TECHNICAL REPORT

D210

WANTIME4EC: ALTERNATIVE POSITION, NAVIGATION AND TIMING (PNT) SERVICES

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1.0	29/10/2021	43	Document update according to JRC RIDs.
1.5	18/02/2022	51	Document update including test results in Section 16.
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1. INTRODUCTION

1.1. PURPOSE

This document is the Technical Report for the **WANTIME4EC** project carried out by GMV for the European Commission (EC). The EC project code is DEFIS/2020/OP/0007 – Alternative Position, Navigation and Timing (PNT) Services.

1.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-1 Acronyms

1PPS	One Pulse Per Second
3D	3 Dimension
AD	Applicable Document
ADEV	Allan Deviation
AGL	Altitude over Ground Level
AHM	Active Hydrogen Maser
BIPM	International Bureau of Weights and Measures
BIPR	Background Intellectual Property Right
BME	Bolsas y Mercados Españoles
CERN	European Organization for Nuclear Research
CFI	Customer Furnished Items
COTS	Commercial Off The Shelf
CfT	Call for Tender
CV	Common View
CV	Curriculum Vitae
d	day
DTM	Dynamic synchronous Transfer Mode
DWDM	Dense Wavelength Division Multiplexing
EC	European Commission
ECSS	European Cooperation for Space Standardisation
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
EIRP	Effective Isotropic Radiated Power
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EU	European Union
FTTH	Fiber To The Home
FR	Final Review

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GSC	Galileo Service Centre
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European GNSS Agency
GST	Galileo System Time
HAS	High Accuracy Service
H2020	Horizon 2020
HVAC	Heating, Ventilation and Air Conditioning
HW	Hardware
IMU	Inertial Measurement Unit
ITT	Invitation to Tender
JRC	Joint Research Centre
KOM	Kick Off Meeting
KPI	Key Performance Indicator
m	month
MJD	Modified Julian Day
MTBF	Mean Time Between Failure
MTIE	Maximum Time Interval Error
MTTR	Mean Time To Repair
MTR	Mid-Term Review
NM	Nautical Mile
NTP	Network Time Protocol
OS	Open Service
PDV	Packet Delay Variation
PHM	Passive Hydrogen Maser
PM	Progress Meeting
PMP	Project Management Plan
PNT	Positioning, Navigation and Timing
PPP	Precise Point Positioning
PR	Progress Report
PTF	Precise Timing Facility
PTB	Physikalisch-Technische Bundesanstalt
PTP	Precise Timing Protocol
PST	PST Progress Status Teleconference
PVT	Position, Velocity and Time
QoS	Quality of Service
RD	Reference Document

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RMS	Root Mean Square
RF	Radio Frequency
RfT	Request for Tender
RIMS	Ranging Integrity Monitoring Station
RM	Review Meeting
ROA	Real Observatorio de la Armada
SFP	Small Form-factor Pluggable transceptor
SIS	Signal In Space
SLA	Service Level Agreement
SyncE	Synchronous Ethernet
SW	Software
TaaS	Time as a Service
TDEV	Time Deviation
TIC	Time Interval Counter
TIMS	Timing Integrity Monitoring Station
TLS	Transport Layer Security
TOD	Time Of Day
TRL	Technology Readiness Levels
TS	Tender Specifications
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UPS	Uninterrupted Power System
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UTC	Coordinated Universal Time
WBS	Work Breakdown Structure
wd	working day
WP	Work Package
WPD	WP Description
WR	White Rabbit

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents.

Ref.	Title	Code	Version	Date
[ITT]	Invitation to Tender: Alternative Position, Navigation and Timing (PNT) Services	DEFIS/2020/OP/0007	-	19 October 2020
[TS]	Tender Specifications: Alternative Position, Navigation and Timing (PNT) Services	DEFIS/2020/OP/0007	-	19 October 2020
[CNTR]	Draft Service Contract: Alternative Position, Navigation and Timing (PNT) Services	DEFIS/2020/OP/0007	-	19 October 2020

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2: Reference documents.

Ref.	Title	Code	Version	Date
[RD.1]	GMV, "TOWR Final Report".	NAVISP2-FR-GMV-033-001	1.0	2020/03/19
[RD.2]	Seven Solutions, "Spanish Stock Exchange Case Study - Inter-datacenter accurate time synchronization in a metro area using commercial telecommunication networks", July 2020.			July 2020
[RD.3]	A. Fernández-Cabezas, R. Píriz, E. Garbin, "A Robust Multi-Source NTP Server Using GPS, Galileo, and a Trusted PPS", International Timing and Sync Forum (ITSF), 4-7 November, 2019, Brighton, UK.			November 2019
[RD.4]	Ricardo Piriz, Esteban Garbin, Raúl Nieto, Daniel Chung, "Accessing UTC from New Mass-market GNSS Receivers", International Timing and Sync Forum (ITSF), November 2020, online.			November 2020
[RD.5]	Magnus Danielson, "Time transfer capabilities in the DTM transmission system", 2014 European Frequency and Time Forum (EFTF).			2014

Ref.	Title	Code	Version	Date
[RD.6]	Umut Keten, "GPS Independent Time Distribution", International Timing and Sync Forum (ITSF), 4-7 November, 2019, Brighton, UK.			2019
[RD.7]	J. Serrano, M. Cattin, E. Gousiou, E. van der Bij, T. Włostowski, G. Daniluk, M. Lipinski, "The White Rabbit Project", IBIC 2013.			2013
[RD.8]	Mills, David L., "Computer Network Time Synchronization: the Network Time Protocol on Earth and in Space", Second Edition, CRC Press 2011.			2011
[RD.9]	Faten Mkacher and Andrzej Dusa, "Calibrating NTP", International Timing and Sync Forum (ITSF), 4-7 November, 2019, Brighton, UK.			2019
[RD.10]	Dieter Sibold and Kristof Teichel, "Network Time Security specification", 2016 European Frequency and Time Forum (EFTF), April 2016.			April 2016
[RD.11]	Martin Langer, "Network Time Security – New NTP Authentication Mechanism", Blog Webernetz.net, 29/10/2019.			October 2019
[RD.12]	Douglas Arnold, Martin Langer, Rainer Bermbach, "Adapting NTS to PTP", International Timing and Sync Forum (ITSF), November 2020, online.			November 2020
[RD.13]	Fulgencio Buendía and Ricardo Píriz, "GNSS Timing Safety Analysis", GMV 20285/19 V3/19.	GMV_EGALITE_SSAD_3_0	3.0	2019/05/27
[RD.14]	Ricardo Píriz, Roseline Lermann, Marc-André Sauvage, Esteban Garbin, Raúl Nieto, GMV; Magnus Danielson, Javier González, Net Insight; Dirk Piester, Andreas Bauch, Kristof Teichel, PTB; Gianluca Caparra, Roberto Prieto-Cerdeira, ESA, "Resilient, Trustworthy, Ubiquitous Time Transfer using DTM and NTP", Proceedings of the 53rd Annual Precise Time and Time Interval Systems and Applications Meeting, Long Beach, California, January 2022, pp. 346-357.			January 2022

3. DESCRIPTION OF TECHNOLOGIES AND APPLICATIONS

This section describes the key technologies used in *WANtime*. It is understood that the usage of GNSS for timing is well known to the EC and does not need a detailed description.

3.1. PASSIVE HYDROGEN MASER (PHM)

PHM is one of the clock technologies flying on board the Galileo satellites. On ground, PHMs provide a short- and long-term stability that is near the stability of an Active Hydrogen Maser (AHM), at a much smaller size and a much more affordable cost.

In the short- and medium-term PHMs are more stable than high-end Caesium clocks of similar price. This makes the PHM ideal for very precise timing applications. However, since the definition of the SI second is based on the Caesium atom, in the long term the PHM deviates slowly from UTC, and a steering mechanism like the one used in *WANtime* (using GNSS time transfer) is needed.

The selected model (actually the only PHM available in Europe) is the Russian-made 1008 PHM from Vremya, distributed and supported in Europe by T4Science in Switzerland. The clock is depicted in Figure 3-1.

Figure 3-1: The PHM 1008 from Vremya/T4Science.

This clock provides excellent stability and robustness, as reported by several national timing laboratories that collaborate with GMV, namely METAS in Switzerland, and PTB in Germany. The Allan Deviation (ADEV) of one PHM unit tested at METAS is shown in Figure 3-2 (left side). The figure is referenced to UTC(CH), which is the Swiss realization of UTC maintained by the national timing laboratory (METAS). The PHM frequency drift has been removed in the calculation of ADEV. The frequency drift was removed by adjusting a second-order polynomial to the data, then subtracting that polynomial from the data, and then calculating the ADEV. We verified that the results are very similar to the calculation of the Hadamard Deviation (HDEV) from the original data. HDEV is insensitive to the frequency drift.

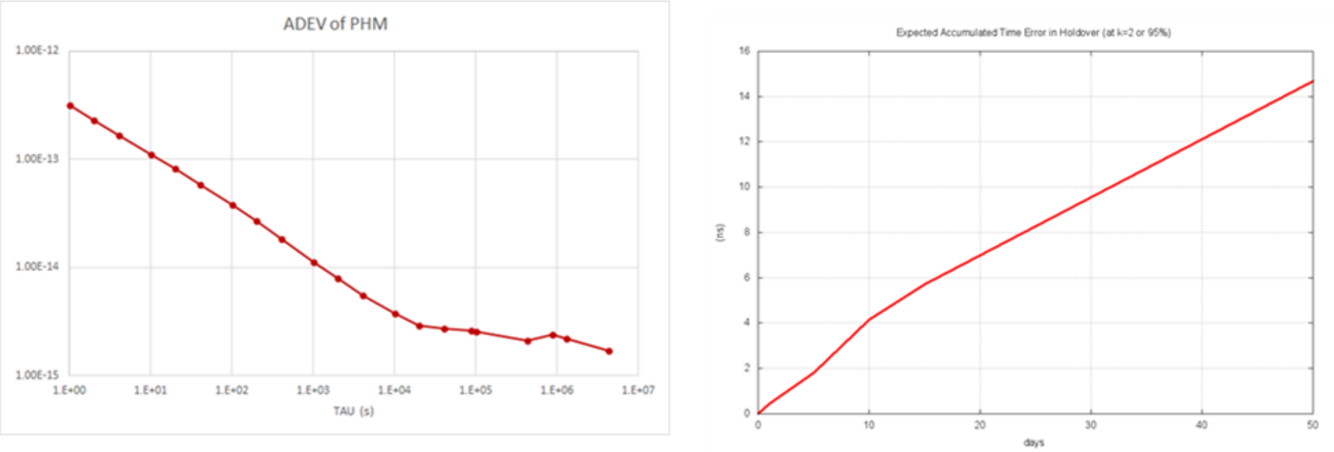

Figure 3-2: PHM Allan deviation (left) and expected accumulated time error (right).

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3.2. CLOCK MODELLING AND STEERING

The *WANtime* time scale is maintained via GNSS Common-View (CV) difference between the local clock and a remote UTC time scale. GNSS CV is the most convenient time transfer method nowadays. Fibre transfer using for example White Rabbit would also be possible, but this would require a dedicated and expensive fibre deployment between the NMI and the PHM.

Currently we are collaborating with PTB, the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany, to align our clocks to PTB's realization of UTC, called UTC(PTB). We chose UTC(PTB) because it is one of the most stable realizations of UTC in the Circular T (BIPM), and also to profit from the availability of free GNSS data for CV (at ftp.ptb.de).

By calculating clock differences over several days it is possible to model and predict the behaviour of the clock, and thus to adjust the clock frequency periodically to minimize its deviation from UTC. In our case we adjust our PHMs to UTC using a quadratic model that accounts for the clock phase offset (A0 term, ns), the mean clock frequency offset (A1 term, ns/day), and the frequency drift (A2 term, ns/day^2).

Every day, we fit the PHM model to the CV results from the 15 previous days, we extrapolate the model to the current day at noon, and we calculate a corresponding frequency correction, which is applied to the PHM by means of a frequency stepper connected at its output. Each PHM is steered independently of the other one.

In nominal operations, time transfer with PTB uses the well-known dual-frequency iono-free combination of GPS P1 and P2 pseudoranges. In the unlikely event of a problem with this combination, for example due to jamming or interference in the GPS L1 or L2 bands, or even due to a total failure of GPS, we need to have alternative time transfer methods that ensure the continuity of operations. This is achieved by incorporating Galileo, and also by using single-frequency time transfer in all the individual GNSS bands. An example of the results is shown in Figure 3-3 that depicts the PHM-A clock model versus UTC(PTB) for April 25, 2019 (MJD 58598). Two dual-frequency combinations are used: P1/P2 for GPS (nominal method), and E1/E5a for Galileo. In single-frequency, the iono models used are Klobuchar for GPS, and NeQuick for Galileo. The receiver is capable to do PNT in Galileo-only mode, without GPS.

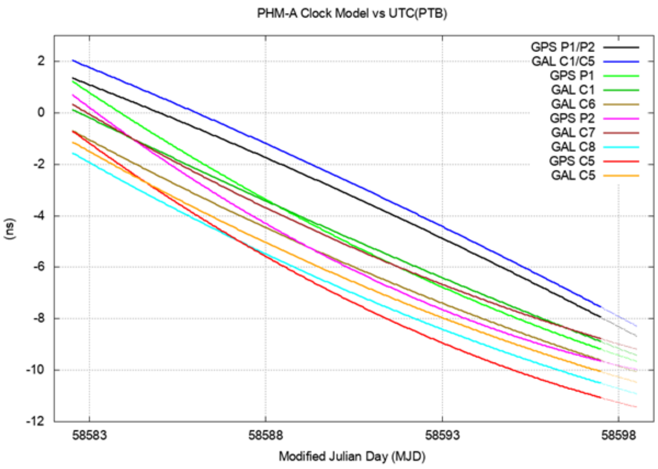


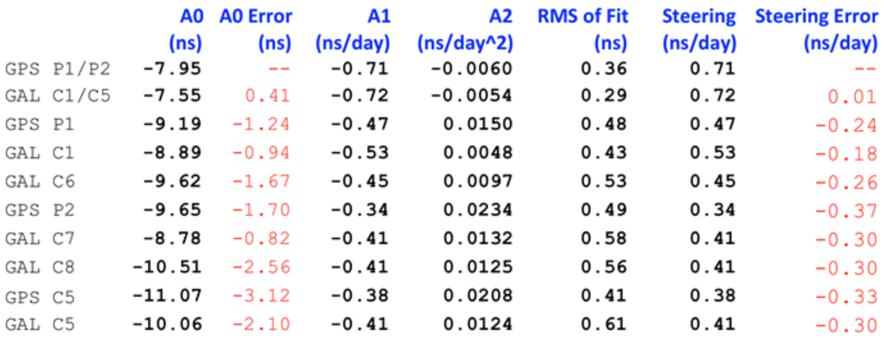
Figure 3-3: GPS vs Galileo clock modelling.

