&TS process. In addition to the Baseline Design, it is clear that many of these ideas will be tested as part of a Galileo System Test Bed (GSTB) during the next Development Phase.

BENCHMARKS FOR GALILEO TIMING SERVICES

The Benchmarks Set by GPS

GPS occupies a dominant position in the timing market because of its global coverage, high accuracy and the relatively low cost and availability of GPS timing receivers. If Galileo is to succeed in this environment, it will have to complement GPS both in terms of technical performance and in terms of price. The most likely route to market success is probably through joint GPS/Galileo timing products in applications that value redundancy such as telecommunication networks, power generation/distribution, and digital broadcasting. The dependence on the world's economy on the reliable delivery of these services is enormous. Such receivers are then likely to be taken up in other applications such as frequency calibration and time-tagging.

The most demanding commercial applications at present are probably Primary Reference Clocks (PRC) for telecommunications networks (10^{-11} normalised frequency offset relative to UTC [3]) and time-stamping for fault location in power networks (1 microsecond accuracy required to locate faults to the nearest 300m [4]). While the accuracy requirements for time-tagging are, in general, not severe (1 ms for network time protocol servers in computer networks to about 1 s for a wide range of every day activities) the demands for frequency calibration do approach 10^{-13} as relative value.

The argument for joint GPS/Galileo timing products assumes that:

Galileo will operate independently of GPS

Galileo will be inter-operable with GPS

Galileo's timing performance will be comparable with GPS

Independence is required for the redundancy. Inter-operability is needed to reduce costs in the user segment, as is the timing performance.

In considering the relationship between Galileo and GPS is vital to recognise that GPS will improve during Galileo's lifetime [5]. If Galileo aims at parity with GPS today, it will almost certainly be behind GPS when it reaches its operational state. The removal of Selective Availability from GPS at the beginning of May 2000 was just a first step in the modernisation process. Further improvements in GPS are anticipated such as new down-link frequencies for improved ionosphere delay corrections and cycle ambiguity resolution.

Galileo: Some Target Specifications

In order to gain acceptance, Galileo needs to provide the key outputs needed by timing users at the right performance levels, and to help those users by specify its performance in a clear and user-friendly format. In terms of *what* to provide, Galileo should provide the user with both the civil time standard Coordinated Universal Time (UTC) and International Atomic Time (TAI) for those applications where a continuous time scale is required (i.e. avoiding leap seconds in UTC).

The Working Group identified the parameters listed in Table 1 as targets for the Galileo's timing services. An initial target accuracy of 33 ns (2σ) on the knowledge of the GST – TAI time offset is recommended in order to approach the GPS performance. The figure of 50 ns for the offset of GST from TAI is based partly on the CCDS recommendations for UTC(k) performance [Ref.6] and partly on what is observed for GPS: in other words, it is a guide for Galileo as to the performance of comparable time systems. **Note that Table 1 identifies target specifications that are appropriate for Galileo today,**

but that further improvement is expected from GPS in the next decade. Galileo should identify a way of updating its specifications in the light of actual system performance. We would expect the performance of Galileo to improve with operating experience, and it would be easier to "sell" Galileo solutions if the published specifications are as stringent as can be safely achieved.

GST-TAI	Specification
Uncertainty, Time Offset	33 ns (2σ)
Uncertainty, Normalised Frequency Offset *(one day averaging time)*	$5.5 \text{ x } 10^{-14} (2\sigma)$
Limits, Time Offset *(95% of time over any yearly time interval)*	50 ns

TABLE 1
The Working Group's recommended target specifications for the Galileo timing services.

Source	Uncertainty budgets: time transfer against UTC over 24 hours using stand-alone GPS, 2σ (ns)		
	GPS today with receiver calibration limitations.	GPS today: improved receiver calibrations	Estimate for GPS in 5-10 years
Signal-in-space (SIS)			
Ephemeris	8	8	4
Ionosphere	16	16	2
Troposphere	2	2	2
Multipath, random	6	6	2
Satellite clock	7	7	7
Broadcast UTC(USNO) offset	2	2	2
Stability of UTC(USNO)	14	14	14
Total for SIS	25	25	17
User segment			
Antenna co-ordinates	4	4	2
Receiver noise	2	2	2
Receiver calibration	60	12	6
Total for SIS & user segment	65	28	18

TABLE 2
Uncertainty budgets for stand-alone GPS time transfer (see [2] for more explanation).

