EXECUTIVE SUMMARY

TIGHT

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Version	Date	Pages	Changes
1.0	13/01/2023	12	Document delivered for project closure.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. PURPOSE AND SCOPE

This document is the final output of the TIGHT project, related to the closure documentation presented for the Final Review of the project.

Its main scope is to summarize the achieved objectives of the TIGHT project and to reflect the general conclusions of the new time transfer process.

1.2. ACRONYMS

The following acronyms have been used across this document:

Table 1-1 Acronyms.

Acronym/Abbreviation	Meaning
1PPS	One Pulse Per Second
BIPM	Bureau International des Poids et Mesures
CGGTTS	Common GNSS Generic Time Transfer Standard
CV	Common View
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GNSST	GNSS Time (i.e., GPSt or GST)
GPSt	GPS Time
GST	Galileo System Time
PHM	Passive Hydrogen Maser
PPS	Pulse Per Second
PTB	Physikalisch-Technische Bundesanstalt
RF	Radio Frequency
ROA	Real Observatorio de la Armada
TIC	Time Interval Counter
ToD	Time of Day
TOWR	Time Over White Rabbit
UTC	Universal Time Coordinated
UTCa	Real-time UTC approximation from averaging several UTC(k) time scales
UTC(k)	A national UTC timing laboratory, where *k* is the lab code (e.g., *k* = PTB, ROA, NPL)
WR	White Rabbit

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents are applicable to the TIGHT project:

Table 2-1: Applicable Documents.

Ref.	Title	Code	Version	Date
[AD.1]	TIGHT Proposal v2	GMV 11261/19	V2/19	July 12, 2019
[AD.2]	TIGHT Contract between ESA and GMV	4000128040/19/NL/CRS	--	September 02, 2019
[AD.3]	TIGHT Contract Change Notice 1			August 18, 2021
[AD.4]				
[AD.5]				

2.2. REFERENCE DOCUMENTS

The following additional documents are referenced in this document:

Table 2-2: Reference Documents.

Ref.	Title	Code	Version	Date
[RD.1]	CALIBRATION PROCEDURES REVIEW TRADE-OFF	GMV-TIGHT-TN1	1.0	11/12/2019
[RD.2]	PROCEDURE FOR THE CALIBRATION OF GNSS AND HGA CHAINS	GMV-TIGHT-TN2	2.0	27/11/2020
[RD.3]	COMMON VIEW TIME TRANSFER METHODOLOGY	GMV-TIGHT-TN3	3.0	27/11/2020
[RD.4]	EQUIPMENT CALIBRATION RESULTS	GMV-TIGHT-TN4	2.0	07/10/2022
[RD.5]	COMMON VIEW TEST RESULTS	GMV-TIGHT-TN5	3.0	13/01/2023

3. EXECUTIVE SUMMARY

3.1. PROJECT OVERVIEW

The TIGHT (Time Transfer using High Gain Antennas) project final objective was to establish a permanent and alternative time-transfer link between ESOC and ESTEC. The link needed to be operational, inexpensive to operate, accurate and precise, potentially surpassing in cost efficiency and performance other techniques such as TWSTFT and optical fibre. In order to achieve such objective we needed to streamline and optimize the individual objectives and requirements of the ITT, and analyse them with a critical mind giving higher priority to the accomplishment of the main project objective.

The above objectives were to be fulfilled by using a code-based GNSS time transfer, exploiting the capabilities of High Gain Antennas. These antennas although not capable of having more than one in view, leverage this providing a better SNR for the GNSS signals, as well as potentially reducing the environmental effects and multipath around the antenna.

For this purpose GMV, together with Prodetel, proposed the use of COTS antenna dish, together with a newly designed and manufactured dish for the L-band reception as the main hardware piece of the project. The dish and antenna is moved by commercial motors that allow for a visibility range from 0 to 90 of elevation, and from 90 to 270 of azimuth visibility.