Individual frequencies will help in the case that all other frequencies are jammed/spoofed or unavailable for any reason, but not in case of total constellation failure, of course. Single-frequency GPS time-transfer was the standard in the NMI community before the arrival of dual-frequency receivers.

The numerical values of the adjusted models, corresponding to the plots above, are shown in Table 3-1. The RINEX pseudorange code names are explained in Table 3-2. The reference time for the model is T0 = MJD 58597.5. "Steering" indicates the frequency correction to be applied to the clock; it is obtained extrapolating the model by one day to MJD 58598.5. In a visual way, the steering is the slope of the tangent to the model curves in Figure 3-3, evaluated at the extrapolated epoch. The steering is conceived to adjust to zero the instantaneous frequency offset at that epoch. An additional steering correction term is used to adjust the clock phase offset versus UTC to zero in the following ten days, but this aspect will not be discussed here. "Error" in the A0 term and in the steering is calculated as the difference versus the nominal dual-frequency GPS solution (GPS P1/P2). "RMS of Fit" indicates the RMS of the time transfer data residuals after adjusting the quadratic clock model; the

RMS value gives an idea of the uncertainty of the time transfer method. As can be seen, single-frequency fits are in general nearly twice as noisy as dual-frequency ones.

Table 3-1: GPS vs Galileo clock steering.



	A0 (ns)	A0 Error (ns)	A1 (ns/day)	A2 (ns/day^2)	RMS of Fit (ns)	Steering (ns/day)	Steering Error (ns/day)
GPS P1/P2	-7.95	--	-0.71	-0.0060	0.36	0.71	--
GAL C1/C5	-7.55	0.41	-0.72	-0.0054	0.29	0.72	0.01
GPS P1	-9.19	-1.24	-0.47	0.0150	0.48	0.47	-0.24
GAL C1	-8.89	-0.94	-0.53	0.0048	0.43	0.53	-0.18
GAL C6	-9.62	-1.67	-0.45	0.0097	0.53	0.45	-0.26
GPS P2	-9.65	-1.70	-0.34	0.0234	0.49	0.34	-0.37
GAL C7	-8.78	-0.82	-0.41	0.0132	0.58	0.41	-0.30
GAL C8	-10.51	-2.56	-0.41	0.0125	0.56	0.41	-0.30
GPS C5	-11.07	-3.12	-0.38	0.0208	0.41	0.38	-0.33
GAL C5	-10.06	-2.10	-0.41	0.0124	0.61	0.41	-0.30

Table 3-2: GPS and Galileo RINEX pseudorange code names.

RINEX pseudorange code	Description
GPS P1	GPS “P” code in L1 frequency
GPS P2	GPS “P” code in L2 frequency
GPS C5	GPS civil code in L5 frequency
GAL C1	Galileo civil code in E1 frequency
GAL C5	Galileo civil code in E5a frequency
GAL C7	Galileo civil code in E5b frequency
GAL C8	Galileo civil code in E5AltBOC frequency
GAL C6	Galileo civil code in E6 frequency

Notice that an actual comparison with UTC could only be done by actually steering the clock using the different time transfer modes; this would disrupt the nominal operational mode (GPS dual-frequency) and would require long evaluation times to compare the performance; if we consider that Galileo or GPS dual-frequency (first two rows in Table 3-1) are the "true" steering to UTC, the rest of the rows can be considered as the steering error to UTC.

Several facts can be observed from the results. In the first place we can see a relatively large dispersion in the adjusted A0 values, with maximum errors of more than 3 ns versus the nominal solution. This is explained by calibration errors in the GNSS receivers. Since receiver chain delays are fairly stable, the error in the A0 can be considered constant, and thus it does not affect frequency transfer, but it does affect the time transfer.

The second remarkable fact from the results is that Galileo and GPS provide nearly identical steering results in dual-frequency, and that in fact the very small frequency drift of the clock (A2 term) can only be properly estimated in dual-frequency. We can observe a large dispersion if the A2 term from the single-frequency solutions, with in fact an opposite sign with respect to dual-frequency.

Finally, we can see that the steering error in single-frequency is roughly inversely proportional to the value of the carrier frequency, with smaller values in L1/E1 and larger values in L5/E5a. This makes sense since the ionospheric error in the pseudorange is inversely proportional to the square of the carrier frequency. We can also observe that the minimum steering error in single-frequency is provided by Galileo in E1 (“GAL C1”), which can be explained by the superior performance of the NeQuick iono model as compared to Klobuchar. However the good single-frequency results in L1/E1 must be taken with caution, since this is the signal most likely to be jammed. Interestingly, the E6 signal, unique to Galileo, is the one providing second-best single-frequency steering, after L1/E1. The worst single-frequency steering is obtained using pseudoranges in the L5/E5 bands, with daily errors of the order of 0.3 ns/day.

As a summary, the clock steering is fit on the last 15 days (using 15 data points) and instantaneously offset at current day at noon. Points are calculated using CV using nominally the ionospheric free GPS L1+L2 combination. Alternatively, Galileo iono-free CV and steering is also possible, as well as many GPS and Galileo single-frequency CV and steering. CV values are calculated every 16 minutes according to the CGGTTS standard, by combining internal CGGTTS file with CGGTTS files from PTB. Note that the steering is done in frequency only. Possible (small) phase errors are corrected slowing by incorporating a second frequency steering component that reduces the phase error to zero over the 10 next days.

As can be seen in Table 3-1, the steering commands in this example are of the order of 0.5 ns/day, which is equivalent to 6 x 10^{-15} in non-dimensional frequency units. This means that in order to maintain a fine and smooth steering to UTC it is essential to use a high-resolution frequency stepper.

WANtime uses the well-known HROG-10 stepper from SpectraDynamics. The HROG-10 is a high-resolution phase and frequency offset generator. The phase and frequency of the output signals are adjustable with respect to a 10-MHz user supplied reference. The output frequency resolution is 6 x 10^{-19}. Both phase and frequency steps are phase continuous. The instrument provides two sine-wave outputs and two pulse outputs.

Figure 3-4: HROG-10 stepper from SpectraDynamics.

3.3. DTM

Dynamic synchronous Transfer Mode (DTM) [RD.5] is an optical networking technology standardized by the European Telecommunications Standards Institute (ETSI) in 2001. DTM is a time division multiplexing and a circuit-switching network technology that combines switching and transport. It is designed to provide a guaranteed quality of service (QoS) for streaming video services, but can be used for packet-based services as well. The DTM architecture was conceived in 1985 and developed at the Royal Institute of Technology (KTH) in Sweden. It was published in February 1996. The research team was split into two spin-off companies, reflecting two different approaches to use the technology. One of these companies remains active in the field and delivers commercial products based on the DTM technology. Its name is NetInsight.

A team composed of Türk Telekom, NetInsight, and Meinberg has been recently proposed the usage of DTM outside the broadcasting industry as a general-purpose synchronization technology over wide area networks (in particular for telecom) [RD.6]. The results show synchronization errors below 500 ns in a 1000-km link based on DTM over a MPLS/DWDM network (11/14 hops), as shown in Figure 3-5. DTM largely solves the problems of asymmetry and Packet Delay Variation (PDV) affecting PTP and can be deployed over existing networks fulfilling certain quality requirements, but without the need of end-to-end network engineering (unlike PTP or White Rabbit).

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

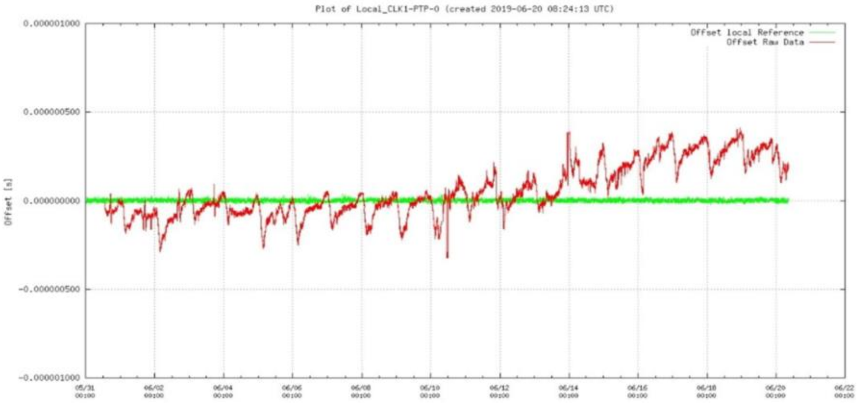


Figure 3-5: Example of DTM time distribution error over a 1000-km link (from [RD.6]).

The DTM equipment to be used for the proposed timing service is the Nimbra 390 unit from NetInsight, shown in Figure 3-6. At the server side, the Nimbra accepts as input 1PPS and 10-MHz signals from a time reference, in our case the signals from the *WANtime* server. One Nimbra unit is already installed at GMV headquarters in Tres Cantos.

The Nimbra is then connected to the network via 1-Gigabit Ethernet interface (SFP/RJ45 connector), to transfer the reference time signals to the end user. On the client side one Nimbra unit connected to the network generates the final output 1PPS and 10-MHz signals locked to the reference *WANtime* server.

Figure 3-6: The Nimbra 390 product from NetInsight.

3.4. WHITE RABBIT

The White Rabbit (WR) project [RD.7] was initiated at CERN in 2008 to synchronize different processes in its particle accelerator network. One of the main aims of the project is to deliver such functionality while using – or extending where needed – existing standards. To achieve sub-nanosecond synchronization WR utilizes Synchronous Ethernet (SyncE) for syntonization (frequency transfer), and IEEE 1588 Precision Time Protocol (PTP) to communicate time. A two-way exchange of the PTP synchronization messages allows precise adjustment of clock phase and offset.

The link delay is known precisely via accurate hardware timestamps and the calculation of delay asymmetry. WR extends PTP in a backwards-compatible way to achieve sub-ns accuracy. WR was originally conceived for synchronization of more than 1000 nodes via fibre or copper connections of up to 10 km, but coverage of longer distances has been already achieved.

Figure 3-7 shows the layout of a typical WR network. Data-wise it is a standard Ethernet switched network, i.e., it follows a typical Ethernet tree or ring topology where any node can talk to any other node according to IP address and network protocol mechanisms. Regarding synchronization, there is a hierarchy established by the fact that switches have downlink and uplink ports and a master/slave relationship. A switch uses its downlink ports to connect to uplink ports of other switches and discipline their time. The uppermost WR switch in the hierarchy is usually called the "grandmaster".

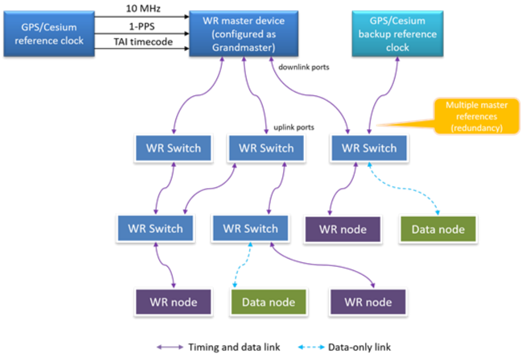


Figure 3-7: Layout of a typical WR network.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

The grandmaster receives its notion of time through external One Pulse Per Second (1PPS) and 10-MHz inputs. Typically the top-level timing signals come from a GNSS receiver, but in our application these signals come from the atomic clock, via the stepper.

Figure 3-8 shows the front panel of the WR-ZEN-TP device developed by Seven Solutions. This device can act at the same time as a WR switch and as a WR node at the end customer. For the particular application of the TOWR project, the WR ZEN was enhanced with an additional holdover mechanism at the client location.

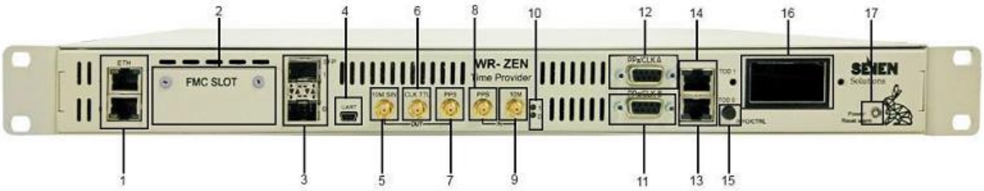


Figure 3-8: WR-ZEN-TP from Seven Solutions.

The holdover mechanism extends the synchronization capabilities of the client, in case the *WANtime* signal is lost. In the TOWR project specification the client holdover error was targeted to be within one microsecond after one day of autonomous operations. If no holdover mechanism were included, the time signal in the ZEN device would be totally unavailable in case of a loss of the WR signal.

The WR-ZEN device installed at BME was enhanced with an OCXO ICQM-200 clock module, disciplined by the WR 1PPS output. This clock is specified to provide synchronization better than 1.5 μs after 24 hours. An example of a holdover test, performed after the installation of the equipment is shown in Figure 3-9. We can observe that the maximum time deviation after one day is below 500 ns, meeting the expected performance.

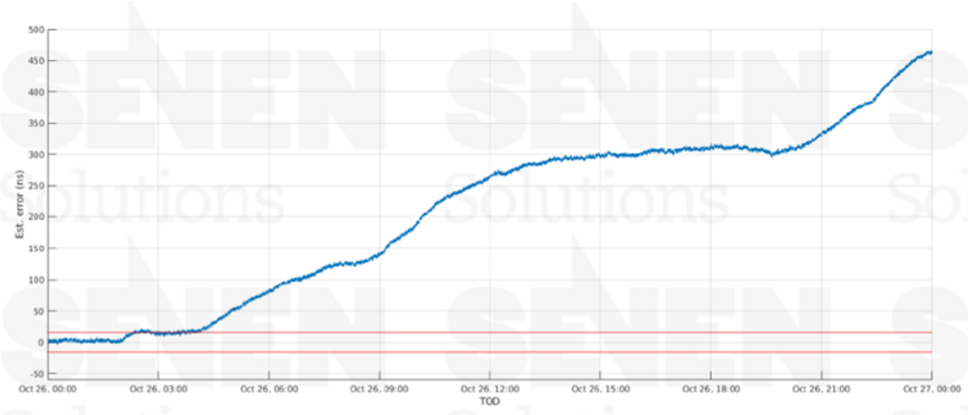


Figure 3-9: Holdover test results for WR client at BME site.

3.5. NTP AND NTS

The Network Time Protocol (NTP) [RD.8] has been the dominant technology over almost three decades to synchronize computer clocks over the public Internet and in numerous private networks. Just about everything today that can be connected to a network wire has support for NTP: print servers, WI-FI access points, routers and printers of every stripe, and even battery backup systems. NTP subnets are in space, on the seabed, on-board warships, and on every continent, including Antarctica. NTP comes with most flavours of Windows as well as all flavours of UNIX. In this sense NTP can be considered a truly ubiquitous technology.