In addition, the WG believes that the specifications for Galileo should be written in a user friendly format, using the metrics adopted in the major time markets, and over averaging times that reflect the interests of the main user groups. In practice, this would mean the main metrological parameters (ADEV, MDEV, TDEV, etc.) and those for telecommunications (TIE, MTIE, etc.), as well as time and frequency uncertainties. Standard statistical reference should be used in specifying uncertainties (e.g. 95% confidence intervals). The specifications should be explicit about the operating modes under which these specifications can be met (e.g. elevation angles, etc.) and choose conditions that are meaningful to the main user groups. Given that the averaging time is a key parameter, it would be extremely helpful to manufacturers and users if Galileo could quantify the stability of the timing signals at averaging times from 1 s to 1 month, at increasing decade intervals. Note that these more detailed specifications would have to be developed as part of further studies based on user requirements.

GPS Example: Stand-alone Use

Uncertainty budgets for the timing output of a stand-alone GPS receiver against UTC, with 24 hour averaging are shown in Table 2. This example was chosen because inexpensive receivers (costing ~ €300) measuring only the C/A-code on a single frequency with a patch antenna are widely used. The best accuracy is achieved with the receiver using fixed co-ordinates and only calculating the time, as opposed to doing a combined time and position solution at each epoch. The table gives results for three scenarios:

Estimates based on the current GPS constellation and with current knowledge of the receiver calibration uncertainties;

Estimates based on the current GPS constellation following improvements in receiver calibration procedures;

Estimates of the uncertainty that may be obtained in 5-10 years following GPS modernisation.

The improvements in receiver calibrations assumes that better data will be available for delay variations in UTC time transfer links, while the most significant of many improvements promised by the GPS modernisation process will be dual frequencies for civilian use enabling more accurate ionosphere corrections.

THE GST-UTC INTERFACE

Generation of Galileo System Time

The WG's view of Galileo System Time (GST) and the Galileo - UTC interface takes account of the need for the Galileo system operators to develop their knowledge and skills in running a state-of-the-art time scale, and the mutual benefit of sharing clocks between the two time scales. Also it recognises the potential for improving the stability of the Galileo time scale by using measurements of the most stable clocks from UTC(k) laboratories including, if appropriate, primary frequency standards and cold atom clocks (anticipating similar developments underway at USNO which would benefit GPS). The WG see the GST generation happening in three stages, as illustrated in Figure 1.