Having two such antennas in ESTEC and ESOC sites, allows for an almost continuous tracking of the Galileo satellites pass by pass considering a common reference point for the visibility in the middle of the two stations (Grevenbroich, DE). For the purpose of having the best possible accuracy in the link solution we performed a relative common-clock calibration of the two HGA chains in Spain, before shipping them to ESA sites. Once in ESA, the procedure for the time transfer between the two stations, using CGGTTS files was automatic and the tests and experimentation phases where done.

At the end of the project, the fulfilled objectives can be summarized as:

- A new HGA hardware has been designed, developed and manufactured for the use of the TIGHT project. These antennas are able to fulfil the project objectives for the continuous time transfer, as well as having a medium cost, making use of new and COTS elements.
- The time transfer procedure between ESOC and ESTEC has been demonstrated to run continuously and with minimum intervention over long periods of time, achieving very good precision in the solution, with minimum values over certain periods of 150 ps.
- Multiple methods and comparisons have been studied and executed regarding the calibration of the elements in the HGA chain. In particular for the antenna element, the initial demonstration is promising regarding the possibility of the absolute feed-only calibration, and adding the dish a-posteriori using a simulation environment.
- The accuracy of the Time Transfer solution is slightly above the expectations, and it is believe to be a calibration offset, which is still under study.
- A thorough review and analysis of potential effects observed in the GNSS code-based time transfer (i.e. GDV, tropo, Graphic, etc.) have been done. With a baseline solution including the most promising solutions to reduce the effects and minimize the final error budget, while being operationally feasible.
- Finally, an initial investigation on the use of SW receivers for TT was done, coming to the conclusion that more powerful hardware is needed w.r.t. SRX3, in order to provide a precision rivalling the continuously tracking receiver.

After the project execution, and considering all the outputs, results and final installation, some of the main topics left open for potential future work can be summarized in:

- Migration of the infrastructure hosted in external servers, into ESA's own infrastructure.
- Absolute calibration of the TURN receivers to have a better comparison of the HGA feed only values.
- Calibration of the second antenna feed in order to validate the initial measurements, and to have the end to end chains absolutely calibrated for the comparison.
- Comparison against other absolutely calibrated chains (i.e. ILMP) for validations of the absolute calibration values.

- Include an automatic processing of NAGUS, to add and remove satellites from the Scheduling software.

3.2. TIGHT SOLUTION DESCRIPTION

The overall setup for the TIGHT experiment working continuously and performing the Tim Transfer is mentioned hereafter:

- High Gain Antenna (HGA)
- Antenna Control Unit (ACU)
- Timing GNSS receiver
- Controlling PC (Raspi4)
- Logging PC (for TURN)
- Processing server

