Peer Review File

Manuscript Title: A hybrid optical-wireless network for decimetre-level terrestrial positioning

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

Please see attached review.

Referee #2 (Remarks to the Author):

A. Summary of the key results
- The authors propose a terrestrial networked positioning system (TNPS) based on a hybrid optical-wireless telecommunication infrastructure, which provides positioning in urban environments with centimetre to decimetre level uncertainty as well as sub-nanosecond time synchronisation.
- A realistic testbed is built at an urban outdoor test site to validate the TNPS both in terms of timing and positioning accuracy.
- The extensive experimental evaluation using real-life data collected in the testbed demonstrates the effectiveness of the proposed methods underpinning the TNPS achieving remarkable timing accuracy with an uncertainty of about 0.2 ns and positioning error of 10.2 cm RMSE in a single direction or less depending on the positioning method.
- The proposed TNPS is compatible with the current 4G/5G telecommunication infrastructures, thus reducing the deployment cost.

B. Originality and significance: if not novel, please include reference
- Existing solutions typically address separately precise (sub-)nanosecond timing, e.g., based on the White Rabbit protocol including commercial solutions by OPNT B.V. and Seven Solutions S.L, as well as meter-level positioning accuracy, e.g., using UHF metropolitan beacons, low orbit satellites, and other technologies. The proposed TNPS is novel as it addresses timing and positioning jointly through a hybrid optical-wireless network by means of fiber-optic time transfer using the White Rabbit Precision Time Protocol technology combined with OFDM modulation format of the wireless signal that enables accurate positioning.
- It is a significant work, as it demonstrates the feasibility of sub-nanosecond timing and decimetre-level positioning accuracy in real-life application scenarios making it an effective and viable alternative to GNSS-based timing and positioning solutions. The results presented will be of interest to many people in the positioning community.

C. Data & methodology: validity of approach, quality of data, quality of presentation
- The approach both for achieving sub-nanosecond timing accuracy and determining position,

though time-delay (TD) and carrier phase (CP) estimation is valid. The data collection process in the experimental testbed is well-designed and solid, while the data are of high quality. The results are clearly presented.
- Regarding the positioning methods TD and CP, for completeness, I suggest including the TDoA method described in the authors' previous work [vi] (see point G.), which avoids calibration of the hardware delays introduced by the transmitters and the receiver.

D. Appropriate use of statistics and treatment of uncertainties
- Statistics are properly used, e.g., reporting the RMSE, the mean and standard deviation, and the 95-th percentile (95% contours) for positioning and timing errors.
- Uncertainties in the underlying models and equations are adequately described and properly handled (estimated) when possible, including the common hardware delay of all Tx-Rx links, the residual transmitter specific hardware delays, the time-dependent clock offset of the receiver, and all remaining errors due to multipath, unknown residual hardware delays, and timing jitter. Profiling of uncertainties in the ground-truth optical land-surveying system is also included.

E. Conclusions: robustness, validity, reliability
- The conclusions and data interpretation are robust, valid and reliable. See point H. about the presentation of conclusions.

F. Suggested improvements: experiments, data for possible revision
- I suggest reporting, together with TD and CP, the results of the TDoA method described in the authors' previous work [vi] (see point G.).
- It would be interesting to see how the positioning error of TD, CP and TDoA is affected by the number of transmitters (i.e., density) in the testbed by varying the number of transmitters.
- With respect to the comparison with other competing PNT solutions, it would be interesting to add a table with a qualitative comparison of the proposed system against the solutions in [i], e.g., NextNav's Metropolitan Beacon System (MBS), low orbit satellites, etc., in terms of timing and positioning accuracy, deployment cost, maturity, compatibility with existing telecommunication networks, etc.

G. References: appropriate credit to previous work?
- Section "Alternative timing and positioning infrastructure" should be revised to outline alternative state-of-the-art position, navigation, and timing (PNT) technologies such as those included in the recent report of the USA Department of Transportation [i].
- From [i] the fiber-optic time transfer systems of OPNT B.V. and Seven Solutions S.L. should be briefly discussed to see how the proposed system goes beyond these timing solutions. In particular, the timing system by Seven Solutions S.L. (also [ii]) is reported to achieve 0.1 nanosecond uncertainty.
- I also suggest outlining recent advancements in GNSS-based positioning including real-time Precise Point Positioning (PPP) approaches that use carrier phase observations from multi-frequency receivers and correction data to achieve centimetre-level accuracy e.g., [iii], or when PPP is combined with Inertial Navigation Systems (INS), e.g., [iv].
- The reference [13] to the Locata terrestrial positioning system is quite old and could be replaced by a reference to more recent terrestrial beacon systems (TBS) such as NextNav's MBS TerraPoint

solution or others, as well as cellular-based positioning based on Positioning Reference Signals (PRS).
- The reference [14] to UWB systems could be replaced by the more recent publication [v].
- I suggest outlining the authors' previous work [vi] that presents early testing of the proposed TNPS to see how the preliminary results and lessons learned were considered in the new experiment and study of this manuscript.

[i] Hansen, Andrew, Stephen Mackey, Hadi Wassaf, Vaibhav Shah, Eric Wallischeck, Christopher Scarpone, Michael Barzach, and Elliott Baskerville. Complementary PNT and GPS Backup Technologies Demonstration Report: Sections 1 through 10. No. DOT-VNTSC-20-07. John A. Volpe National Transportation Systems Center (US), Jan. 2021.
[ii] Jiménez-López, F. Girela-López, J. López-Jiménez, E. Marín-López, R. Rodríguez and J. Díaz, "10 Gigabit White Rabbit: Sub-Nanosecond Timing and Data Distribution," in IEEE Access, vol. 8, pp. 92999-93010, 2020.
[iii] V. L. Knoop, P. F. de Bakker, C. C. Tiberius, and B. van Arem, "Lane determination with GPS precise point positioning," IEEE T. on ITS,
vol. 18(9), pp. 2503–2513, 2017.
[iv] P. S. Henkel, "Tightly coupled precise point positioning and attitude determination," IEEE T.-AES, vol. 51(4), pp. 3182–3197, 2015.
[v] Alarifi, Abdulrahman, AbdulMalik Al-Salman, Mansour Alsaleh, Ahmad Alnafessah, Suheer Al-Hadhrami, Mai A. Al-Ammar, and Hend S. Al-Khalifa. "Ultra wideband indoor positioning technologies: Analysis and recent advances." Sensors 16, no. 5 (2016): 707.
[vi] Diouf, Cherif, Han Dun, Tarik Kazaz, Gerard Janssen, and Christian Tiberius. "Demonstration of a decimeter-level accurate hybrid optical-wireless terrestrial positioning system." In Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), pp. 2220-2228. 2020.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions
- The abstract and introduction are appropriate and clear. In the "Compatibility with telecommunication infrastructure" I would add for completeness the alignment of the proposed system with current and evolving standards such as 3GPP 36.305 and 38.305 for 4G and 5G.
- The experimental findings and the conclusions, even though adequate as described in point E., are spread throughout the manuscript. I suggest putting the analysis of findings and conclusions together in a "Discussion" section.