The typical time accuracy that can be obtained from NTP over the Internet is of the order of a few ms at best. This level of accuracy is enough for most computing tasks such as DNS cache creation and expiry dates, data file update time, time-stamping of email sending and arrival, etc. For specialized applications requiring synchronization at the microsecond level or below, such as telecom, energy, broadcasting, etc., NTP is clearly not accurate enough. For such applications NTP was soon replaced

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

by the Precision Time Protocol (PTP), and more recently by the even more accurate PTP extension called White Rabbit. However both PTP and White Rabbit require some kind of specialized hardware (not just computers) and a carefully engineered network also with dedicated hardware support (not just the Internet), which make them in general expensive to deploy and difficult to scale up.

Some relatively simple ideas can improve the accuracy of standard NTP, like for example “calibrating” the network asymmetry using GNSS [RD.9], or using a very high rate of time-stamp packet exchange, as it is done in DTM. The usage of NTP as a starting point has many advantages, in particular the re-use of reliable, well-tested software with a huge user base, and the application of NTS, the new Network Time Security protocol [RD.10]. Moreover, NTP works on standard computers at operating system clock level, without the need of dedicated hardware, although with a limited clock resolution at the level of 1 µs. Also, despite its lack of accuracy, NTP is a very practical way to disseminate the Time Of Day (TOD), including leap seconds. TOD is essential information to provide a complete timing service, in addition to precise 1PPS and frequency signals. To this purpose GMV has developed a robust multi-source local NTP server that combines TOD from GPS (from one GNSS receiver), TOD from Galileo (from a different GNSS receiver), and TOD from three NTP servers located at different UTC laboratories [RD.3].

In summary, in parallel to the usage of DTM, we propose to demonstrate an advanced version of NTP based on Red Hat’s Chrony[1], with a target accuracy of a few µs on the client side. This level of accuracy will be perhaps difficult to achieve over the public internet, and some kind of advanced wide-area network service will probably be needed, as in the case of DTM.

Chrony already implements NTS, the new NTP authentication mechanism, and the implementation has already been tested at GMV. A very good description of NTS can be found in [RD.11]. In many areas, the use of authentication mechanisms in NTP is important to prevent the manipulation of time information by an attacker. For many years, NTP has been offering solutions such as a *Symmetric Key* based method and the *Autokey* approach. However, both have serious disadvantages, for which reason they are rarely used to secure NTP connections. After years of development, a new standard is to be adopted in 2020 that solves the problems of the current mechanisms and offers a real alternative. First implementations of the so-called Network Time Security protocol (NTS) are already available and interoperate with each other.

NTS consists of sub-protocols, which currently form two phases of communication (see Figure 3-10). The first phase takes place once at the beginning of the communication and serves the negotiation of parameters as well as the exchange of key material in the form of cookies. In the second phase, the NTS-secured NTP connection takes place. For this purpose, the client uses the cookies provided by the server, which it attaches to the NTP requests. The client remains in this phase until the connection is terminated or if cookies are no longer available due to repeated packet loss. In this case, the first phase is executed again.

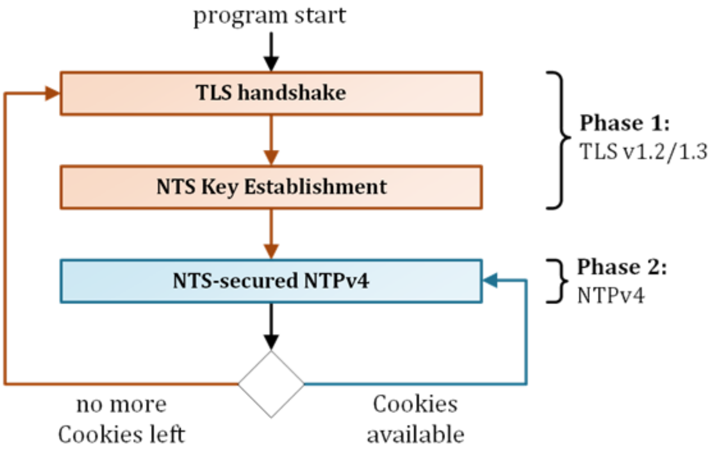


Figure 3-10: Phases of the NTS secured communication (from [RD.11]).

NTS provides strong cryptographic protection against packet manipulation, prevents tracking, scales, is robust against packet loss and minimizes the loss of accuracy due to the securing process. To protect the time information, NTS uses the NTP Extension Fields (EF), in which parameter and status information are also transferred between client and time server. The secured time protocol remains untouched so that the usage of NTS in other protocols (e.g. the Precision Time Protocol (PTP), and

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[1] https://chrony.tuxfamily.org/

eventually White Rabbit) is possible as well. This also means that the time data is not encrypted by NTS – but authenticated.

3.6. GNSS TIMING FOR CALIBRATION AND MONITORING

As explained above, on the server side *WANtime* is relatively independent of GNSS and robust to GNSS outages, failures, and attacks. Once initialized, *WANtime* can survive without GNSS during weeks and months with a negligible loss of accuracy.

On the client side *WANtime* is totally independent of GNSS, except possibly for calibration of network asymmetry in case of usage of DTM or NTP over standard internet connections. Notice that in the case that GNSS is used for calibration on the client, once initialized (calibrated), and similarly to the server, the client can continue to work without GNSS permanently, unless there are major changes in the packet exchange routes over the network. The idea is to calibrate the link with GNSS only once at the beginning, and then to develop an algorithm to detect and correct possible network path changes (jumps in time offsets) automatically. The system will work exactly the same without GNSS on the client; GNSS is just a practical method to measure the performance of the system (on the client).

Aside from calibration, GNSS on the client is also a very practical and accurate method to verify the *WANtime* service accuracy, and also to demonstrate (partially) traceability to UTC, at the few-ns level. In most cases GNSS is actually the only feasible method to demonstrate performance and traceability at the endpoint. By partial traceability we mean that mass-market GNSS receivers providing just a 1PPS output are nowadays not "approved" by the BIPM to demonstrate traceability to UTC. GNSS receivers used by NMIs for time transfer are advanced receivers accepting 10-MHz and 1PPS inputs from an external clock; for such receivers, a full calibration method is provided by the BIPM, which fulfils formal traceability to UTC.

GMV is currently developing a timing product called *WANtime receiver*, based on multi-band, multi-GNSS capabilities (in particular Galileo and GPS), and generating precise and accurate 1PPS and 10-MHz time signals aligned to GNSS Time or UTC. Furthermore, the *WANtime receiver* provides a holdover capacity better than 1.0 μs after 24 hours in case of GNSS signal outage, thanks to a smart internal crystal clock.

The *WANtime receiver* comes calibrated from factory following the procedure developed by GMV [RD.4], against a reference travelling GNSS time-transfer receiver calibrated by the BIPM.

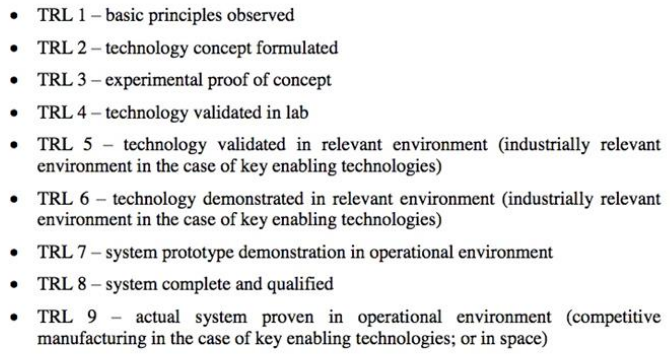
Once calibrated, the *WANtime receiver* provides a typical timing error versus GNSS-based UTC of 2 ns (1-sigma), in open-sky, using an accurate “fixed” antenna position (calculated for example using Precise Point Positioning), and when locked to GNSS signals. The device can also be used as an NTP client, totally independent of GNSS, including the generation of a physical 1PPS signal from NTP, which is a novel feature. Figure 3-11 shows the *WANtime receiver* front panel (1U of a standard 19’’ rack).

Figure 3-11: The *WANtime receiver* front panel.

4. TRL JUSTIFICATION

WANtime has been operating uninterruptedly in Spain since August 2019 for a first pilot customer, the Stock Exchange in Madrid (*Bolsa de Madrid*). Most of the *WANtime* service is based on well-proven technology, and we believe that the proposed service can be considered TRL 7 on average. This is justified in the following. The definitions to be used for each TRL in this project are shown in Table 4-1, as referenced in the Tender Specifications [TS].

Table 4-1: Technology Readiness Levels (TRL) definitions.



- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The key technologies used in *WANtime* were identified in Section 3. . All of them have a high TRL (minimum 6), but each one can be considered to have a different TRL, as follows:

- Atomic clocks, clock modelling and steering, and time transfer technology based in GNSS or TWSTFT are very mature technologies, used since decades by UTC labs participating in the BIPM, and since several years used also in the operational generation of Galileo System Time (GST) in the Galileo Precise Timing Facilities (PTFs). These technologies can be considered TRL 9.
- White Rabbit is fully operational in European particle accelerators including the CERN (Geneva) and the GSI Helmholtz Centre for Heavy Ion Research (Darmstadt). It is also used operationally in the Frankfurt Stock Exchange (within a building) and by many UTC labs to distribute time locally. However long-range WR poses still quite a few challenges and requires careful network engineering, thus we can consider that for this application WR is TRL 8.
- DTM is widely used in the broadcast industry by many TV and video operators with relatively loose synchronization requirements, but the application to timing application with strict requirements is under development. We can consider that in this field DTM is TRL 7.
- Although NTP has been synchronizing the computers connected to the internet worldwide during decades at the level above the ms, the application of NTP to higher-precision is a relatively new, experimental area. In this sense NTP can be considered TRL 6. NTP is proposed because it is cheap and open-source technology, whereas DTM is proprietary and relatively expensive equipment. Our intention is to develop in the future a new NTP hardware and software platform providing an accuracy similar to DTM (at the microsecond level).

All in all, and taking into account that the pilot project with Bolsa de Madrid described above is a very representative example of the "System Prototype Demonstration in Operational Environment", we consider that the overall TRL level of WANtime is 7.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

5. CURRENT DEPLOYMENT AND USAGE

On the server side, the described *WANtime* technology is fully deployed at GMV headquarters in Tres Cantos near Madrid, Spain. The core equipment is duplicated in two parallel time generation chains, including PHM clock, frequency stepper, GNSS time transfer receiver, and White Rabbit switch. Additionally the system includes one Nimbra box, and one NTP server (including multi-source TOD and NTS authentication). This deployment is totally available to the EC for examination.

On the client side two deployments are available:

- The client at BME, the Stock Exchange in Madrid, based on White Rabbit exclusively. The network service required to provide this service (Colt *Wave*) has currently been discontinued due to its high price (more than 2000 € per month). Also, BME has expressed concerns about the dependence on a particular network provider, and GMV also believes that a timing service over such expensive network service is not competitive and alternatives must be explored (DTM, NTP). Another problem with a service such as Colt *Wave* is that it is only available in some metropolitan areas, and scalability over longer distances seems quite difficult. Also, to guarantee that the WR link will actually work over the network service, lengthy and time-consuming discussions with the provider are necessary (“network engineering” needed). In these conditions GMV does not intend to pursue maintaining the link with BME, although this might change in the future. Having in mind also the mild interest of BME in the service, we consider that the deployment at BME is not available for examination.

- Experimental DTM+NTP client at GMV offices in Boecillo, Valladolid, 130 km away from Tres Cantos on a straight line. A map of the link and a picture the equipment installation in early 2020 are shown in Figure 5-1. The setup is currently based on dedicated but inexpensive “home internet” access on the server and client sides, namely Fiber To The Home (FTTH) provided by Telefónica. Current client equipment at Boecillo includes a Nimbra box, a NTP client based on a Raspberry Pi, and a single-frequency GPS-only receiver for calibration and monitoring purposes. Despite the low cost of the network service (around 50 € per month per site), the stability of the network asymmetry seems to be quite good and, after calibration with GNSS, a timing accuracy at the level of 1 μ (1-sigma) using DTM and 10 μs (1-sigma) using NTP seem to be possible. This deployment is totally available to the EC for examination, and in fact is the platform we intend to use for the project demonstrations. Some upgrades are foreseen for the proposed demonstration activities, in particular the installation of a VPN-IP link between Tres Cantos and Boecillo (in addition to the existing link based on FTTH), and the replacement of the current GPS receiver for the more advanced *WANtime receiver* described above (acting also as NTP client).

Figure 5-1: *WANtime* experimental link between Tres Cantos and Boecillo.

In addition Boecillo client site, as part of the proposed demonstration activities, we plan to use our White Rabbit link within GMV's main building in Tres Cantos ("Newton"), between the datacentre and the timing lab. Proprietary optical fibre has been deployed by GMV between the two sides.

6. SYSTEM AND SERVICES’ MODES OF FAILURE

Typical failure modes of the *WANtime* service include:

- Hardware equipment failures / glitches: In our experience operating the service, equipment failures are quite unusual, as we are using well-proven technology from high-end manufacturers. Although hardware problems are very uncommon, the atomic clocks are essential critical items since they are at the core of the time generation chain. The a-priori probability of failure of atomic clocks is not very high, but they need a quite long time to repair in case of failure. As an example, a comparative study[2] between the Vremya-CH 1008 passive maser and the Microsemi 5071A Cesium indicates a Mean Time Between Failure (MTBF) of 50.000 hours for the maser versus 160.000 hours for the Cesium. Mean Time To Repair (MTTR) is not provided in the study, but the experience of our partner timing labs indicate repair times of typically 4 months or longer for these clocks. Clearly, *WANtime* cannot rely on a single clock as time source, and therefore two PHMs are used in parallel.
- Software failures: The *WANtime* SW has been thoroughly verified and tested in order to mitigate potential SW errors leading to service interruption.
- Power / network outages: They are critical and the datacentres hosting *WANtime* servers must provide redundant power / network services. To mitigate possible power outages, we have recently installed a dedicated UPS next to the *WANtime* server rack, which acts in addition to the general UPS system at GMV. The nominal service is based on a dedicated internet access for the datacenter where the PHMs are installed; this access is outside GMV's corporate network and firewall; in case of failures we can retrieve the necessary GNSS data from PTB and ROA manually using the corporate network.
- Datacentre temperature instability: This is the most worrying potential problem. To prevent or at least identify such problems the *WANtime* server includes a web-based monitoring system that includes an email-based alarm system. The room temperature is controlled in real time, and also the deviation of the two time generation chains from each other (using a Time Interval Counter), and the deviation of each chain from GNSS time. All these parameters are measured every 5 minutes and displayed on the web, and email alarms are sent if predefined thresholds are surpassed. Temperature alarms are sent by email to GMV's general services department, who immediately go down to the datacenter to check what the problem is.
- GNSS outages: The clock steering process to UTC is physically decoupled from the GNSS measurement collection: a frequency micro-stepper is used between the clock and the GNSS receiver. In case of GNSS receiver failure, the clock model is not updated and the steering is based on the extrapolation of the latest model, until the GNSS receiver is repaired or replaced.