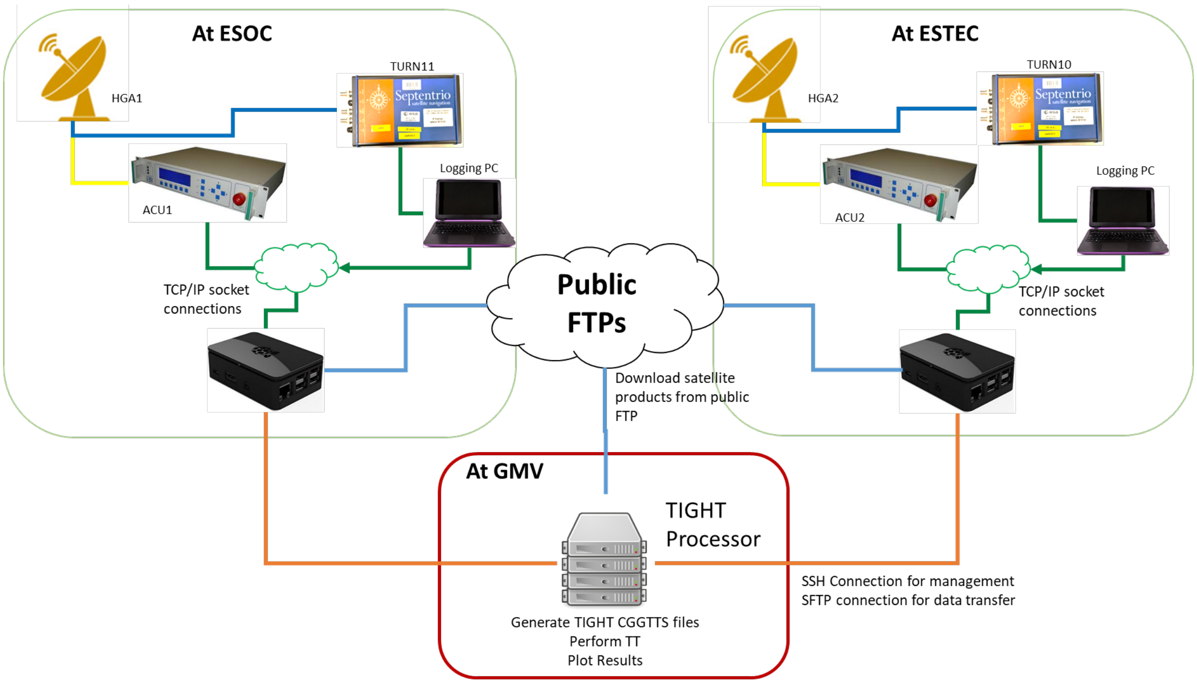

Figure 3-1: Final TIGHT Time Transfer setup when using TURN V2 receivers

In Figure 3-1 we can see the different elements mentioned, and the connections between them. The following connections are needed for the correct functioning of the TIGHT process:

- TCP/IP connection
- Public FTP access
- SSH/SFTP connection from the processing PC to the two sites.

We can see that the hardware setup is not very complex, and could be centralized on one site, while on every other node we could only deploy the HGA, the receiver and the raspi. With this schema, multiples sites could become part of the experiment with a minimum (not considering the antenna) size. The images of the HGAs installed at ESTEC and ESOC can be seen in Figure 3-2.

Figure 3-2: Final Antenna installation in ESTEC (left) and ESOC (right) rooftop

The general concept for GNSS Common-View time transfer using HGA chains is essentially not very different to the classical approach using omni-directional antennas (CGGTTS or PPP techniques). The main differences are the following:

- In the HGA approach, only one satellite is tracked at any time: satellite averaging per epoch (as in CGGTTS) is not possible/needed, and multi-parameter estimation techniques such as PPP are simply not possible.
- During the project, two satellite tracking techniques were tested: usage of standard GNSS receivers (and thus classical pseudorange differencing as in CGGTTS) or usage of RF recorders (and cross-correlation techniques) which was finally discarded due to complexity and HW non-compliances. In both cases, geometrical, orbit and tropospheric corrections must be applied (see next bullets).
- In our HGA design, the Calibration Reference Point (CRP) is the nominal (conventional) antenna point where pseudorange measurements are acquired, but this point has no fixed position with respect to the Earth. A geometrical transformation in needed between the Antenna Reference Point (ARP) and the CRP. By contrast, a constant antenna phase centre position is used as input in CGGTTS, and the antenna marker position is estimated in the PPP process (which is not possible in the HGA approach). The estimation of the ARP and the transformation from ARP to CRP is critical for the success of the project and is discussed below.
- Regarding tropospheric corrections, the application of the relatively simple "STANAG" model used in CGGTTS is a factor to be reduced in order to obtain the best time-transfer precision. During the project the processing of PPP tropospheric products was implemented and included in the process.
- The impact of the satellite Group Delay variations was also assessed, and a procedure was implemented to apply their corrections in the CGGTTS files. Nevertheless the impact was very small compared to the final noise level, and the corrections not fully validated so in the end the correction was not included in the nominal time transfer process.
- Given the lower noise level of the pseudoranges, the CGGTTS file REFSYS precision needs to be improved. Thus the generation have been updated to output the CGGTTS with 1 ps resolution.