Christos Laoudias

Referee #3 (Remarks to the Author):

This work presents a decimeter-level accuracy terrestrial networked positioning system (TNPS), and performance is evaluated via experimental tests. However, there have been many TDOA-based and OFDM-based positioning systems, e.g., [1-5]. I see this work as a successful project but has limited contribution in localization regarding the system deployment, signal design, and localization algorithms.

This work is technically sound, and the results are reasonable. However, I would like to see more about the compatibility with different types of receivers, scalability with multiple user equipment, the robustness of the system dealing with blockage and multipath, and the system costs for a specific application scenario. This information is crucial to evaluate the utility of the system.

Some comments on the paper:

Page 3, Line 4: ‘The systems rely on two-way communication’ is not necessarily true. If the pilot signals and transmission schemes are predefined, positioning and can be done with only uplink or downlink communication.

Page 3, Line 9: It is true that GNSS outperforms existing mobile-network-based positioning methods (e.g., 4G signals). Nevertheless, the deployment of 5G systems has already been completed in some areas, and integrated communication, localization, and sensing are expected. What is the advantage of this TNPS system then? A dedicated designed positioning system for a specific scenario, what kind of scenario?

Page 6, Line 7: Why sparse-band and full-band OFDM-TD positioning have similar performance, how similar it is. The performance can be easily analyzed theoretically (e.g., by CRLB), and it is not convincing to just mention ‘we find’.

Page 7 Line 20: WR equipment has been commercially available for over one decade; what is the limitation that prevents the application of this technique in positioning. If this technique is mature, what is your contribution?

Page 8, Line 9: I am afraid the bandwidth scarcity issue can hardly be solved by the reported TNPS system. The mentioned 160 MHz bandwidth can be easily obtained by mmWave systems.

Suggestions:

I would suggest this work be submitted to more technical journals (e.g., IEEE transactions) where more solid suggestions can be provided.

[1] Ni, Hao, Guangliang Ren, and Yilin Chang. "A TDOA location scheme in OFDM based WMANs." IEEE Transactions on consumer electronics 54, no. 3 (2008): 1017-1021.
[2] Podevijn, Nico, David Plets, Jens Trogh, Luc Martens, Pieter Suanet, Kim Hendrikse, and Wout Joseph. "TDoA-based outdoor positioning with tracking algorithm in a public LoRa network." Wireless Communications and Mobile Computing 2018 (2018).
[3] Han, Shuai, Yi Li, Weixiao Meng, Cheng Li, Tianqi Liu, and Yanbo Zhang. "Indoor localization with a single Wi-Fi access point based on OFDM-MIMO." IEEE systems journal 13, no. 1 (2018): 964-972.
[4] Yang, Mingyu, Li-Xuan Chuo, Karan Suri, Lu Liu, Hao Zheng, and Hun-Seok Kim. "ilps: Local positioning system with simultaneous localization and wireless communication." In IEEE INFOCOM 2019-IEEE Conference on Computer Communications, pp. 379-387. IEEE, 2019.

[5] Exel, Reinhard, Georg Gaderer, and Patrick Loschmidt. "Localisation of wireless LAN nodes using accurate TDoA measurements." In 2010 IEEE Wireless Communication and Networking Conference, pp. 1-6. IEEE, 2010.

REVIEW OF
A HYBRID OPTICAL-WIRELESS NETWORK FOR ROBUST DECIMETRE-LEVEL POSITIONING IN URBAN ENVIRONMENTS

Summary of Review

This work presents an exciting vision of future positioning and timing in urban areas anchored not to satellites, as is the case today, but rather to wideband terrestrial transmitters synchronized at the sub-nanosecond level via optical fiber. The arguments for this system are quite convincing, the description is well-written, and the demonstration shows promise. But the authors leave some critical questions unanswered and downplay too much the capabilities of existing PNT schemes.

Major Points

(1) It appears from Figs. 1 and 3 that the six TNPS transmitters were all in line-of-sight view of the recevier throughout the test reported. This is an unnaturally benign scenario. One of the primary problems with using GNSS in urban areas is the presence of signals (called non-line-of-sight or NLOS) whose line of sight to the overhead satellite is completely blocked (e.g., by a building or bridge) but whose multipath signals arrive at the receiver and are tracked. Recognizing and rejecting NLOS signals is key to radionavigation in urban environments. TNPS will suffer from NLOS signals just as GNSS does. A demonstration in which there is a clean line of sight to all TXs, and in which these TXs are distributed in a favorable geometrical pattern around the receiver, is not realistic for urban radionavigation.

(2) The paper's vision for practical deployment depends on integration with 5G (or perhaps 6G) cellular networks so that additional deployment and infrastructure costs are low. But spectrum sharing in the way the paper presents (with low-entropy pilot signals used for ranging) implies that some portion of the precious licensed cellular spectrum would be unavailable for communications. Even if, as the paper states, 93% of the telecommunications capacity remains available, the cost of 7% of the capacity for PNT is far above what carriers will likely accept for PNT. The authors envision that the 7% capacity loss could be reduced by using existing training signals for PNT, but they don't offer any numbers here.

In short, loss of 7% telecommunications capacity to support PNT would almost surely be unacceptable for carriers, and the authors have not shown that their system would operate with better-than-GNSS precision if it was reduced to exploiting existing training symbols used for cellular channel estimation as opposed to dedicated ranging signals allocated in a careful way to achieve a 160-MHz virtual bandwidth.

Date: November 17, 2021.

(3) The paper proposes dual-tasking the optical fiber links that connect cellular base stations (and possibly WiFi access points) to convey both data and timing information. They mention that the White Rabbit time synchronization protocol can be operated at "unusued wavelengths in the fibre-optic spectrum that are not suitable for high-capacity data transmission systems." The authors need to clearly state what timing accuracy should be expected for such "opportunistic" use of the fiber backhaul. Will WR offer 0.2-nanosecond timing synchronization on these fiber backhaul links even when they are fully burdened with data traffic so that the WR protocol must be relegated to relatively narrow "leftover" bands?