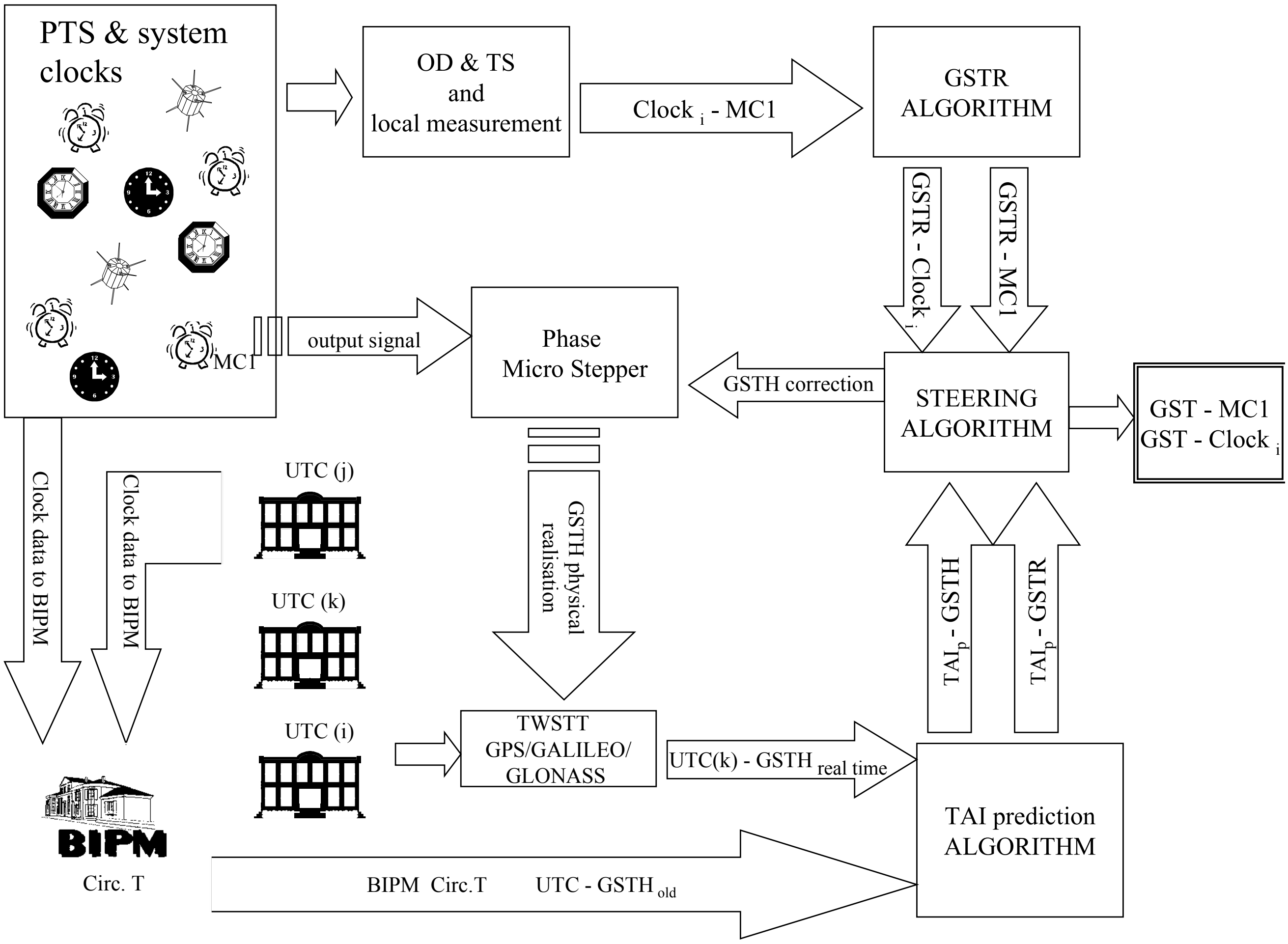

FIGURE 1: Schematic diagram of showing the proposed GST –UTC interface

A free-running time scale, GSTR, is generated from the PTS clocks and GST is generated from GSTR by applying a rate correction. A physical realization of GST called GSTH (hardware) is provided at one PTS, with a second realization at the other PTS which acts as a hot spare.

The rate difference between GST and GSTR is updated at regular intervals (e.g. daily) so that GST is steered to a *prediction* of TAI (denoted here "TAIp") in the medium-term. A maximum correction step not to degrade GSTR stability has to be fixed;
Through TAIp, GST is designed to track TAI in the long-term (month).

We emphasise the need for a physical reference point providing the realization of GST. This is required for two main purposes: validation of the equipment calibration through delay measurements with respect to any other system; and determination of the differences GST-TAI through UTC(k) and GST-GPS time, based on measurements at the PTS.
One dedicated atomic clock [MC1] will be the master clock in PTS#1 and its output signal (standard frequency and 1 PPS) will be shifted by a phase micro stepper PMS to be a realization of GST, here named GSTH. The group clocks operated in the PTS#1 are compared to one physical output (MC1 as in the example shown in Figure 1) and these measurements are processed in an algorithm to generate GSTR [Here an up-date interval has to be defined, e.g. one hour or it may be the same of the OD&TS update rate]. According to two independent inputs, the results of GSTR-MC1 and that on GSTR-TAIp, the relation between MC1 and PMS output (GSTH) is updated. For security, a redundant master clock and PMS are envisaged.