Apart from these differences, the overall time transfer procedure is fairly straightforward, as the receiver is able to generate an observation RINEX file, which is then transformed to a CGTTS file (using the modifications described above) and the two CGGTTS files from both stations are differentiated to obtain the time transfer value. Such a process allows also for an easy comparison with other CGGTTS generated in other stations, only taking into account each file resolution.

3.3. TESTS OUTCOME

Overall, the results for the different experimentation phases done during the project follow closely the trend of the time transfer solution from ESA, but with an offset due to the calibration. As an example, we show the results over the TURN experimentation period in Figure 3-3. In the figure we observe that several breaks have happened during the campaign. The major one happened during the calibration campaign of the feed, as it had to be dismounted and mounted again after the measurement was finished. Other breaks are due to errors in the logging PCs, were one of the two chains failed to LOG properly the files (due to network shutdown, laptop reboot, or other issues).

Looking closely at the plot, it can be seen how initially the comparison was quite clean of outliers and the TIGHT solution had very small deviation, nevertheless, in the second block, from 59655 to 59710 the comparison ran automatically without interruptions, but multiple outliers started to happen. Changes in the antenna environments should be looked for to identify the reason behind these.

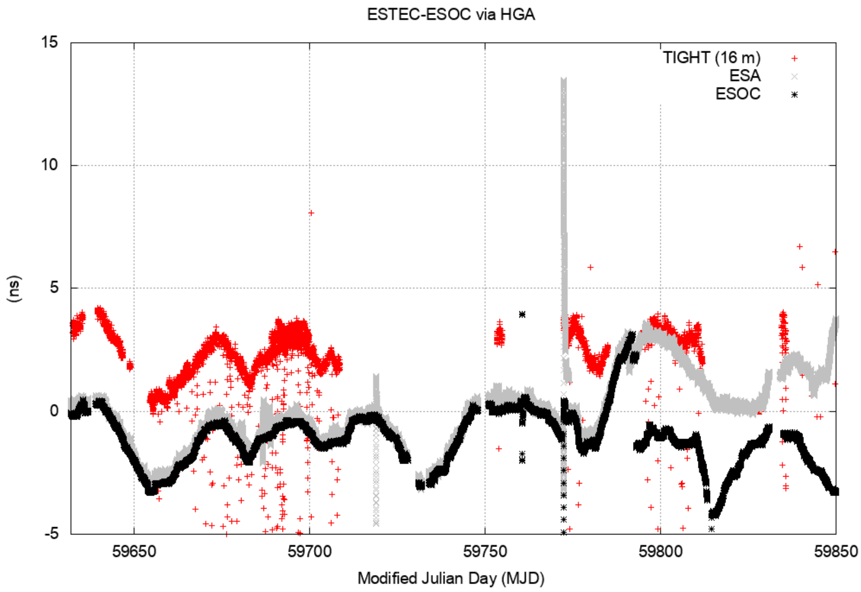

Figure 3-3: Time transfer comparison for the full TIGHT experimentation phase 2

In Figure 3-4 we can see the results of the TIGHT solution versus the PPP for the first period of the experimentation, where a cleaner solution was obtained. Even if this period had a larger offset than what observed afterwards for the full duration, the solution precision is the best obtained so far, getting close to the 100 ps. This serves as an example of what might be considered the best achievable results for this Time Transfer process.

Overall the results in the second experimentation phase are quite promising, and point to a very precise solution provided by TIGHT. Nevertheless, improvement on the robustness of the overall setup should be considered in order to have a more continuous solution and provide more data for further analysis. The calibration offset is maintained at around 4ns which still needs to be understood.