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[2] https://time.pcss.pl/wp-content/uploads/2015/11/Vremya-CH-2015-PL.pdf, page 14.

7. REQUIRED LICENCES

No special licenses such as spectrum band licences are needed at all for *WANtime* service provision.

8. SERVICE SCALABILITY

WANtime is currently available in Spain, providing formal traceability to UTC(ROA)[3], the Spanish legal realization of UTC. The server is located at GMV premises in Tres Cantos near Madrid, central Spain.

The service could be extended to other countries in Europe, using typically one or several servers in the country, and providing formal traceability to the legal UTC realization of the country (upon agreement with the local UTC laboratory). The number of servers to be installed would depend on the size of the country, and also on the level of redundancy and robustness required. Ideally at least three servers would be needed per country, in order to avoid single points of failure, and also to be able to discard on the client side a "falseticker" if one of the server sources is providing the wrong time with respect to the other two.

In this sense *WANtime* is scalable to local, regional and continental scale, with the following reservations and remarks:

- *WANtime* is not applicable to territorial waters (50 NM from land), since it is based on time distribution through terrestrial telecom networks.
- *WANtime* is not applicable to airspace (as a minimum, up to 20 km AGL altitude over ground level), for the same reason.
- *WANtime* is in general not applicable worldwide to open waters, for the same reason.

Our project assumes that the above reservations are acceptable as they do not imply a real limitation to the target applications that would make use of the service (e.g.; critical infrastructures, power grids, telecom networks, finance and banking datacentres).

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[3] We steer our clocks to UTC(PTB), but we also monitor the difference versus UTC(ROA) via GNSS Common-View.

9. SERVICE ROBUSTNESS

As explained above, *WANtime* is immune to interference or jamming in the GNSS frequencies. On the server side, the clock steering process is physically decoupled from the GNSS measurement collection: a frequency micro-stepper is used between the clock and the GNSS receiver. The application of the steering command is only done a-posteriori at noon on the next day after a number of sanity and consistency checks. If GNSS problems are detected, the clock model is not updated and the steering is based on the extrapolation of the latest model, until GNSS problems are solved or disappear. Even in the case of persistent GNSS interference or jamming, once initialized the system can survive without GNSS at all during months with negligible loss of accuracy.

For both jamming and spoofing, the system checks automatically the level of residuals of the GNSS CV in the adjustment to the clock model, and also the "continuity" of the obtained steering values versus the previous-day values (only reasonably small changes are accepted). The steering is calculated in the early morning but only applied at noon (UTC), so there is plenty of time to react to attacks; we believe that only a very sophisticated hacker with good knowledge of timing could successfully disrupt the service.

On the server, the UTC Time Of Day (TOD) is implemented in a robust multi-source local NTP server that combines TOD from GPS (from one GNSS receiver), TOD from Galileo (from a different GNSS receiver), and TOD from three NTP servers located at different UTC laboratories [RD.3]. In the case of GNSS interference or jamming where the TOD from GNSS is totally lost, the system can survive based on the TOD from the three external NTP servers. NTP selects automatically the "best" source form all the available ones; in practice, the external NTPs are used as a backup.

On the client side the service is totally independent from GNSS, although the GNSS could be used for initial calibration and operational monitoring of the network time signals.

Regarding network security, in the case of time distribution via “private” fibre services we consider that the probability of an attack is small. This applies to all the timing protocols envisaged (DTM, WR, and NTP). In the case of time distribution using NTP over standard internet connections the probability of an attack is higher, and to this purpose we intend to use the new Network Time Security protocol (NTS). In the case of DTM over standard internet connections NTS is in principle not applicable, but since DTM is a proprietary protocol whose description is not publicly available, we consider that the probability a DTM attack is small, even over standard internet.

Eventually, in addition to NTP, the NTS approach could be applied to other network time protocols. If fact, some activity is already underway to adapt NTS to PTP [RD.12]. Since at packet level WR is based on PTP, possibly NTS could be applied to WR as well.

In any case, as explained above, NTS does not *encrypt* the NTP packets, but does *authenticate* the packet exchange. NTS is a new authentication scheme for NTP and fixes many issues of the previous security methods. It uses a separate TLS connection (Transport Layer Security) for the initial parameter and key exchange. The subsequent NTP connection is then secured by NTS extension fields. The functionality of NTP remains untouched and the time data is *not* encrypted by NTS – but authenticated.

The first phase takes place via a TLS 1.2/1.3 connection on a separate TCP channel to protect the initial data exchange from manipulation (see Figure 9-1). Thus NTP shifts the entire overhead of the parameter negotiation to the well-established TLS communication and prevents possible design mistakes when implementing an own handshake solution via NTP. Potential fragmentation of IP packets, e.g., during the transmission of large certificates, is therefore excluded. This procedure also allows the easy use of the PKI (Public Key Infrastructure) structure and the reliable checking of the time server, as long as the certificate issuer is trustworthy.

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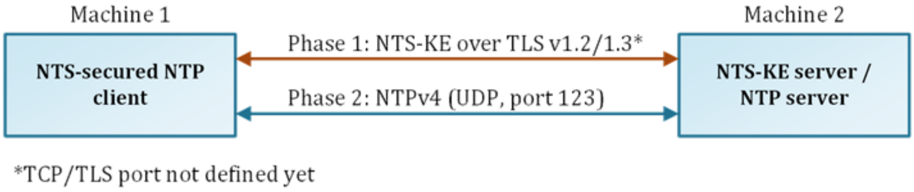

Figure 9-1: NTS: separate communication channels between client and server.

After completion of the TLS handshake and verification of the certificates, the negotiation of the NTS parameters takes place. This is done with so-called NTS Records (or rather TLS records) via the TLS Application Data Protocol. Among other things, the records contain connection information, crypto algorithms and a set of cookies.

Currently there are seven known implementations of NTS, which are in different stages of development. These include NTPsec, Ostfalia, Cloudflare, and Chrony (Red Hat).

10. SUPPORTED ENVIRONMENTS

WANtime is based on time distribution through terrestrial telecom networks, therefore it supports almost all types of terrestrial environments, with the exception of water, underwater, and airspace applications. In particular *WANtime* is capable to provide services in the environments where GNSS cannot be delivered efficiently, including urban canyons, indoor (including deep indoor), and underground.

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11. SUPPORT TO FAST MOVING PLATFORMS

As explained above, *WANtime* is based on time distribution through terrestrial telecom networks, and therefore it cannot support fast moving platforms.

12. PERFORMANCE AFTER GNSS SERVICE LOSS

In this section we describe the performance of *WANtime* service after 1 day, 14 days and 100 days of GNSS services loss. We must distinguish between the performance at server level (driven mainly by the high stability of atomic clocks), and the performance at client level (driven mainly by the distance to the server and the network time protocol and network service employed).

The performance at server level is shown in Table 12-1. The Availability and Continuity values are based on operational experience. We have taken and integrity value of 10-5 per hour as a target (this is equivalent to a probability of one failure every 11.4 years). Such value has been taken from the EGALITE study led by GMV for the EC [RD.13]. As Time To Alarm we have considered the maximum time that the *WANtime* server takes to send an alarm to the operator in case of problems (5 minutes). For the Allan Deviation (ADEV), we have considered as reference the ADEV of the PHM (shown in Figure 3-2), at taus of 1, 14, and 100 days. The value at 100 days was obtained by means of a rough linear extrapolation of Figure 3-2 (plot on the right), and considering that Figure 3-2 is at 2-sigmas, not 3-sigmas.

The initial time accuracy when locked to GNSS is considered to be 2 ns; in case of GNSS the accumulated error is obtained multiplying the ADEV by the corresponding tau, and multiplying by 3 to obtain a 3-sigma value. The initialization time is the time necessary to compute an initial PHM clock model versus UTC, using GNSS time-transfer to a UTC laboratory. Metrological traceability to UTC is obtained using a calibrated receiver traceable to BIPM calibrations, and comparing to final UTC from the Circular T using GNSS time-transfer to a UTC laboratory included in the Circular T, for example UTC(PTB).

Notice that the ADEV shown in Table 12-1 (taken from Figure 3-2) does not contain the PHM frequency drift. This means that even if the clock is in holdover, its deterministic behaviour must be corrected by adjusting a quadratic model and applying a daily deterministic steering (using the stepper).

Table 12-1: *WANtime* performance levels (server).

Performance parameter (X days after GNSS outage)	1 day	14 days	100 days
Availability (%)	> 99.7	> 99.7	> 99.7
Continuity (%/per hour)	> 99.9	> 99.9	> 99.9
Integrity (failures per hour)	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
Time to Alarm (seconds)	< 300	< 300	< 300
Frequency stability (Allan Deviation)	3×10^{-15}	2×10^{-15}	2×10^{-15}
Timing accuracy to UTC (ns, 3-sigma)	3	10	54
Initialization time (days)	10	10	10
Metrological traceability to UTC	Yes	Yes	Yes

The performance at client level is shown in Table 12-2. The Availability, Continuity, and Integrity values are assumed to be the same ones as in the server, assuming no network outages. The Time To Alarm is currently not applicable on the client side, since no alarm system is currently in place. The ADEV at the client is totally dominated by the network jitter and thus we believe this parameter is not so interesting. The timing accuracy is calculated for a "reference case" using DTM over VPN-IP over a distance of up to a few hundred km. Other combinations are possible with better or worse timing accuracy. In principle the timing accuracy on the client depends directly on the accuracy of the server, but since the maximum error at the server is only 54 ns even after 100 days (see Table 12-1), we assume that this effect is negligible on the client. The initialization time on the client is assumed to be zero, since the timing service over the network is nearly instantaneous, assuming that the server has been properly initialized. Metrological traceability to UTC is only partially possible, for example using the *WANtime receiver* (see Section 3.6), which comes calibrated from factory following the procedure developed by GMV [RD.4], against a reference travelling GNSS time-transfer receiver calibrated by the BIPM.

Table 12-2: *WANtime* performance levels (client, for a "reference case").

Performance parameter (X days after GNSS outage)	1 day	14 days	100 days
Availability (%)	> 99.0	> 99.0	> 99.0
Continuity (%/per hour)	> 99.0	> 99.0	> 99.0
Integrity (failures per hour)	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
Time to Alarm (seconds)	N/A	N/A	N/A
Frequency stability (Allan Deviation)	N/A[4]	N/A	N/A
Timing accuracy to UTC (ns, 3-sigma)	< 1000	< 1000	< 1000
Initialization time[5] (days)	0	0	0
Metrological traceability to UTC	Partially	Partially	Partially

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[4] Technically it would be possible to calculate the ADEV at the user, but it would not be very useful as it would be totally dominated by the network jitter; also, it would be difficult to define a priori performance levels for the client ADEV. In any case observations will be recorded at the user (Boecillo) for tests T2x and in the same time at server (PHM) as part of tests T3x.

[5] It assumes that the server has been properly initialized.

13. TEST PLAN

13.1. PROPOSED APPROACH

13.1.1. PROPOSED TEST SITES AND JUSTIFICATION

Given the nature of the WANtime service and the current availability of test platforms, as described above, we propose to carry out the demonstration activities in Spain, at GMV premises in Tres Cantos near Madrid (WANtime server and WR client demonstrators) and in Boecillo near Valladolid (DTM and NTP clients) instead of at JRC premises.

Our approach is justified by the following reasons:

- As indicated, *WANtime* equipment is already set-up at GMV datacentres (HQ and "Boecillo"), and in operation for pilot projects.
- As explained, the proposed approach permits to test the service under different conditions, including different baselines (in terms of distance to the main server station), and combinations of protocols and communication lines (e.g., White Rabbit over "private" fibre links, DTM/NTP over VPN-IP and FTTH).
- Some pieces of *WANtime* equipment made available to the project (see section 15.) are fragile and could be easily damaged during transportation. This is the case for instance of the two PHMs made available to the project.

Note that, in any case, it will possible to monitor the DTM and NTP performance at Boecillo in real time remotely from the JRC (or from anywhere else) using a web client with internet access.

This remote monitor will be used to demonstrate the service at the Test Results Presentation + Live Demo Event to be organised at T0+6 months.

The remote monitoring at the JRC will be possible thanks to a dedicated web application running in Boecillo, using the 1PPS from GNSS as reference and using the internal measuring capabilities of DTM and NTP. Figure 13-1 shows an example of how the web interface looks like.

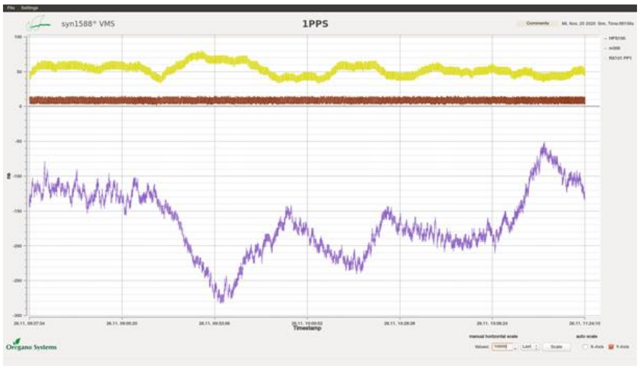

Figure 13-1: DTM and NTP monitoring web.

Apart from graphically displaying the offset in real time, statistical data (mean value, standard deviation, minimum and maximum value) is calculated as well. The web application is capable of reporting any outliers, abnormalities or disturbances in the synchronization performance via email.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

13.1.2.PROPOSED TESTS

From the tests proposed by the EC, we understand that Kinematic and Kinematic 3D tests do not really apply to a network-based timing service such as *WANtime*. The rest of tests (Static, Indoor, Long Term, and Interference) can be combined in a single test scenario in the case of *WANtime*, as shown in Table 13-1.

At "Newton" and Boecillo, the performance of the WR, DTM, and NTP links will be demonstrated against a local *WANtime* receiver (see Section 3.6). The two receivers will have been previously calibrated against the GNSS receiver of Chain-B, following the procedure developed by GMV [RD.4]. The WANtime receivers will also be used to demonstrate (partially) traceability to UTC.