A similar strategy is followed for the PTS#2. Here the redundantly generated time scale GSTX serves as the reference for the local clocks as well as for comparison with GST. The WG identify TWSTFT as a strong candidate for linking PTS#1 to PTS#2, as the difference between the two physically separated sources of the operational time should be known in real time with an accuracy and a precision of 1 ns. In contrast, every one-way time transfer method would need longer averaging times, while every geodetic method would need at least several hours of data for processing. However, note that the PTS#1 to PTS#2 link would have to be operated nearly continuously to be consistent with the update rate of GSTR, which has cost implications for a TWSTFT link.

If such a close link between the two PTS, operating with the update rate of GSTR, comes to existence, one can treat the clocks in both PTS as a common ensemble, and one can envisage an algorithm of combining the clocks to yield an optimum GST (the latest information from the Galileo developers indicates that GST will be calculated using all the clocks from both PTS sites). The PMS in PTS#2 is to be adjusted so that GSTH and GSTX agree with each other. In due course, it could also be possible to add more clocks, and hence stability, for the GSTR ensemble if Galileo could incorporate clocks from some of the national time laboratories, provided that links operating with the required accuracy and continuity are available.

Linking and steering GST to TAI/UTC

In order to fulfil the goal of steering GST to TAI and, by that means, to broadcast GST-UTC to the required uncertainty, GST should be steered in the medium term (e.g. daily) to TAIp, a prediction of TAI. To be able to make such a prediction, GST would need an explicit link to one or more UTC(k)s by an appropriate and redundant link (GPS/Galileo common-view or TWSTFT link). In fact any UTC(k) is a real time prediction of UTC and therefore also of TAI (apart from the integer number of seconds difference between UTC and TAI). However, at this time, the uncertainty of the UTC prediction from each UTC(k) is not precisely specified in general. The advantage of developing TAIp is that it would be dedicated to predicting TAI as accurately as possible in real-time. The exact mechanism for making the TAIp prediction depends on the relative stability and accuracy of the GST and UTC(k) time scales, the time transfer links used to compare those time scales, the need for redundant UTC links to aid reliability, and the actual accuracy target for |GST-TAI|. In the present situation, the WG considered three broad scenarios for the Galileo-UTC interface:

Galileo self-sufficient
Each of Galileo's PTSs has the necessary clocks, equipment and expertise to manage the GST steering and UTC dissemination alone;

Galileo dependent on UTC(k)
UTC(k) laboratories provide the GST steering recommendations on the basis of GSTH-UTC(k) time transfer links;

A Mixed Solution
A solution combining (i) and (ii), in which Galileo PTS independently maintains clocks, generates GST and manage TAI steering but a strict collaboration with UTC(k) labs is established.

The WG prefers option (iii) because it allows skills and clocks to be shared by Galileo and the European UTC(k) labs for mutual benefit, and enables Galileo to move up its learning curve more quickly. All three options involve:

- TWSTFT and/or Galileo common-view, Galileo carrier-phase and GalileoSat time transfer equipment to link the PTS to UTC through UTC(k);
- PTS consisting of a number of clocks, the exact number depending on the accuracy target;
- A time scale algorithm generating GSTR;
- A procedure to compute TAIp, a real-time prediction of TAI.

The specific advantages of option (iii) are :

- The total number of clocks is higher than the number of clocks available in the PTS itself which can help improve the stability and accuracy of GST;
- Existing laboratories can provide UTC(k) in real time and therefore can provide the means for evaluating TAIp, even if the necessary GST steering is calculated at the PTS itself;
- Redundancy in the TAIp provision;
- Caesium fountain frequency standards developed in UTC(k) laboratories could be introduced into TAIp computation;
- A wider pool of expertise from UTC(k) laboratories would be available to Galileo, in particular concerning the calibration of the time transfer equipment.