(4) The paper's authors are surely aware of carrier-phase (CP)-based techniques for GNSS positioning, but nonetheless claim that GNSS "suffer(s) from many-metre errors due to multipath propagation, especially in urban areas." With CP-based GNSS, positioning errors can be driven to the sub-dm level. And modern robust CP GNSS techniques, coupled with low-cost inertial sensing, perform remarkably well in urban areas on vehicular platforms, which is one of the high-impact applications the paper mentions (see, e.g., [1, 2]. For example, it's almost surely the case that modern CP GNSS would have offered sub-dm positioning will continuous availability over the entire length of the test track in the paper's Green Village demonstration area. The paper's current characterization of the state of the art in urban precise GNSS positioning is unfairly pessimistic.

(5) The paper's proposed TNPS is similar to other terrestrial radionavigation systems such as Locata. The paper mentions Locata, but references an old 2003 paper that describes an early Locata version. More recent papers (e.g., [3–5]) indicate that Locata's bandwidth is 80 MHz, not ∼20 MHz as the current paper claims. This reviewer believe's that the paper's proposed TNPS is in many ways superior to Locata, but the authors need to do a better job of presenting Locata in a more realistic (favorable) light.

References

[1] T. E. Humphreys, M. J. Murrian, and L. Narula, "Deep-urban unaided precise global navigation satellite system vehicle positioning," *IEEE Intelligent Transportation Systems Magazine*, vol. 12, no. 3, pp. 109–122, 2020.

[2] T. Li, H. Zhang, Z. Gao, Q. Chen, and X. Niu, "High-accuracy positioning in urban environments using single-frequency multi-GNSS RTK/MEMS-IMU integration," *Remote Sensing*, vol. 10, no. 2, p. 205, 2018.

[3] J. W. Cheong, X. Wei, N. Politi, A. G. Dempster, and C. Rizos, "Characterising the signal structure of locata's pseudolite-based positioning system," in *Symp. on GPS/GNSS (IGNSS2009)*, Citeseer, 2009.

[4] F. A. Khan, *Locata Positioning System Performance Evaluation and Improvement in the Presence of RF Interference*. PhD thesis, Ph. D. Thesis, School of Surveying & Spatial Information Systems, The University of New South Wales, 2011.

[5] C. Rizos and L. Yang, "Background and recent advances in the locata terrestrial positioning and timing technology," *Sensors*, vol. 19, no. 8, p. 1821, 2019.

Author Rebuttals to Initial Comments:

2021-04-06565A – Authors' response to referees & list of revisions

General notes

Cited text from the referee reports is printed in *blue italic font*. Our responses to points raised by referee #1 are numbered R1.1, R1.2, …, in the same order as in the referee's report; similar numbering applies to replies to comments by referees #2 and #3 (R2.1, R2.2, R3.1, etc.)

Literature references, figures, tables, and sections referred to in this document are those of the revised manuscript, unless noted otherwise.

Cited text from the revised manuscript is printed in Cambria font against a grey background, with revised or newly added phrases underlined.

Summary of unsolicited changes to the Main Text and Supplemental Materials

Apart from changes ensuing from the referees' comments, a small number of unsolicited improvements were made to the Main Text and Supplementary Materials.

Main Text

- In the summary paragraph, we replaced 'in the urban areas' with 'in urban areas'
- In section 'Alternative timing and positioning infrastructure', we changed 'profound obstacle to large-scale deployment' to 'major obstacle to large-scale deployment'
- In the same section, we replaced 'one-way (silent) GNSS receivers' with 'downlink-only (silent) GNSS receivers'
- At the end of the first sentence of section 'Compatibility with existing infrastructure' we added '(because the relatively high signal levels and anticipated density of base stations will limit jamming and in particular spoofing attacks to a small geographic area).'
- Figure 1b was updated to include a 'radio wave' symbol at Tx-5, which was unintentionally left out
- In the caption of Fig. 3, we replaced 'Trajectory of a 210-s run' with 'Trajectory of a 210-second run'
- In Fig. 3b, we modified the layering so that the histograms are no longer blocking the frame and frame ticks of the graph

Methods

- In subsection 'USRP configuration and OFDM signals' we discovered a typo in the original sentence 'This translates to a coverage distance of d = 320 if a signal-to-noise ratio (SNR) of 0 dB is to be achieved, which supports the estimation of pseudo-ranges with a precision of about 1 cm (Cramér-Rao lower bound).' The 1 cm should have been 10 cm. Since we anyway intended to write 10 cm here, the change has no consequences (i.e. the message remains the same: also at 320 m distance, robust positioning at the decimetre level should be possible).

Response to referee #1

Summary of Review - This work presents an exciting vision of future positioning and timing in urban areas anchored not to satellites, as is the case today, but rather to wideband terrestrial transmitters synchronized at the sub-nanosecond level via optical fiber. The arguments for this system are quite convincing, the description is well-written, and the demonstration shows promise. But the authors leave some critical questions unanswered and downplay too much the capabilities of existing PNT schemes.

We would like to thank referee #1 for the time and effort spent on reviewing our manuscript. We are also grateful for the overall positive appraisal of our work as well as the criticisms, which helped us improve our manuscript; see our detailed responses below. Regarding the comparison between our TNPS and existing PNT schemes, we regret that our manuscript left an impression of downplaying the capabilities of the latter. We have made a number of changes to improve this: in some cases, we provide a clearer substantiation (by objective standards) of claims of superiority of our system over existing methods (see response R1.4 below), whereas in other cases we put more emphasis on the strong points of existing PNT schemes relative to our TNPS, in order to achieve a fair balance (response R1.5).

Major Points

(1) It appears from Figs. 1 and 3 that the six TNPS transmitters were all in line-of-sight view of the recevier throughout the test reported. This is an unnaturally benign scenario. One of the primary problems with using GNSS in urban areas is the presence of signals (called non-line-of-sight or NLOS) whose line of sight to the overhead satellite is completely blocked (e.g., by a building or bridge) but whose multipath signals arrive at the receiver and are tracked. Recognizing and rejecting NLOS signals is key to radionavigation in urban environments. TNPS will suffer from NLOS signals just as GNSS does. A demonstration in which there is a clean line of sight to all TXs, and in which these TXs are distributed in a favorable geometrical pattern around the receiver, is not realistic for urban radionavigation.

R1.1 – In our original manuscript, we indeed showed results for rather favourable LoS situations, but with dense multipath (MP). Although both MP and NLoS conditions are detrimental to GNSS positioning, MP arguably presents the bigger challenge of the two: even under LoS conditions, dense MP (i.e. MP components that arrive shortly after the LoS component within the duration of the correlation peak) will cause large GNSS errors, because such MP cannot be separated from the LoS path. Another reason for our initial focus on MP is the intended deployment in dense urban areas, where (i) MP will be inevitable, and (ii) one may anticipate a large number of base stations, some indeed with NLoS, but most having LoS.