The demonstrations will be based on one of the two time generation chains at the *WANtime* server in Tres Cantos, for example Chain-B. Chain-A will continue to operate undisturbed, for other operational purposes. At the start of the demonstration Chain-B will be properly initialized with a typical maximum error versus UTC of 2 ns. At this point the GNSS receiver of Chain-B will be turned off and the system will continue to operate in holdover mode for the rest of the demonstration, or even longer (up to 100 days) if requested by the EC. Recall that the timing performance at the client in Boecillo can be monitored remotely from JRC via web at any time. The demonstrations will be carried out in Spain over two days in three sites:

- A few weeks (14-21 days) will be necessary to allow Chain-B at the server (in holdover) to accumulate some noticeable time error. At this point a visit to the datacentre in Tres Cantos near Madrid ("Newton" building) will be organized to explain the server setup to the EC.
- On the same day a visit will be organized to the timing lab in "Newton", to demonstrate the performance of the WR link at the client.
- The next day, a visit will be organized to GMV's building in Boecillo near Valladolid, to demonstrate the performance of the DTM and NTP links at the client. Boecillo can be conveniently reached from Madrid in a two-hour car drive.

At "Newton" and Boecillo, the performance of the WR, DTM, and NTP links will be demonstrated against a local *WANtime* receiver (see Section 3.6). The two receivers will have been previously calibrated against the GNSS receiver of Chain-B, following the procedure developed by GMV [RD.4]. The *WANtime* receivers will also be used to demonstrate (partially) traceability to UTC.

Figure 13-2: Schematics of test T2B.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

Table 13-1 shows the list of proposed tests. As explained, all KPIs will be measured using a local *WANtime receiver* and a Time Interval Counter (TIC) to compare the 1PPS from WR/DTM/NTP against the 1PPS from GNSS. The Keysight 53230A counter, shown in Figure 13-3, is available at GMV. Additionally, a web application will be running at Boecillo for permanent and remote comparison of the 1PPS from DTM and NTP against the 1PPS from GNSS.

In all cases, "true" UTC for comparison is provided by the 1PPS from the calibrated local GNSS receiver (*WANtime receiver*). Two UTC realizations are possible from GNSS, the one disseminated by GPS or by Galileo (this is just a matter of receiver configuration). In this demonstration we will use the UTC disseminated by Galileo ("UTC_Galileo" hereafter).

All test data, as defined in Table 13-1, will be duly recorded and made available to the JRC upon request.

Figure 13-2 shows the schematics of test T2B ("DTM over FTTH"). Variations of this setup are used in the rest of tests.

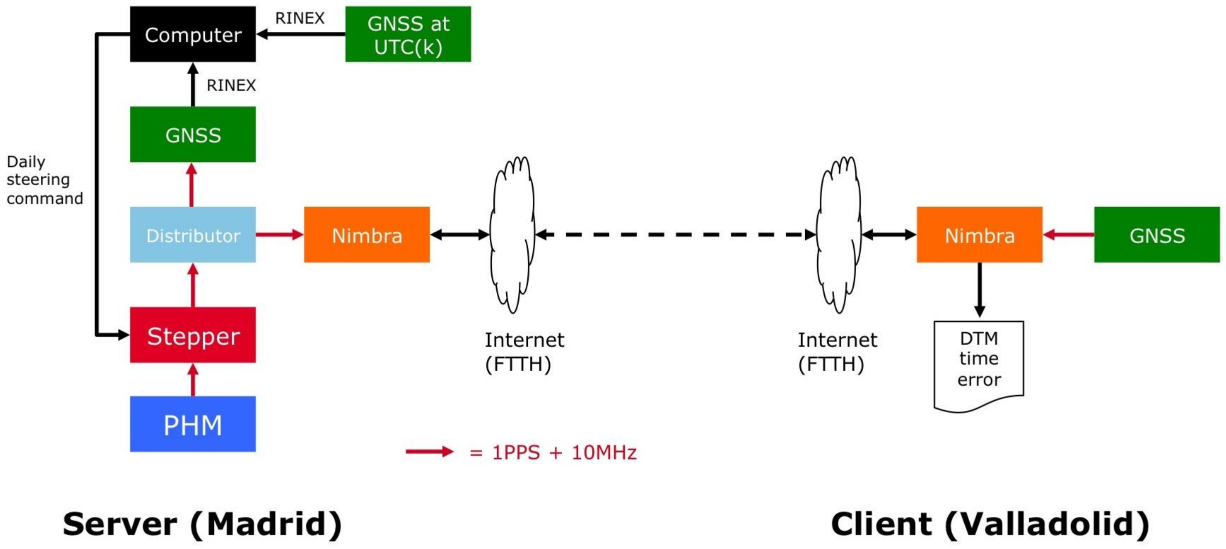

Figure 13-2: Schematics of test T2B.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

Table 13-1: Proposed test plan.

Test ID	Test Name	Objective	Description	Location	Start Time	Duration (days)	Setup	Measurements	Metrics
T1A	**Test Verification and Preparation**	To prepare the infrastructure and software to conduct all the tests below	Preparation of infrastructure and software to conduct all the tests below	All locations below	(September 22, 2021)	1	All equipment below	N/A	N/A
T2A	**White Rabbit**	To demonstrate the performance of WR over a direct fiber link inside a building	Test of the WR link between the datacentre (server) in the basement and the timing lab on the first floor, over direct optical fibre	Timing lab at GMV Newton near Madrid	2 months after start of server Chain A holdover (November 18, 2021)	1	▪ PHM Chain A in holdover ▪ WR-ZEN #1 as server locked to Chain A ▪ Direct fibre link active ▪ WR-ZEN #2 as client ▪ Client GNSS receiver locked to UTC_Galileo ▪ TIC measures WR-ZEN #2 vs GNSS receiver	1PPS time differences between the WR client and a local GNSS receiver, measured with a TIC (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV
T2B	**DTM over FTTH**	To demonstrate the performance of DTM over a "home internet" link across ≈100 km	Test of the DTM link between Newton near Madrid and Boecillo near Valladolid, over FTTH network	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	7	▪ PHM Chain A in holdover ▪ Nimbra box #1 as DTM server locked to Chain A ▪ FTTH fibre link active ▪ Nimbra box #2 as DTM client ▪ Client GNSS receiver locked to UTC_Galileo ▪ Nimbra box #2 measures its time difference vs GNSS receiver	Time difference between the DTM client and the 1PPS from a local GNSS receiver, measured internally by the DTM client (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV

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Test ID	Test Name	Objective	Description	Location	Start Time	Duration (days)	Setup	Measurements	Metrics
T2C	**DTM over VPN-IP**	To demonstrate the performance of DTM over a "VPN" link across ≈100 km	Test of the DTM link between Newton near Madrid and Boecillo near Valladolid, over VPN-IP network	Datacentre at GMV Boecillo near Valladolid	2.5 months after start of server Chain A holdover (December 2, 2021)	7	▪ PHM Chain A in holdover ▪ Nimbra box #1 as DTM server locked to Chain A ▪ VPN-IP fibre link active ▪ Nimbra box #2 as DTM client ▪ Client GNSS receiver locked to UTC_Galileo ▪ Nimbra box #2 measures its time difference vs GNSS receiver	Time difference between the DTM client and the 1PPS from a local GNSS receiver, measured internally by the DTM client (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV
T2D	**NTP over FTTH**	To demonstrate the performance of NTP over a "home internet" link across ≈100 km	Test of the NTP link between Newton near Madrid and Boecillo near Valladolid, over FTTH network	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	7	▪ PHM Chain A in holdover ▪ Raspberry Pi #1 as NTP server locked to Chain A ▪ FTTH fibre link active ▪ Raspberry Pi #2 as NTP client ▪ Client GNSS receiver locked to UTC_Galileo ▪ Raspberry Pi #2 measures its time difference vs GNSS receiver	Time difference between the NTP client and the 1PPS from a local GNSS receiver, measured internally by the NTP client (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

Test ID	Test Name	Objective	Description	Location	Start Time	Duration (days)	Setup	Measurements	Metrics
T2E	**NTP over VPN-IP**	To demonstrate the performance of NTP over a “VPN” link across ≈100 km	Test of the NTP link between Newton near Madrid and Boecillo near Valladolid, over VPN-IP network	Datacentre at GMV Boecillo near Valladolid	2.5 months after start of server Chain A holdover (December 2, 2021)	7	▪ PHM Chain A in holdover ▪ Raspberry Pi #1 as NTP server locked to Chain A ▪ VPN-IP fibre link active ▪ Raspberry Pi #2 as NTP client ▪ Client GNSS receiver locked to UTC_Galileo ▪ Raspberry Pi #2 measures its time difference vs GNSS receiver	Time difference between the NTP client and the 1PPS from a local GNSS receiver, measured internally by the NTP client (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV
T3A	**Long term server holdover**	To demonstrate the holdover capabilities of the PHM over 100 days	Test of the accumulated time error on the server after 100 days in holdover	Datacenter at GMV Newton near Madrid	At the start of server Chain A holdover (September 22, 2021)	100	▪ PHM Chain A in holdover ▪ PHM Chain B steered to UTC(PTB) ▪ TIC measures Chain A vs Chain B	1PPS time differences between the two PHM chains, measured with a TIC (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV

Test ID	Test Name	Objective	Description	Location	Start Time	Duration (days)	Setup	Measurements	Metrics
T2F	**GNSS interference simulation**	To demonstrate the holdover capabilities of the client GNSS receiver clock over 24 hours	Test of the accumulated time error on the GNSS monitoring client after 24 hours in holdover (no GNSS signal)	JRC, Ispra, Italy	4 months after start of server Chain A holdover (January 10, 2022)	1 + 1	▪ UTC realization at JRC active ▪ Client GNSS receiver locked to UTC_Galileo ▪ TIC measures UTC(JRC) vs GNSS receiver during 1 day ▪ Client GNSS antenna is disconnected ▪ Client GNSS receiver in holdover (no GNSS signal) ▪ TIC measures UTC(JRC) vs GNSS receiver (in holdover) during 1 day	1PPS time differences between an independent UTC realization at the JRC and the shipped GNSS receiver (in holdover), measured with a TIC (every second)	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV
T4A	**Resilience and network monitoring**	To monitor the behaviour of the "home internet" and "VPN" network provision from the point of view of time-stamping packet exchange	Monitoring of DTM and NTP packet exchange through the network, over FTTH and VPN-IP	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	14 (During T2B, T2C, T2D, and T2E)	Same as T2B, T2C, T2D, and T2E	Time Forward, Time Backward, Delay, and Offset of DTM and NTP packets	Daily time series and histograms (plots)

Regarding interference testing, in our demonstration this does not really apply as time distribution is done using non-RF telecom networks. However, since GNSS is used to some extent, some minimal testing must be conducted.

On the server side, recall that all tests start already with the GNSS receiver switched off and the PHM in holdover mode. This could be considered a simulated case of severe and persistent GNSS interference at the server location.

On the client side, interference tests will not be carried out by actually jamming the GNSS signals but instead by disconnecting the GNSS antenna of the *WANtime* receiver. A few seconds after disconnecting the antenna the 1PPS coming from GNSS will be lost but the internal disciplined oscillator of the *WANtime* receiver, continuously calibrated by GNSS, will continue to provide a 1PPS signal in holdover. Given the excellent holdover properties of the internal oscillator, which provides a maximum error of 1.0 µs after 24 hours (see Figure 3-9 for a similar type of clock), it will be possible to continue using its output 1PPS as "true time" during several hours after the loss of GNSS. This means that the time error of WR, DTM, and NTP can still be monitored locally for a few hours in case of GNSS "interference" (i.e., disconnection of GNSS antenna). The interference tests will be carried out during 2 days at the end of the nominal tests shown in Table 13-1 (see test T2F).

Additionally, one *WANtime receiver* will shipped to the JRC to execute test T2F (see Table 13-1), but in this case the connection to the *WANtime* server in Madrid would be possible via NTP only, probably with a degradation of accuracy due to the length of the link.

We are aware that interference testing by disconnecting the GNSS antenna is not fully representative of real-life interference events.

Figure 13-3: Keysight 53230A Time Interval Counter (TIC).

However we believe that for demonstration purposes this approach would be sufficient to prove the robustness of the network time solution, without the complexity of using a GNSS simulator or the danger of actually jamming the GNSS signals.

13.2. REQUIRED INPUT / OUTPUT INFORMATION

No particular input information is needed by *WANtime*, except for the usage of GNSS signals on the server side (for initialization of clock model by means of time transfer to a UTC laboratory), and the usage of GNSS signals on the client side (*WANtime receiver*) for calibration of network asymmetry and overall monitoring of the network timing solution.

As output information, the test demonstration will provide mainly comparisons between the output 1PPS signals from the network solution at the client (DTM, NTP, WR) and the reference 1PPS signal from a local GNSS receiver (*WANtime receiver*), considered as "true time". As explained above, the 1PPS signals will be compared using the Keysight 53230A Time Interval Counter (TIC) at "Newton" for WR monitoring, and web application at Boecillo for DTM and NTP monitoring. The reason to use a web application at Boecillo instead of a TIC is the possibility of remote evaluation from the JRC (or from elsewhere) over longer periods of time.

1PPS comparison plots from the TIC and web monitoring application will be generated as needed to demonstrate the results. Additional estimators such as ADEV, TDEV, etc., can be generated from the 1PPS phase comparisons using the Stable32 software on the TIC raw data.

13.3. NEEDED INFRASTRUCTURE

GMV will make available the entire infrastructure necessary for the intended demonstrations at Tres Cantos and Boecillo, which is described in detail in section 15. hereinafter. The service performance at Boecillo can be monitored in real time remotely from the JRC (or from anywhere else) from any web client with internet access.

13.4. REQUIRED RF BANDS AND POWER LEVELS

No dedicated RF signals are used by *WANtime*, apart from open GNSS signals (Galileo and GPS).

13.5. CONSTRAINTS

No particular constraints have been identified for the intended demonstrations at Tres Cantos and Boecillo.

13.6. INTERFACES AND DATA FORMATS

At client endpoint, *WANtime* generates a 1PPS signal for the time service provision, from DTM, WR, and NTP. The generation of 1PPS from NTP is a unique feature that GMV has been recently developing, and is included in our *WANtime receiver* and NTP client (see Section 3.6). The resolution of the 1PPS from NTP is limited to around 1 µ due to the resolution of the internal computer clock and Linux operating system.

In addition to the 1PPS, the DTM and WR clients provide 10-MHz frequency signals, phase-coherent with the 1PPS. The NTP client does not provide a 10-MHz signal.

For DTM and WR, the UTC Time Of Day (TOD) is distributed via NTP, including leap seconds. The NTP connection between the server and the client is authenticated using NTS.

13.7. DATA RETENTION

All test data will be recorded and delivered to the JRC (upon request) for independent processing and analysis.