Contracts would be needed to standardise outputs and service agreements, in addition to the resources needed to develop these systems.

Note that the "redundancy" principle should apply to the number of UTC(k) comparisons, the number of time transfer methods on individual UTC(k)-UTC(j) or UTC(k)-PTS links and the number of clocks at a given UTC(k). Ideally, triple redundancy is needed to isolate performance deficiencies as quickly and unambiguously as possible. Fortunately, Galileo can gain from the investments already made by the UTC(k) laboratories where a high level of redundancy already exists in many cases.

Linking GST to GPS system time

In long term (monthly) TAIp and hence GST would track TAI and UTC as calculated by the BIPM. Because UTC(USNO) is steered to UTC (i.e. TAI), and GPS time is steered relative to UTC(USNO), GPS time also tracks TAI in the long term so that both GST and GPS time will maintain close agreement. However, this would only be realized to the combined level of uncertainty to which both time scales are expected to match TAI/UTC, i.e. of order several tens of ns. We recommend that, in addition, Galileo directly monitors the difference GST-GPS time by using GPS receivers in the Galileo ground segment, at the physical realization of GST, in order to estimate, predict and broadcast this difference with a better accuracy (some nanoseconds) than GST – UTC. Calibration of the receivers is pre-requisite for this process. The reason for recommending this approach is for Galileo to be interoperable with GPS in timing applications. It is possible that such data could be provided to Galileo by an independent service provider, rather than being measured directly in the Galileo ground-segment.

Galileo contributions to UTC

The WG highlights that the PTS could contribute directly to TAI and UTC through the BIPM, and that GSTH becomes a UTC(k) in its own right (with the addition of the necessary number of leap seconds), here denoted UTC(PTS). The advantage of having a UTC(PTS) is the demonstration of GST traceability to UTC. This could be a Galileo high quality service for those users that ask for traceability to international standards. The realisation of UTC by BIPM would benefit from having more high-stability clocks, while Galileo would at the same time have more control over a key parameter needed for its timing services.

As an aside, it is worth noting that since GST and other satellite navigation systems' time scales are steered on TAI, the long term stability of TAI is a guarantee of long term stability of the GNSS time scale also. Therefore it would always be beneficial for GalileoSat to make its PTS clocks available to the BIPM for the computation of TAI. The marginal cost of collecting and forwarding the relevant data to BIPM would not be significant in terms of the long-term benefits of being able to access a more stable TAI.

The BIPM would report UTC-UTC(PTS) in the same way as for the other UTC(k)s, currently at five-day intervals in the monthly Circular T . When a Galileo signal-in-space (SIS) is available, the BIPM would report UTC-GST in a similar way as is done for GPS time and GLONASS time, currently at one-day intervals in the monthly Circular T.

CONCLUSIONS

The WG has been able to take a brief look at the GalileoSat Baseline Design and to make comments and top-level recommendations on the Galileo timing systems. Some of the key recommendations are that:

- Galileo time dissemination system should be designed to be competitive with GPS, both now and in the future;
- Galileo should specify its performance with standardised measures for timing uncertainty, instability, etc;
- Galileo should predict and broadcast the difference TAI-GST in real time along with TAI-UTC (i.e. leap seconds), and the difference GST-GPS time;
- Galileo's PTS should become UTC(k) laboratories and its clocks should be made available to the BIPM for the computation of TAI and UTC;
- In the frame of Galileo System Test Bed (GSTB), the Galileo-UTC Time Interface should be formed from a network of at least three UTC(k) laboratories and the two PTS stations to test the Galileo timing infrastructure;
- Also, the WG strongly recommends the Two-Way Time Transfer Method as an independent means of validating Galileo's time transfer performance in the GSTB.

Looking forward, there is much detailed design work to be completed. However, there is also a need for a more general interface between the global time community and Galileo, one that is open to all timing users. We hope that the mechanisms for such an interface will be established in the future.

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