That having been said, we do acknowledge referee #1's comment regarding the issue of loss of base stations due to NLoS conditions, and we agree that this topic deserves some discussion in our manuscript. We therefore added new results to the manuscript, as described in the following (new) passage in the main text (not underlined for better readability):

Apart from multipath, radio navigation systems suffer from scenarios where the direct LoS to the transmitter is blocked, but where non-LoS (NLoS) multipath signals are still detected by the receiver, thus leading to position errors. Various strategies to detect and mitigate NLoS propagation in (ultra)wideband systems exist[24,25]. A conservative measure against NLoS is to omit the pseudo-range of an impaired base station from the positioning algorithm. To illustrate the robustness of our

TNPS to such NLoS-implied omission of one or two base stations, we have computed position solutions for one of the runs at TGV for various reduced constellation sizes; see Extended Data Fig. 5 and Extended Data Table 1. Owing to the redundancy of the constellation, decimetre-level positioning remains possible in most cases if one or two arbitrary base stations are removed. One exception is base station Tx-6, whose exclusion renders a large section of the test run outside the remaining constellation's coverage area, where – due to a mechanism known as geometric dilution of precision – positioning errors of several decimetres to up to a few metres may readily occur. Errors of a few decimetres may also occur for situations in which three base stations – i.e. half of the constellation – are excluded. For CP positioning, at least five base stations are required[22], so that only one base station may be lost from our constellation. Our experimental data show that CP positioning with centimetre-range uncertainty remains possible also if one base station is removed (Extended Data Table 2).

Extended Data Fig. 5 shows the horizontal positioning precision (including the effect of horizontal dilution of precision) for the full constellation as well as for three reduced constellations. It furthermore shows the position solutions that were found, for one of the test runs, for these reduced constellations. The graphical results are supported numerically by Extended Data Table 1, which displays the RMSEs that were achieved for eleven different reduced constellations (including those of Extended Data Fig. 5). Extended Data Table 2 shows results for CP positioning with one base station removed.

In previous work, the new Ref. 25, some of us have shown that reliable NLoS detection based on ToA and received signal strength is possible, and for this a large bandwidth is highly beneficial (and our TNPS offers a large bandwidth compared to GNSS and many GNSS back-up systems). At the same time, we consider a detailed consideration and implementation of the NLoS detection itself beyond the scope of the present work, and more suitable for a technical follow-up paper.

As pointed out above, we anticipate a high density of urban TNPS transmitters, automatically resulting into robustness against NLoS. This is reflected by the following line in the concluding paragraph of the main text:

With the continuing densification of cellular networks and wireless access points, the density of such integrated telecom/TNPS transmitters may ultimately become sufficient to achieve city-wide or even nation-wide coverage, with a high level of robustness against MP and NLoS signals. The TNPS demonstrated here may therefore [...]

(2) The paper's vision for practical deployment depends on integration with 5G (or perhaps 6G) cellular networks so that additional deployment and infrastructure costs are low. But spectrum sharing in the way the paper presents (with low-entropy pilot signals used for ranging) implies that some portion of the precious licensed cellular spectrum would be unavailable for communications. Even if, as the paper states, 93% of the telecommunications capacity remains available, the cost of 7% of the capacity for PNT is far above what carriers will likely accept for PNT. The authors envision that the 7% capacity loss could be reduced by using existing training signals for PNT, but they don't offer any numbers here. In short, loss of 7% telecommunications capacity to support PNT would almost surely be unacceptable for carriers, and the authors have not shown that their system would operate with better-than-GNSS precision if it was reduced to exploiting existing training symbols used for cellular channel estimation as opposed to dedicated ranging signals allocated in a careful way to achieve a 160-MHz virtual bandwidth.

R1.2 - We agree with referee #1 that a 7% capacity loss (or overhead) may be above what mobile carriers will find acceptable. The term ‘acceptable’ here is somewhat subjective, as this depends not only on the economic damages caused by capacity loss, but also on the economic profits offered by a TNPS – a discussion that goes beyond the scope of this paper. We can nevertheless obtain an idea of what may be ‘acceptable’ by considering the overhead for network-based positioning in LTE. For settings specified in 3GPP TS 36.133, this overhead varies between 0.26% and 0.63% [see also Table 5.2 of the Qualcomm white paper “Observed Time Difference of Arrival (OTDOA) Positioning in 3GPP LTE” by Sven Fischer, June 6, 2014].

Let us explain why we believe such sub-1% overheads are achievable with TNPS without loss of performance. First and foremost, we stress that the design choices for the PNT transmission scheme in our testbed were motivated by ease of implementation and inclusion of additional diagnostic features (see below), and no attempt was made to minimise the overhead. The overhead is also due to the relatively high 1 kHz PNT message rate, which is (for example) 160 times higher than that used for 3GPP LTE positioning, and 10-100 times higher than for GNSS positioning. For many practical applications, the 1 kHz PNT message rate (and thereby the overhead) may be reduced by at least one order of magnitude. But even at 1 kHz, the overhead may be reduced to below 1% as follows.

First, we should point out that the 0.16 duty cycle figure in the original manuscript was an overestimate: we let the receiver record for 160 µs, which is longer than actually needed. The exact value of the duty cycle is 0.1446, based on the 142.1 µs TDM burst duration plus a final 2.5 µs guard interval, divided by a 1000 µs repetition interval. When transmitting over only 7 out of 16 bands, the overhead relative to the total system bandwidth is (7/16)*0.1446*100% = 6.326% (which is still a large number).

In the original manuscript, we did not mention that the two training symbols are identical, and that only one symbol is used in the processing of the data for positioning (the second symbol was only used for diagnostics, in this case to improve channel estimation). We can therefore remove one cyclic prefix and one training symbol, reducing the PNT signal duration from 21.6 µs to 14.4 µs. This would reduce the overhead to 4.4%.

The used training symbols are identical for all transmitters; however, we could in principle have used training symbols based on orthogonal codes for each transmitter (like the symbols we implemented for the ID symbol). This would enable the simultaneous transmission – employing code-division multiple access (CDMA) – of a 14.4 µs symbol plus 2.5 µs guard interval by all transmitters, reducing the overhead to 0.74% (using 7 out of 16 bands). This is close to the ‘acceptable’ overhead in LTE OTDoA positioning, while still offering a much higher PNT transmission rate of 1 kHz (compared to 1/(160 ms) = 6.25 Hz in LTE; see 3GPP TS 36.211, and the above-mentioned Qualcomm White Paper Sec. 5.4).