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14. PERFORMANCE ANALYSIS

14.1. ADDITIONAL PERFORMANCE PARAMETERS

Some of the *WANtime* performance parameters shown in Table 12-1 and Table 12-2 will not be formally tested during the demonstrations, but their achievement can be justified as follows:

- Integrity at the level of 10^{-5} failures per hour (equivalent to a probability of one failure every 11.4 years): This requirement can be verified either by direct observation and measurement after many years of service operation, or by analysis (e.g., identifying all possible failure modes and evaluating their potential impact on performance). In this sense, the pre-operational service currently available is a very valuable tool that is being used to identify potential failure modes to feed at a later development stage (e.g., when higher TRL levels are targeted) a dedicated the service integrity performance analysis.
- Time to Alarm at the server can be justified by demonstrating the *WANtime* email-based alarm system during the visit to the datacentre in Tres Cantos. The room temperature is controlled in real time, and also the deviation of the two time generation chains from each other (using a Time Interval Counter), and the deviation of each chain from GNSS time. All these parameters are measured every 5 minutes and displayed on the web, and email alarms are sent if predefined thresholds are surpassed.
- Frequency stability (ADEV) at the server can be calculated on demand, for each of the two PHMs, and for the resulting *WANtime* time scale after steering, versus UTC(PTB) via GNSS time transfer.

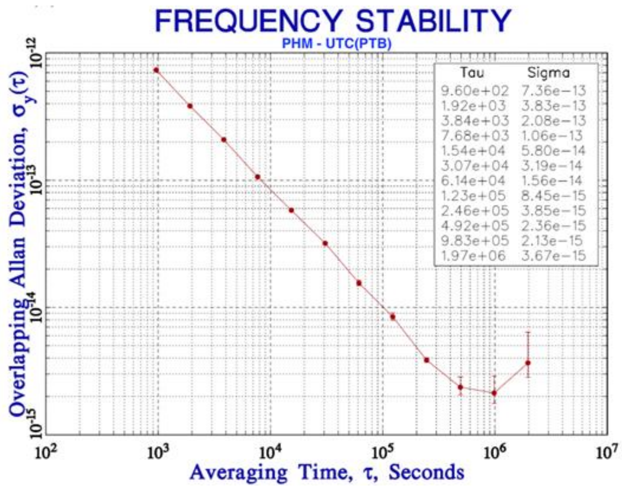

Figure 14-1: Example of PHM ADEV versus UTC(PTB) from Stable32 software.

ADEV and other estimators such as MDEV, TDEV, etc., can be easily calculated easily with the well-known Stable32 software. An example of is shown in Figure 14-1 for one of the two PHMs up to a tau of 23 days, calculated from a period of 100 days in 2020.

14.2. EXAMPLES OF CURRENT PERFORMANCE

This section includes some recent results obtained using DTM and NTP in the link between Tres Cantos and Boecillo described in Section 5. . Recalled that the link is based on one inexpensive (but dedicated) “home internet” connection on each side. The network service is called Fibre To The Home (FTTH), provided by Telefónica. Both sites have a symmetric bandwidth of 300 Mbps. By “dedicated” we mean that the connections are exclusively used for DTM and NTP time-transfer packet traffic between the two sites.

Recall that on the server side (Tres Cantos) the time signals comes from the very precise *WANtime* time scale, which can be considered a “perfect” realization of UTC. This time scale is distributed via DTM and NTP to Boecillo. On the client side (Boecillo), a calibrated GNSS receiver is used as reference to monitor the DTM and NTP error. The DTM client is a Nimbra box that is able to monitor to measure autonomously its time error versus GPS, by injecting 1PPS and 10-MHz signals form the GNSS receiver. The NTP client is a Raspberry Pi (RPi) running Chrony as NTP daemon. The 1PPS from GNSS is injected into the RPi through one of its GPIO pins. The RPi can measure its time error versus GNSS using Chrony commands. The results over December 11-13, 2020, are shown in Figure 14-2. The plot on the right shows the same DTM results as the plot on the left, but with a different scale on the Y-axis.

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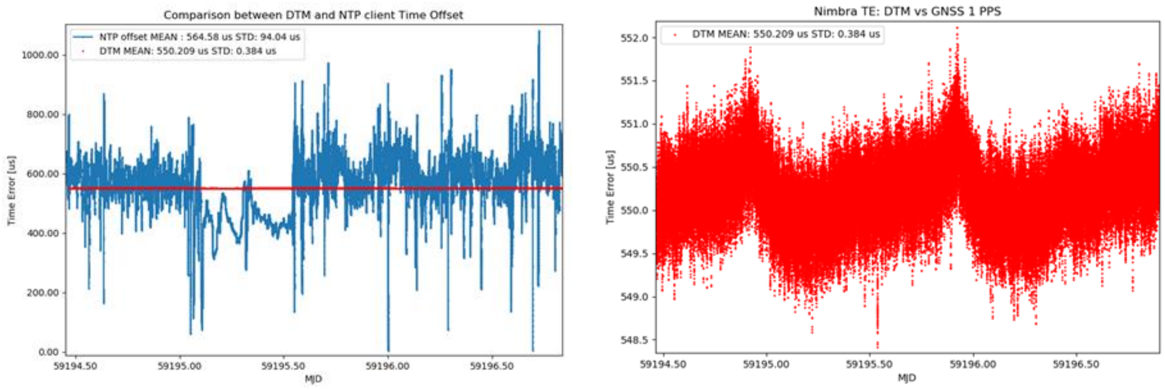

Figure 14-2: DTM and NTP time error at Boecillo (DTM zoomed-in on the right).

As can be seen, both DTM and NTP show a large but constant offset versus GNSS (around half a ms). This means that in principle it would be possible to calibrate the link using GNSS. The DTM noise is much smaller than the NTP, with a standard deviation of 384 ns, which is slightly above the EC requirement for the Alternative PNT demonstrator (333 ns at 1-sigma). The NTP results have been obtained in a very preliminary way, by increasing the Chrony packet rate to the maximum possible by configuration (16 messages per second), and by selecting only "lucky packets" with a minimum total delay. As can be seen, the resulting NTP noise is still quite high (94 us).

Further work must be done to decrease the NTP noise, ideally down to 1 to 10 us (1-sigma). This could be done using a combination of techniques such as further increasing the message exchange rate (similarly to DTM), developing a smarter way of selecting "lucky packets" with minimal jitter, using network cards with hardware time-stamping, and tuning the clock-disciplining algorithm accordingly.

Both in DTM and NTP, special attention must be paid to possible network reconfigurations that could change the average offset. Ideally such reconfigurations should be detected and mitigated automatically, in order to obtain a jump-free time solution. As explained above, the usage of a more professional network will be explored for the demonstration.

15. EQUIPMENT, TOOLS AND FACILITIES AVAILABLE FOR THE EXECUTION OF THE TASKS

A summary list of equipment, tools and facilities available for the execution of the tasks is presented in the following table:

Table 15-1: Equipment, tools and facilities available for the execution of the tasks.

#	Category	Item Name	Description	Number of Units Available	Remarks
E1	Equipment	Passive Hydrogen Maser (PHM)	Vremya/T4Science PHM 1008 See section 3.1 for further details.	2	Currently installed and running at GMV's HQ datacentre.
E2	Equipment	High-Resolution Frequency Stepper	SpectraDynamics HROG-10 See section 3.2 for further details.	2	Currently installed and running at GMV's HQ datacentre.
E3	Equipment	DTM Media Transport over IP	Nimbra 390 See section 3.3 for further details.	2	Currently installed and running at GMV's Tres Cantos and Boecillo datacentres.
E4	Equipment	White Rabbit Grandmaster	Seven Solutions WR-ZEN-TP See section 3.4 for further details.	2	One unit currently installed and running at GMV's HQ datacentre. The second one will be used as end user WR node in the proposed tests.
E5	Equipment	Timing Receiver	GMV's *WANtime receiver* See section 3.6 for further details.	2	Both units will be available for tests in order to generate the measurements for KPIs evaluation.
E6	Equipment	*WANtime* processing, control, and monitoring software	The TOWR SW package is used for the generation of the *WANtime* timing service. The TOWR SW package has been developed by GMV.	N/A	Installed and running at GMV's HQ datacentre.
E7	Equipment	Time Interval Counter	Keysight 53230A See section 13.1 for further details.	1	To be used to compare the 1PPS from WR against the 1PPS signal generated by the GNSS Timing Receiver.
E8	Equipment	Time Interval Analyser	Web monitoring application See section 13.1 for further details.	1	To be used to compare the 1PPS from DTM/NTP against the 1PPS signal generated by the GNSS Timing Receiver. This unit will be installed at Boecillo datacentre.
F1	Facilities	GMV's HQ Datacentre	GMV HW Datacentre is currently hosting the *WANtime* timing server.	N/A	
F2	Facilities	GMV's "Newton" timing lab	Some of the proposed tests will be executed at GMV's "Newton" timing lab.	N/A	
F3	Facilities	GMV's "Boecillo" Datacentre	Some of the proposed tests will be executed at GMV's "Boecillo" Datacentre as indicated in Table 13-1.	N/A	
T1	Tools	Processing SW tools for KPIs Evaluation	GMV's toolset for timing KPIs evaluation.	N/A	

16. TEST STATUS AND RESULTS

Table 16-1 shows the current status of the tests. Some columns of the table have been removed for better readability. In view of the unsatisfactory results of the original **T2C** (DTM over VPN-IP), a new test T2C is proposed recovering DTM over MPLS results obtained in 2021 during a GMV project with ESA called *UTIME* [RD.14].

Table 16-1: Test status.

Test ID	Test Name	Location	Start Time	Duration (days)	Metrics	Status
T1A	**Test Verification and Preparation**	All locations below	(September 22, 2021)	70	N/A	Finished
T2A	**White Rabbit**	Timing lab at GMV Newton near Madrid	2 months after start of server Chain A holdover (November 18, 2021)	1	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Successful Results available
T2B	**DTM over FTTH**	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	7	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Successful Results available
T2C ***NEW***	**DTM over MPLS** *Results from project UTIME* [RD.14]	GMV offices in Munich, Germany, with server in Darmstadt, Germany	July 21, 2021	7	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Successful Results available
T2D	**NTP over FTTH**	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	7	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Unsuccessful
T2E	**NTP over VPN-IP**	Datacentre at GMV Boecillo near Valladolid	2.5 months after start of server Chain A holdover (December 2, 2021)	7	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Partially successful Results available
T3A	**Long term server holdover**	Datacenter at GMV Newton near Madrid	At the start of server Chain A holdover (September 22, 2021)	100	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Finished Successful Results available
T2F	**GNSS interference simulation**	JRC, Ispra, Italy	4 months after start of server Chain A holdover (January 10, 2022)	1 + 1	Average and standard deviation of time error, maximum time error, MTIE, TDEV, ADEV	Pending
T4A	**Resilience and network monitoring**	Datacentre at GMV Boecillo near Valladolid	2 months after start of server Chain A holdover (November 18, 2021)	14 (During T2B, T2C, T2D, and T2E)	Daily time series and histograms (plots)	Finished Successful Results available

In the following sections we present the most relevant results and findings of the tests.

16.1. T2A – WHITE RABBIT

This test case evaluates a WR link between the atomic clock server in the basement and the timing lab on the first floor of GMV's building in Madrid, over direct optical fibre. 1PPS time differences between the WR client and a calibrated local GNSS receiver are measured with a TIC (every second). The results are shown in Figure 16-1 (top left). Here the noise is actually dominated by the error in the local GNSS receiver, the WR error in such a short link is normally of the order of **1 ns**. ADEV, TDEV, and MTIE for the corresponding period are also reported in Figure 16-1.

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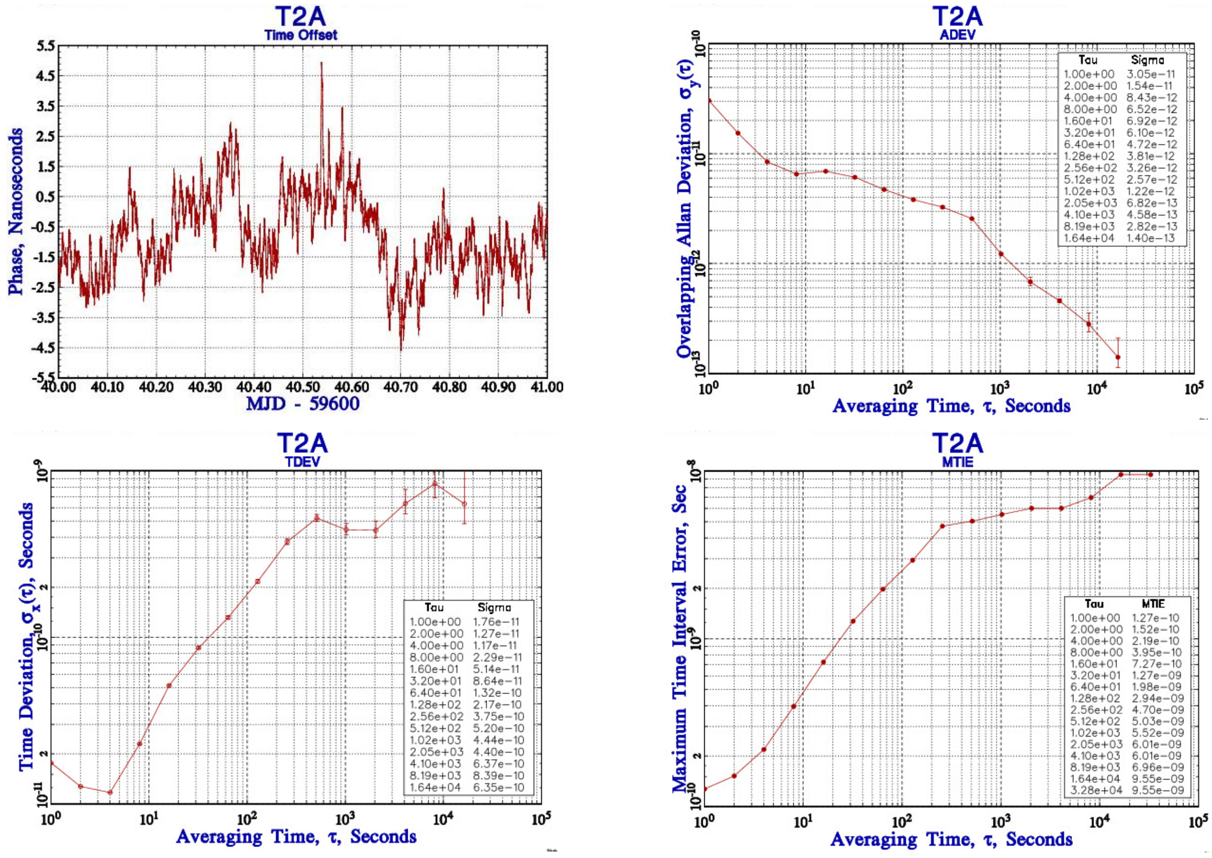

Figure 16-1: WR error over direct fibre.