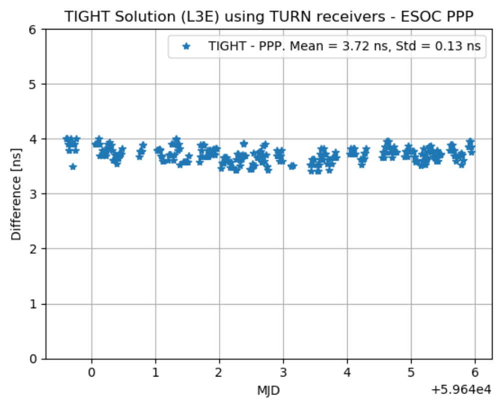

Figure 3-4: TIGHT minus PPP solution for first TURN period (best achieved precision)

3.4. PROJECT CONCLUSIONS

The main project conclusion is that a new operational time transfer link between ESOC and ESTEC was designed, implemented and deployed, and have been running for more than one year. This link uses high gain antennas and GNSS receivers in order to obtain the time difference between the two sites.

It has achieved unparalleled precision for a GNSS code-based solution which could run in real time, and which uses a straightforward process. The current accuracy is under investigation, as there is currently a mismatch between the calibration performed and the one from the BIPM, but overall it is expected to have a better accuracy than nominal GNSS.

On top of this solution, a thorough analysis and investigation of the different option for the hardware setup, for the effect to be considered and corrected and for the calibration methods applicable has been done, thus getting the solution very close to its optimal configuration trading off the complexity of the solution and the achieved performance. Given the simplicity of the TIGHT solution, and the alignment with the metrology procedure, the TIGHT solution is inter-operational with other omnidirectional chains traditionally use in GNSS CV.

Finally, a couple of delta tasks have been identified in order to bring the solution one step forward, converting it to fully operational, and finally assessing the overall achieved accuracy.

For phase 1 of the experimentation, using commercial receivers, it was seen how the TIGHT Time Transfer follows closely the trend of the PPP solutions, with an added bias due to calibration.

For phase 2, the results with the TURN receiver are better than with the PolaRx5TR in terms of pass to pass repeatability and thus in the solution precision, but the overall setup is less robust and more prone to have holes than the solution with the PolaRx5TR. The TURN experiments require closer monitoring of the day to day situation to guarantee a level of continuity or an upgrade of the setup.

The TIGHT solution, using TURN receiver has a constant offset w.r.t. ESA solution of around 4ns. These are related to the calibration of the full chain, and in particular of the TURN receivers given that several calibrations and equipment campaigns have been put together to extract the value used in this experimentation. Due to this, further analysis is needed in order to find the 4 ns offset, in particular reviewing the calibration campaigns.

Overall, the validations activities carried during the second experimentation phase of the project targeted the identification of errors and mismatches between the absolute calibrations values in GMV, used for the operational process of the TIGHT time transfer and the BIPM calibration values which are the ones used by ESA in its GNSS chains.

It was demonstrated that the absolute calibration, including the antenna values from the second campaign, show a promising alignment with the BIPM values, which might encourage the absolute calibration of ESOC's feed. Having the two chains absolutely calibrated will result in a second operational solution for the TIGHT time transfer, and to have a third solution for comparison and try to understand where differences are.

In addition it was also demonstrated that the calibration from the BIPM can be correctly transferred to the TIGHT HGA chains, and that in this case, the E1 value differ from the relative one by 1.5 ns, which is in the limit of the uncertainty of such comparison. This demonstration can become handy in the future of the HGA chains, as it demonstrate the full compatibility with other GNSS CV techniques, and allows for the interoperability of HGA and omnidirectional chains.

The overall achieved precision of the TIGHT solution improves over the omnidirectional GNSS solution by a factor of 3.3. The TIGHT solution relies on code measurements, with a traditional and simplified time transfer procedure, aligned with the BIPM ones.

END OF DOCUMENT