When employing orthogonal codes and CDMA, the ID symbol is in fact no longer needed (because each PNT code is unique to each Tx). Such a scheme is analogous to what is used in GNSS. Use of only one symbol would cut the PNT signal duration to 7.2 µs. Including the 2.5 µs guard interval, and using CDMA transmission, the overhead would become 0.42%, and without significant loss of positioning performance. Such a figure is quite comparable to the ‘acceptable’ positioning overhead in LTE systems mentioned above – and arguably a small price to pay for robust network-based positioning at the dm-level at a fix rate of 1000 Hz. And in case that even lower overheads are needed, our system offers the flexibility to do so (just like existing OFDM cellular positioning methods such as OTDoA/3GPP TS 36.133), since the transmission rate, duration, and bandwidth can be adjusted to decrease the overhead. Of course, like in cellular positioning methods, adjusting these parameters might affect positioning performance. For example, if we would maintain the original TNPS signal structure and transmission schemes, but reduce the transmission rate by a factor of 160 to achieve the same positioning update rate as in 3GPP OTDoA, the overhead would be immediately reduced to 0.09%.

To make it clear, also in the manuscript, that sub-1% overheads are feasible, we made the following changes. We rewrote part of the Methods section, where the subsection 'USRP configuration and OFDM signals' now reads:

PNT burst transmissions are driven at a rate of 1 kHz and a duty cycle of 0.14, with […] The TDM transmission scheme, shown in Fig. 2a, was chosen for its ease of implementation in the testbed and for diagnostic purposes. The two OFDM training symbols in Fig. 2b contain identical pseudorandom noise sequences that are binary phase-shift-keyed on all available subcarriers. Both symbols are used for channel estimation, whereas only one symbol is used for packet synchronisation and ranging. The third symbol contains a Gold sequence, unique to each transmitter, for identification by the receiver. In principle, ranging and identification could be achieved using only the third symbol. When transmitting over 7 out of 16 bands, the overhead of the TDM scheme is 6.3%, and 2.5% if only the third symbol is used. A further reduction of the overhead to 0.42% would be enabled by joint transmission and detection of the PNT symbols using CDMA (analogous to GNSS signals), without significant loss of positioning performance.

In the main text, subsection 'Compatibility with telecommunication infrastructure', this information is referred to as follows:

In our prototype TNPS, at a PNT message rate of 1 kHz, up to 94% of the telecommunication capacity remains available; however, this figure may improve to well above 99% by straightforward modifications of the PNT signal structure (such as joint PNT transmissions employing CDMA instead of TDM, or a reduced PNT message rate), and without loss of positioning performance (Methods).

(3) The paper proposes dual-tasking the optical fiber links that connect cellular base stations (and possibly WiFi access points) to convey both data and timing information. They mention that the White Rabbit time synchronization protocol can be operated at "unused wavelengths in the fibre-optic spectrum that are not suitable for high-capacity data transmission systems." The authors need to clearly state what timing accuracy should be expected for such "opportunistic" use of the fiber backhaul. Will WR offer 0.2-nanosecond timing synchronization on these fiber backhaul links even when they are fully burdened with data traffic so that the WR protocol must be relegated to relatively narrow "leftover" bands?

R1.3 – The short answer is yes: WR will provide deep sub-nanosecond time synchronisation, also if operated in less popular wavelength bands of the fibre-optic spectrum (the main reason for their unpopularity usually being larger attenuation, and/or such bands being located outside the gain spectrum of erbium-doped fibre amplifiers that are used in high-capacity systems to overcome attenuation), and also if propagating together with tens of dense-wavelength-division-multiplexed optical signals over the same fibre. WR differs greatly in this respect from older versions of PTP/IEEE-1588, whose performance is notoriously dependent on the traffic load (more traffic, worse performance). The independence of WR timing performance from other optical traffic has been demonstrated before, and is emphasised through the following changes to the main text:

> [...] and, owing to its relatively modest bitrate, WR can operate (without loss of performance) at wavelengths in the fibre-optic spectrum that experience relatively large attenuation. Such wavelengths are often available as they are less suitable for high-capacity data transmission systems. Employing wavelength division multiplexing (WDM), WR operating in such unused wavelength bands has already been successfully integrated into long-distance fibre-optic networks that simultaneously carry live high-capacity data traffic, showing no interaction between the WR signals and the other data traffic, and achieving sub-nanosecond timing performance[29,30,31].

(4) The paper's authors are surely aware of carrier-phase (CP)-based techniques for GNSS positioning, but nonetheless claim that GNSS "suffer(s) from many-metre errors due to multipath propagation, especially in urban areas." With CP-based GNSS, positioning errors can be driven to the sub-dm level. And modern robust CP GNSS techniques, coupled with low-cost inertial sensing, perform remarkably well in urban areas on vehicular platforms, which is one of the high-impact applications the paper mentions (see, e.g., [1, 2]. For example, it's almost surely the case that modern CP GNSS would have offered sub-dm positioning will continuous availability over the entire length of the test track in the paper's Green Village demonstration area. The paper's current characterization of the state of the art in urban precise GNSS positioning is unfairly pessimistic.

R1.4 – We agree with referee #1 that GNSS CP techniques were underexposed in the original manuscript (partly because of space constraints), and deserve mentioning. We also agree that inertial-aided GNSS CP can provide dm-level and even cm-level positioning under clear view of the sky and limited multipath conditions. However, there are also crucial differences with our TNPS:

1. Because of the 20 MHz bandwidth (compared to the 160 MHz virtual bandwidth of TNPS), GNSS is intrinsically more sensitive to multipath than TNPS. This also holds for CP techniques: severe multipath (i.e. many reflections, with significant power compared to the LoS) may lead to a large (unknown) number of cycle slips, with one cycle corresponding to 19 cm for the GPS L1 band, and 7.6 cm for our TNPS (note that this difference stems purely from the different carrier frequencies used). Under such circumstances, the reduced sensitivity to multipath of TNPS allows one to switch back from CP-positioning to positioning based on time-delay (TD) measurements with errors at the decimetre level, whereas GNSS TD measurements may contain errors at the metre level (and many metres in case of severe multipath, like in urban canyons).
2. Auxiliary inertial systems have indeed been used to take over navigation in situations of severe multipath and/or NLoS reception (during which GNSS-CP will produce large errors or even no position fix at all). However, in the paper [2] cited by referee #1, Li et al. also state that: "Generally, centimeter-level positioning accuracy can be obtained when the outage duration is within 4 s for the POS1100 MEMS grade IMU." In other words, if GNSS-CP positioning fails (for example in urban canyons), inertial systems provide only limited cm-level holdover, and errors will build up to the many-metre level during sustained unavailability of GNSS signals, whether due to blocking of the sky or severe multipath. Our TNPS, by contrast, would continue to provide dm-level positioning based on TD measurements indefinitely (and cm-level CP measurements when possible), assuming that the local TNPS infrastructure was designed to provide sufficient coverage.