16.2. T2B - DTM OVER FTTH

This is the most relevant test case providing the most promising results over inexpensive networks. The general result is that the DTM error at the client (measured against a local calibrated GNSS receiver) is quite stable, with a jitter of the order of 1 microsecond over one day. The time error is affected by a daily "bump" occurring every night with an amplitude of around 4 microseconds. Outside the hours affected by the bump, the jitter is smaller, of the order of 300 ns. These errors are measured by the client Nimbra box autonomously, by injecting into it the 1PPS from the local GNSS. An example is shown in Figure 16-2 (left). When measuring the output 1PPS from the Nimbra against the 1PPS from GNSS, the jitter is roughly halved, i.e. it is reduced from 300 ns to **150 ns**, as can be seen in Figure 16-2 (right). Except for a constant offset that will be discussed below, this result fulfils the EC requirement of 1-microsecond error at 3 sigmas (i.e. **333 ns** at 1 sigma).

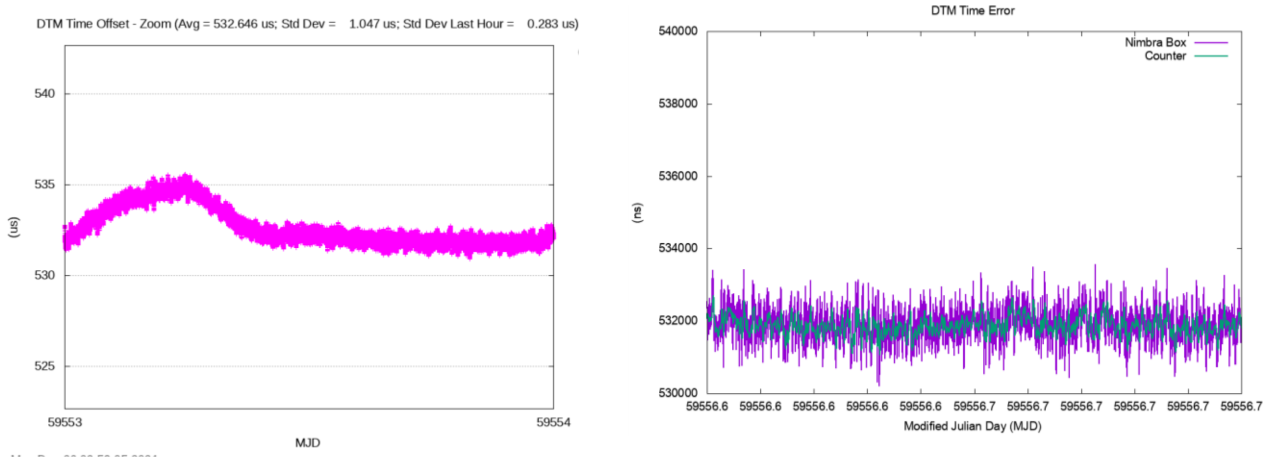

Figure 16-2: DTM error measured autonomously (left) and by a counter (right).

When measured over several days, one can see that the daily pattern is repeatable, with the apparition of occasional peaks. Figure 16-3 (top left) shows an example of DTM error over 6 days. Notice that the constant offset is quite large, of the order of half a millisecond. ADEV, TDEV, and MTIE for the corresponding period are also reported in Figure 16-3.

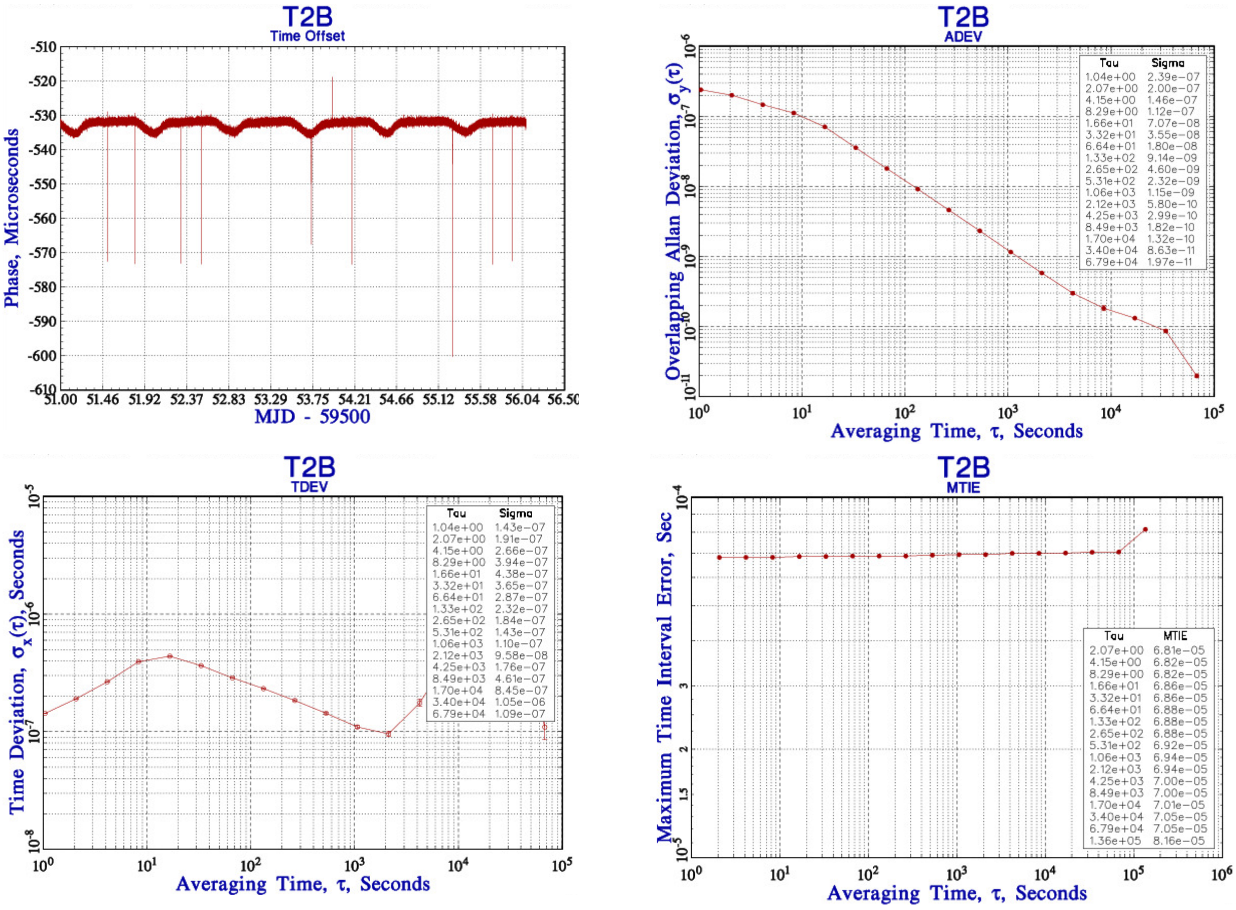

Figure 16-3: DTM error over FTTH.

From time to time, every several days, there is a sudden jump in the mean offset. An example can be seen in Figure 16-4, with a jump of around 250 microseconds.

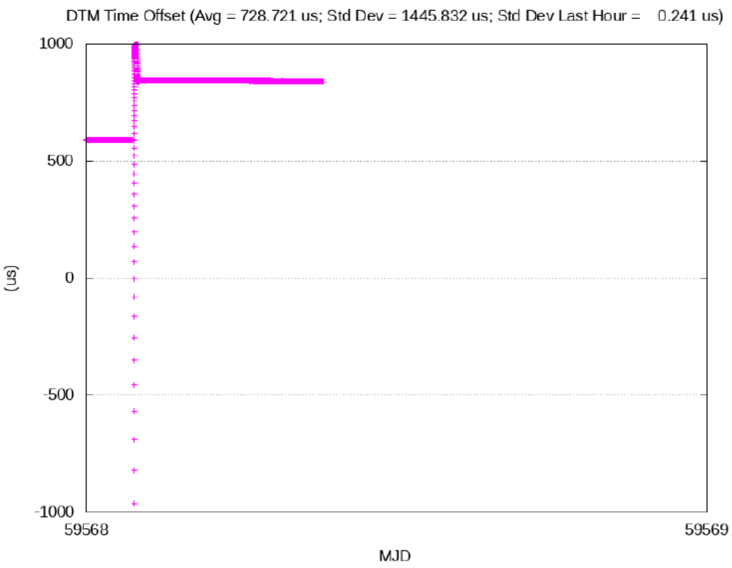

Figure 16-4: Jump in mean DTM offset.

There are typically 4 or 5 such jumps every month. The jumps are believed to be due to network reconfigurations, i.e. changes in the forward and/or backward paths of the DTM packets.

We are currently discussing with Net Insight and testing a new Nimbra firmware to mitigate the main problems that have been observed, namely the jumps in mean offset, the daily bump, and the occasional peaks. Notice that in any case a mean (and eventually constant) offset will always be present in the link, due to the asymmetry of the network. This offset can be calibrated with GNSS or by other means. Once the link has been calibrated and removed, it could continue to operate continuously without GNSS, meeting the overall requirement of 1-microsecond error at 3 sigmas.

16.3. T2C - DTM OVER MPLS

NEW test

In view of the unsatisfactory results of the original T2C test (DTM over VPN-IP), a new T2C test is proposed recovering results obtained in 2021 during a GMV project with ESA called *UTIME* [RD.14]. In this test the DTM server is located in Darmstadt, Germany, connected to a local calibrated multi-band GNSS receiver (not an atomic time scale), and the DTM client is in Munich, Germany. The distance between the two sites is around 300 km. The DTM error is measured relative to another local calibrated multi-band GNSS receiver. The network link is based on an MPLS access on each side (around 600€ per month per site).

The results are excellent as can be seen in Figure 16-5 (top left), with a mean offset of **243 ns** and a standard deviation of **141 ns** around the average. Notice that no additional mean offset has been artificially removed from the results: the small 243-ns offset proves the good symmetry of the MPLS link. As can be seen, the maximum time error over one week is **500 ns**, which fulfils the EC requirement of 1-microsecond error by a factor of two. ADEV, TDEV, and MTIE for the corresponding period are also reported in Figure 16-5.

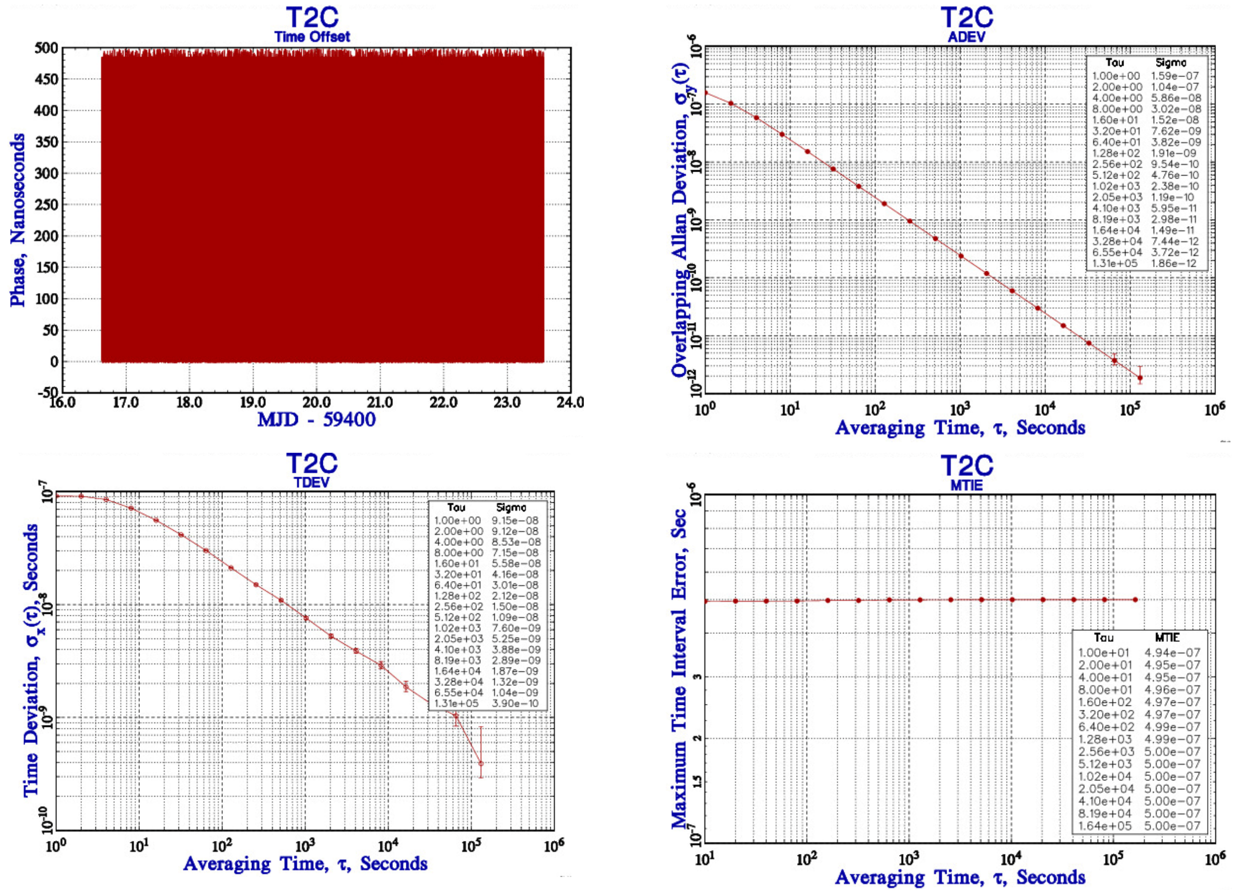

Figure 16-5: DTM error over MPLS.

16.4. T2D - NTP OVER FTTH

The usual configuration of NTP is to exchange packets over the Internet between server and client only every several seconds or even minutes. In our configuration we try to maximize the packet rate as much as possible in order to select only “lucky packets” with minimum delay (and therefore minimum jitter) for the NTP discipline algorithm. Previous tests showed that as a minimum of 8 packets per second are needed to get a noticeable improvement with respect standard NTP. It turns out that our FTTH access was not able to keep up the minimum packet rate needed, and the NTP client was not able to lock on the server, therefore the test was unsuccessful.