The statement in our original abstract: “GNSS, however, suffer from many-metre errors due to multipath propagation, especially in the urban areas where accurate positioning is needed most” is correct in the sense that unaided GNSS receivers (which are widespread in personal and automotive applications) frequently produce such errors in urban areas, while even advanced multi-GNSS and inertial-aided navigation devices (as Li et al.[2] point out) cannot prevent such errors of occurring. However, we agree with referee #1 that this formulation seems to deny that GNSS *can* achieve cm-level performance under the right conditions. For this reason, we changed the relevant sentence in the abstract to:

While GNSS can provide centimetre-level precision under favourable conditions, GNSS receivers are prone to many-metre errors due to multipath propagation and obstructed view of the sky, which occur especially in urban areas where accurate positioning is needed most.

Furthermore, in the introductory text following the abstract we now refer to GNSS-CP positioning as follows (with the newly inserted references 8,9 corresponding to papers [1,2] of referee #1):

Potential high-impact applications, such as automated driving and indoor navigation, require positioning with an uncertainty at the decimetre level, or better. In areas with open sky, carrier-phase (CP) techniques for GNSS can provide decimetre and even centimetre level position information[1]. However, the demand for such applications will be typically greatest in built-up areas with limited view to the sky, where even advanced GNSS receivers aided by inertial navigation systems are prone to several-metre errors[8,9]. The underlying limitations of GNSS are [...]

We also changed the earlier formulation “Moreover, even if the performance of GNSS could be improved by the required 1-2 orders of magnitude, [..]” to:

Moreover, even if GNSS errors could be reduced by the required 1-2 orders of magnitude, [...]

(5) The paper's proposed TNPS is similar to other terrestrial radionavigation systems such as Locata. The paper mentions Locata, but references an old 2003 paper that describes an early Locata version. More recent papers (e.g., [3{5]) indicate that Locata's bandwidth is 80 MHz, not ~20 MHz as the current paper claims. This reviewer believe's that the paper's proposed TNPS is in many ways superior to Locata, but the authors need to do a better job of presenting Locata in a more realistic (favorable) light.

R1.5 – We thank referee #1 for pointing out the newer references to Locata (which somehow had failed to surface during our literature search). We replaced the reference (Ref. 15) to the 2003 Locata paper with the 2009 conference paper by Cheong et al. [3] and the 2019 review of the system by Rizos and Yang [5], which will provide the reader with up-to-date information about Locata and its performance. We also extended the description of Locata in the main text to emphasise that Locata comes with additional features (citing referee #1’s references [3,5] for a more exhaustive description):

Several systems have been developed to cope with the limitations of GNSS. These include low Earth orbit satellite constellations[14] and local terrestrial positioning systems with GNSS-inspired signal structures with augmentations [one example being the Locata system, which employs two code-division multiple access (CDMA) signals with a 10 MHz chip rate on two frequencies, 51 MHz apart, within the 2.4 GHz band[16,17]] for improved signal power, coverage, and resilience (if combined with GNSS).

We realise that, hypothetically speaking, the two 20 MHz bands (one for each 10 MHz chip-rate signal) could be coherently connected by a Locata receiver to create a virtual 80 MHz band (similar to our sparse-band method). However, we did not find any evidence for such a technique, which is why we believe a formulation in terms of "two 10 MHz chip-rate signals separated by 51 MHz" is more accurate.

Response to referee #2

We thank referee #2 for the thorough review of our manuscript, the positive assessment of our work, and the valuable suggestions for improvement. Responses to specific comments and questions are provided in-line in his report below.

A. Summary of the key results

- The authors propose a terrestrial networked positioning system (TNPS) based on a hybrid optical-wireless telecommunication infrastructure, which provides positioning in urban environments with centimetre to decimetre level uncertainty as well as sub-nanosecond time synchronisation.

- A realistic testbed is built at an urban outdoor test site to validate the TNPS both in terms of timing and positioning accuracy.

- The extensive experimental evaluation using real-life data collected in the testbed demonstrates the effectiveness of the proposed methods underpinning the TNPS achieving remarkable timing accuracy with an uncertainty of about 0.2 ns and positioning error of 10.2 cm RMSE in a single direction or less depending on the positioning method.

- The proposed TNPS is compatible with the current 4G/5G telecommunication infrastructures, thus reducing the deployment cost.

B. Originality and significance: if not novel, please include reference

- Existing solutions typically address separately precise (sub-)nanosecond timing, e.g., based on the White Rabbit protocol including commercial solutions by OPNT B.V. and Seven Solutions S.L, as well as meter-level positioning accuracy, e.g., using UHF metropolitan beacons, low orbit satellites, and other technologies. The proposed TNPS is novel as it addresses timing and positioning jointly through a hybrid optical-wireless network by means of fiber-optic time transfer using the White Rabbit Precision Time Protocol technology combined with OFDM modulation format of the wireless signal that enables accurate positioning.

- It is a significant work, as it demonstrates the feasibility of sub-nanosecond timing and decimetre-level positioning accuracy in real-life application scenarios making it an effective and viable alternative to GNSS-based timing and positioning solutions. The results presented will be of interest to many people in the positioning community.

C. Data & methodology: validity of approach, quality of data, quality of presentation

- The approach both for achieving sub-nanosecond timing accuracy and determining position, though time-delay (TD) and carrier phase (CP) estimation is valid. The data collection process in the experimental testbed is well-designed and solid, while the data are of high quality. The results are clearly presented.

- Regarding the positioning methods TD and CP, for completeness, I suggest including the TDoA method described in the authors' previous work [vi] (see point G.), which avoids calibration of the hardware delays introduced by the transmitters and the receiver.

R2.1 – As a matter of fact, we do present results obtained through time difference of arrival positioning (TDoA), to which we refer as time delay (TD) positioning. As a result, hardware delays in the transmitters and receiver equipment need not be known, as also mentioned in the first sentence of subsection 'Estimated uncertainty of Rx clock offsets and wireless time distribution' in the Methods:

From Eq. (1) it can be seen that the common hardware delay τ_h does not need to be known for positioning, since its value can be absorbed in the receiver clock offset.

However, referee #2's question made us realize that our manuscript does not clearly explain that we use TDoA. The referee correctly points out that TDoA positioning and time of arrival (ToA) positioning are different methods. ToA positioning quite literally involves time-delay measurements from which the range can be determined directly (this assumes that the hardware delay and Rx clock offset are known), whereas TDoA positioning employs pseudo-ranges which incorporate the range as well as hardware delays and a possible time offset of the Rx clock, multiplied by the speed of light [cf. our Eq. (1)]. As referee #2 will surely know, TDoA can be implemented in at least two ways [for an in-depth review of the subject see Yan et al., Review of range-based positioning algorithms. *IEEE Aerospace and Electronic Systems Magazine,* **28,** pp. 2-27 (2013), doi: 10.1109/MAES.2013.6575420] . The first way is by differencing pseudo-ranges so that the receiver clock offset and common hardware delays in the system drop out, and then solve for the position (this was done in the paper by Diouf et al., cited by referee #2, and now cited in our manuscript as Ref. 36).

The second way is to define a set of observation equations involving the measured ToAs, from which the Rx position and clock offset δt (+ possible hardware delays) are solved by least-squares optimization or maximum likelihood estimation (MLE). In our manuscript we employed the second way, in combination with MLE. This constitutes a TDoA method, because any common time offset in the pseudo-ranges is absorbed in the estimate of the Rx clock offset; in other words, only the differences between arrival times matter for positioning.

In fact, the need to calibrate hardware delays arises exclusively from the desire to use our TNPS system for *time transfer* (by relating the time of the Rx clock to the WR network time). This is explained in more detail in the Methods, subsection 'Estimated uncertainty of Rx clock offsets and wireless time distribution'.

So, we believe it is sufficiently clear from our manuscript that hardware delays – to the extent that they are identical for each Tx-Rx combination – need not be calibrated to enable positioning. We did however add a sentence to make it clear that our TNPS system employs a TDoA positioning method, in the subsection 'Ranging and positioning through time-delay measurements' of the Methods:

After all six pseudo-ranges $\rho_r^i(t)$ have been determined (for a given time t) using Eq. (2), the receiver position $\mathbf{x}_r(t)$ and clock offset $\delta_r(t)$ are found by maximum likelihood estimation (MLE)[37], which effectively constitutes a time difference of arrival method.

D. Appropriate use of statistics and treatment of uncertainties

- Statistics are properly used, e.g., reporting the RMSE, the mean and standard deviation, and the 95-th percentile (95% contours) for positioning and timing errors.

- Uncertainties in the underlying models and equations are adequately described and properly handled (estimated) when possible, including the common hardware delay of all Tx-Rx links, the residual transmitter specific hardware delays, the time-dependent clock offset of the receiver, and all remaining errors due to multipath, unknown residual hardware delays, and timing jitter. Profiling of uncertainties in the ground-truth optical land-surveying system is also included.

E. Conclusions: robustness, validity, reliability

- The conclusions and data interpretation are robust, valid and reliable. See point H. about the presentation of conclusions.

F. Suggested improvements: experiments, data for possible revision

- I suggest reporting, together with TD and CP, the results of the TDoA method described in the authors' previous work [vi] (see point G.).

R2.2 - See our response R2.1 above. Results of TDoA positioning are described in the manuscript.

- It would be interesting to see how the positioning error of TD, CP and TDoA is affected by the number of transmitters (i.e., density) in the testbed by varying the number of transmitters.

R2.3 – We created Extended Data Fig. 5, where we show the theoretical effect of removing up to three base stations on TD positioning (including the effect of horizontal dilution of precision on the 2D positioning performance), as well as the effect on the position solutions found during runs at TGV for various reduced constellations. We also added Extended Data Table 1 showing RMSEs (for TD positioning) for eleven different reduced constellations, and Extended Data Table 2 for CP positioning for two reduced constellations. The new figure and tables are referred to in the main text, in the new paragraph about NLoS conditions (see R1.1 above). Note that for CP positioning, the number of base stations that can be removed is limited to one (because the remaining five transmitters are needed for carrier-phase estimation). In general, our TNPS is found to be fairly robust against loss of base stations.

- With respect to the comparison with other competing PNT solutions, it would be interesting to add a table with a qualitative comparison of the proposed system against the solutions in [i], e.g., NextNav's Metropolitan Beacon System (MBS), low orbit satellites, etc., in terms of timing and positioning accuracy, deployment cost, maturity, compatibility with existing telecommunication networks, etc.

R2.4 – We welcome the suggestion of the referee to include a reference to the 2021 report [i] of the U.S. Department of Transportation (DoT) as it includes several state-of-the-art systems that we had not considered originally. We added reference [i] (or 14 in our revised manuscript) in several locations; for example in the introductory paragraph:

Amidst mounting concerns about the vulnerability of GNSS-dependent systems to (un)intentional disruptions[5], network operators[3] and governments[12,13,14] have begun looking into possible back-up systems for GNSS.

and in subsection 'Alternative timing and positioning infrastructure' (which also contains some revisions regarding Locata following R1.5 above):

Several systems have been developed to cope with the limitations of GNSS. These include low Earth orbit satellite constellations[14,15] and local terrestrial positioning systems[14] based on GNSS-inspired signal structures with augmentations [one example being the Locata system, which employs two code-division multiple access (CDMA) signals with a 10 MHz chip rate on two frequencies, 51 MHz apart, within the 2.4 GHz band[16,17]] for improved signal power, coverage, and resilience (if combined with GNSS). Other systems make use of two-way ranging to Wi-Fi access points for positioning at the metre level[14], or involve local networks of [...]

as well as in subsection 'Compatibility with telecommunication infrastructure':

Second, our TNPS system may be implemented in ways that circumvent the scarcity of radio bandwidth. Present terrestrial PNT systems primarily make use of unlicensed frequency bands (e.g. the Industrial, Scientific and Medical band at 2.4 GHz in which Wi-Fi operates), while some other systems operate in proprietary spectrum (such as the NextNav Metropolitian Beacon System, which operates in an 8 MHz band around 923.75 MHz[14]). The sparse-band radio system demonstrated here [...]

From the viewpoint of the reader and potential user of PNT back-up/complements, it would be very useful to include a table as suggested by referee #2. It would also make our TNPS appear strong in comparison with other technologies. We made an effort to build such a table, but we ultimately decided against including it for a number of reasons, as explained below.

One of the key performance indicators suggested by referee #1 is the deployment cost. Estimating the deployment cost is a daunting task – let alone defining a uniform cost indicator that allows comparing different systems. Costs of previous installations (if any) are typically undisclosed, and the costs that may be known (e.g. list prices) are subject to strong fluctuations that depend on the nature and size of the installation (e.g. volume discounts), the negotiation power of the customer, the presence of auxiliary infrastructure (for example, the cost for a terrestrial beacon network will be significantly lower for an operator who already has secured access to rooftop installations and cell towers), the cost of local labor force for installation, et cetera. We therefore fear that any estimate towards the cost made by us will be handwaving at best. In our humble opinion, such information might also be considered to fall outside the scope of this type of research article in *Nature*.

For similar reasons we are hesitant to indicate the maturity of the various systems, which would require an effort similar to that made by the DoT in preparation of their report (which goes beyond the scope of the present work).

Some relevant technical performance indicators, such as timing and positioning uncertainty, are available, but they depend on the local conditions (static versus dynamic receiver, presence and severity of multipath effects). We would inevitably end up comparing PNT performance indicators obtained under incomparable conditions.