16.5. T2E - NTP OVER VPN-IP

See T2D above for an introduction of NTP testing. Contrary to FTTP, our VPN-IP access was able to cope with NTP exchange rates of up to 64 packets per second. However, even after tuning NTP by selecting packets with minimum delay, the resulting jitter was still rather high, around 40 microseconds, as can be seen in Figure 16-6 (top left). ADEV, TDEV, and MTIE for the corresponding period are also reported in Figure 16-6.

The general conclusion about NTP is that this technology would need a major upgrade at hardware, algorithmic, and software level in order to reach a level of accuracy similar to DTM. GMV is investigating means of funding such NTP development.

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.

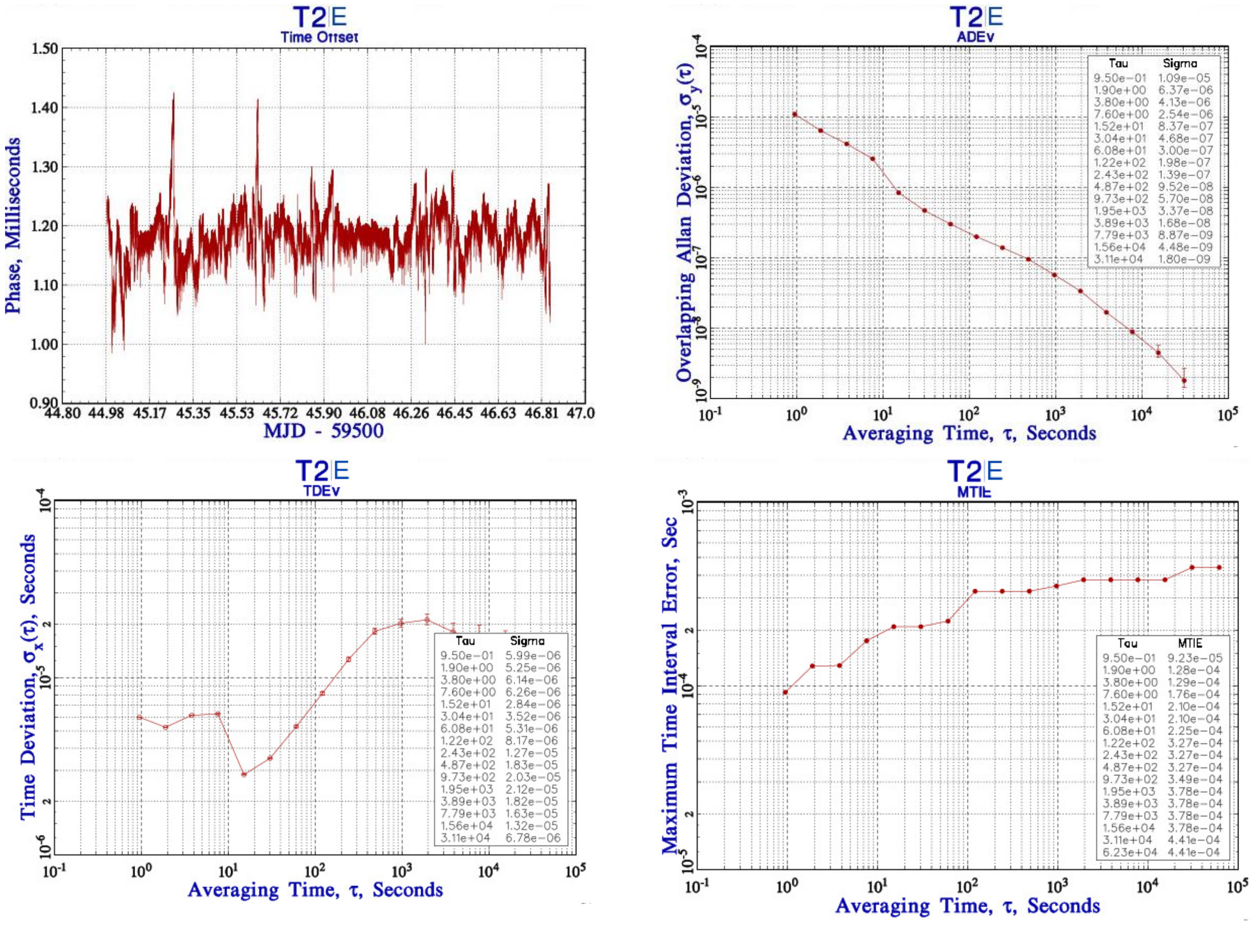

Figure 16-6: NTP error over VPN-IP.

16.6. T3A - LONG TERM SERVER HOLDOVER

The PHM of Chain A was set in holdover mode on September 23, 2021 (MJD 59480). The accumulated time error is measured by means of time interval counter with respect to Chain B. The PHM of Chain B is continuously steered to UTC(PTB) by means of GNSS Common-View, therefore the measured accumulated error of Chain A can be considered to be the true error versus of UTC, with an uncertainly of just a couple of ns. Figure 16-7 shows the accumulated error of Chain A after 100 days in holdover. As can be seen, the error is around 57 ns, which is slightly above the target of 54 ns at 3-sigmas after 100 days. ADEV, TDEV, and MTIE for the corresponding period are also reported in Figure 16-7.

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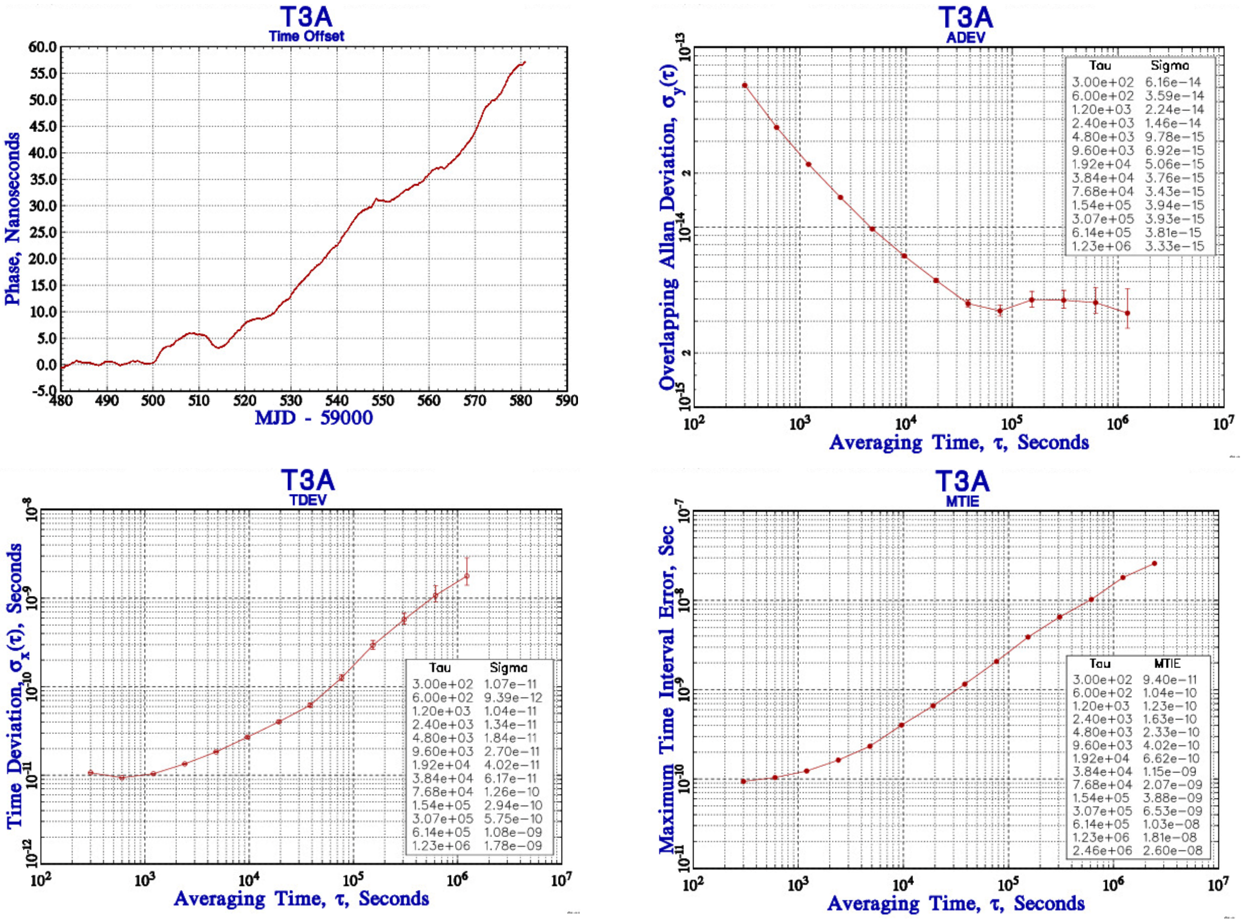
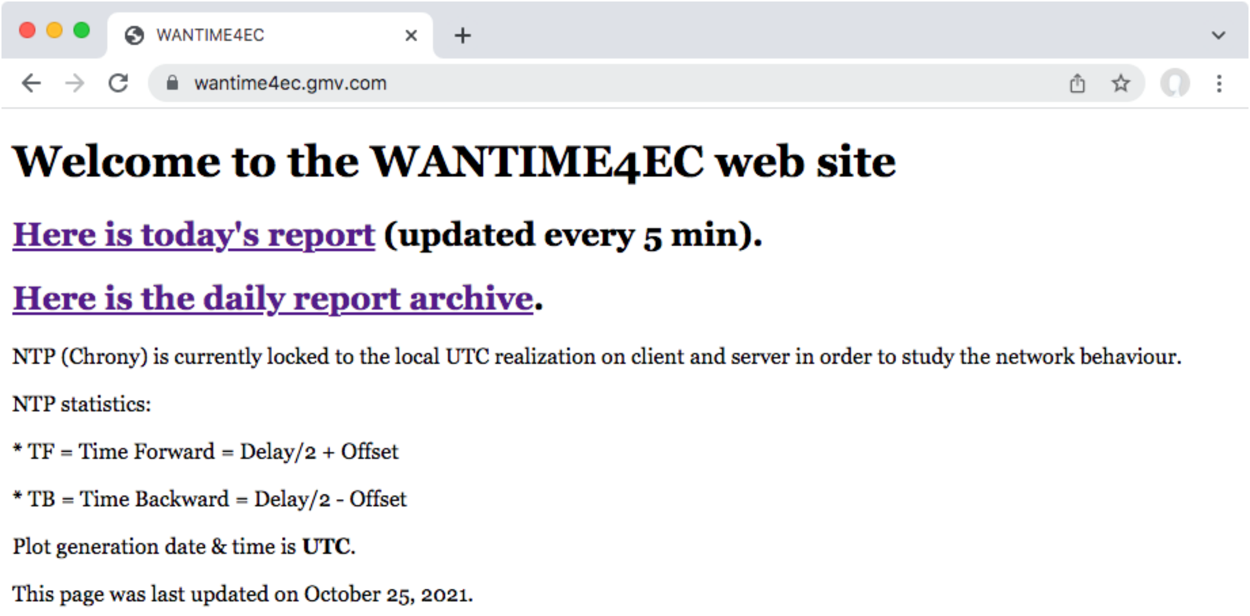


Figure 16-7: PHM error in holdover.

16.7. T4A - RESILIENCE AND NETWORK MONITORING

The purpose of this test is to monitor the behaviour of the "home internet" and "VPN" network provision from the point of view of time-stamping packet exchange. To this purpose measure the Time Forward, Time Backward, Delay, and Offset of NTP packets, in the form of daily time series and histograms (plots). A daily report is generated automatically every day with DTM time error and NTP histograms. The report for the current day is updated every 5 minutes in order to show "real-time" results. The historical series of daily reports is also stored. All this information can be accessed from a very simple web site (https://wantime4ec.gmv.com/) whose main page is shown in Figure 16-8.



Welcome to the WANTIME4EC web site

Here is today's report (updated every 5 min).

Here is the daily report archive.

NTP (Chrony) is currently locked to the local UTC realization on client and server in order to study the network behaviour.

NTP statistics:

* TF = Time Forward = Delay/2 + Offset

* TB = Time Backward = Delay/2 - Offset

Plot generation date & time is **UTC**.

This page was last updated on October 25, 2021.

Figure 16-8: WANTIME4EC demonstration project web page.

Shows an example of NTP daily histograms generated with Delay and Offset values from the Chrony log file. Recall that on NTP the server and client clocks are both locked to UTC in order to analyse the true network behaviour in absence of clock errors.

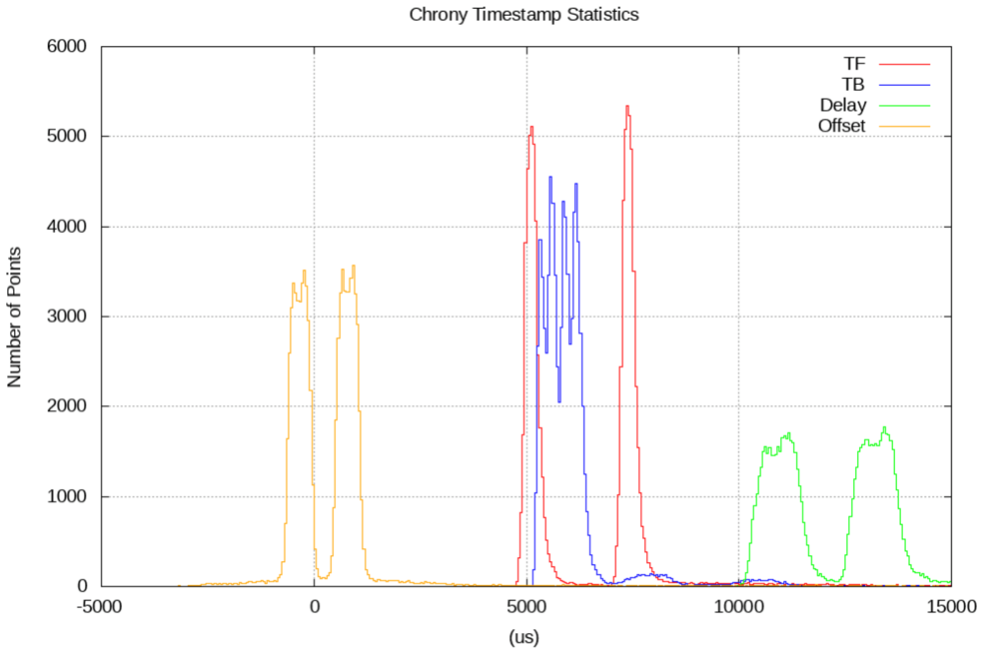


Figure 16-9: Example of NTP daily histograms.

END OF DOCUMENT

The WANTIME4EC project is funded by the European Commission under contract DEFIS/2020/OP/0007.