The resilience to multipath itself would be a crucial indicator for the comparison too. The resilience to multipath may be quantified (be it in a somewhat coarse manner) through the radio signal bandwidth of the system, thereby allowing a quantitative comparison between systems. However, the radio signal structure and signal bandwidth are in many cases kept secret by system vendors (note that the DoT report only gives the bandwidths in which the various systems operate, which are not necessarily equal to the signal bandwidths). Without bandwidth information, the table would lack information regarding this crucial performance indicator.

We would also insist on including a column in the table concerning holdover capability during GNSS outage (i.e. the duration for which a PNT system will continue to run on its own before errors start to accumulate beyond the specified system uncertainty). Again, it is difficult to find a uniform measure of holdover capability, because it depends on e.g. the quality of the local reference oscillator that is used (OCXO, Rb atomic clock, Cs atomic clock), which in turn would have an impact on the deployment cost.

Therefore, rather than providing a table that would in our opinion be incomplete and in some respects imprecise, we choose to keep the textual comparison between the various systems, this time also referring to the systems mentioned in the DoT report [i] as outlined above.

G. References: appropriate credit to previous work?

- Section "Alternative timing and positioning infrastructure" should be revised to outline alternative state-of-the-art position, navigation, and timing (PNT) technologies such as those included in the recent report of the USA Department of Transportation [i].

R2.5 – As explained in R2.4, we now refer to the DoT report, and some of the systems described in there, in several instances, which we agree to be a must in this context. However, we are hesitant to review all the systems described in the DoT report. To appreciate the pros and cons of each system, a multidimensional graph or extensive textual description would be required to enable a fair comparison (time transfer capability yes/no, two-way or downlink-only, GNSS-level positioning backup yes/no, …) Such a presentation would go beyond the scope of and space available for this type of article. Moreover, the DoT have done an excellent job providing such an overview, in a report that is readily available, so we believe the references to the DoT report to be adequate here.

- From [i] the fiber-optic time transfer systems of OPNT B.V. and Seven Solutions S.L. should be briefly discussed to see how the proposed system goes beyond these timing solutions. In particular, the timing system by Seven Solutions S.L. (also [ii]) is reported to achieve 0.1 nanosecond uncertainty.

R2.6 – The TNPS system makes use of equipment of both OPNT and Seven Solutions. In Fig. 1b, the Timing Nodes (TNs) at the base stations were provided by OPNT, while the WR switches (WR-BC1, WR-BC2) and WR time providers (WR-SL, WR-GM) were purchased from Seven Solutions. All WR equipment is capable of achieving 0.1 ns (and even smaller) synchronization uncertainty, and the TNs used at TGV were delay-calibrated to 0.1 ns.

For our TNPS, we are interested in the level of synchronization at the RF interfaces of the transmitters, which we determined to be 0.2 ns. This is larger than the bare 0.1 ns synchronization level of the WR TNs (as measured at the 1 PPS output), because the timing at the RF interface suffers from some additional jitter that is added internally by the USRP, relative to the 1 PPS of the TN.

We realize it would be useful for the reader if we would mention the providers of the WR equipment. At the same time we have been hesitant to explicitly mention the name of OPNT in this paper, since one of the authors owns stock in this company (as stated in the Competing Interests section). We therefore implemented the following sentence as a compromise (Methods, subsection 'TNPS testbed'):

The network consisted of a mix of WR equipment obtained from the two WR providers mentioned in Ref. 14.

Ref. 14 (the DoT report) contains company descriptions of Seven Solutions and OPNT (the only two WR providers considered).

- I also suggest outlining recent advancements in GNSS-based positioning including real-time Precise Point Positioning (PPP) approaches that use carrier phase observations from multi-frequency receivers and correction data to achieve centimetre-level accuracy e.g., [iii], or when PPP is combined with Inertial Navigation Systems (INS), e.g., [iv].

R2.7 – We thank the referee for this suggestion, which we gave consideration. After having discussed this in the team (which includes one of the authors of [iii]), we decided to leave out a discussion about PPP and PPP-inertial systems for the following reason. In automotive applications, CP-GNSS offers higher accuracy and faster convergence than PPP-GNSS. An introduction of PPP-GNSS should therefore be accompanied by a comparison with CP-GNSS, and we feel that the required extra details would distract too much from the main flow of the text, while adding only marginally to the descriptions of CP-GNSS and inertial-system-aided GNSS that have now been added to the revised manuscript (see R1.4 above).

- The reference [13] to the Locata terrestrial positioning system is quite old and could be replaced by a reference to more recent terrestrial beacon systems (TBS) such as NextNav's MBS TerraPoint solution or others, as well as cellular-based positioning based on Positioning Reference Signals (PRS).

R2.8 – On the suggestion of referee #1 (see R1.5 above) we have replaced the 2003 Locata reference with two newer references from 2009 and 2019 (Refs. 16 and 17). Unfortunately there is insufficient space to review all terrestrial PNT systems individually, but we believe that with the new reference to the DoT report (Ref. 14) the reader is adequately referred to other systems (including NextNav's MBS, which is now also explicitly mentioned in the main text). A reference to cellular positioning based on PRS signals was already included (Ref. 21, Razavi et al.)

- The reference [14] to UWB systems could be replaced by the more recent publication [v].

R2.9 – We thank referee #2 for pointing out this work, and we chose to include reference [v] (which provides a broad and indeed more recent overview of UWB systems) alongside with the original Ref. 14 (now Ref. 18), as the latter provides an overview with more in-depth technical background. Reference [v] is Ref. 19 in the revised manuscript.

- I suggest outlining the authors' previous work [vi] that presents early testing of the proposed TNPS to see how the preliminary results and lessons learned were considered in the new experiment and study of this manuscript.

R2.10 – We included a reference to [vi] (Diouf et al.) in the Methods, subsection 'TNPS testbed':

The setup at TGV is described in more detail by Diouf et al., who presented a preliminary analysis of positioning based on pseudo-random noise sequences instead of OFDM signals, achieving an uncertainty at the several-decimetre level[36].

This illustrates the preliminary character of the approach and results presented by Diouf et al. One reason for the lower positioning accuracy achieved by Diouf et al. was the impairment of received signals, which was found to be due to a receiver gain setting that was too high. This 'lesson learned' is now described in the Methods, subsection 'USRP configuration and OFDM signals':

The Rx gain is kept at 20 dB; higher gains are possible but these lead (in our setup) to occasional impairment of the received signals[36].

[i] Hansen, Andrew, Stephen Mackey, Hadi Wassaf, Vaibhav Shah, Eric Wallischeck, Christopher Scarpone, Michael Barzach, and Elliott Baskerville. Complementary PNT and GPS Backup Technologies Demonstration Report: Sections 1 through 10. No. DOT-VNTSC-20-07. John A. Volpe National Transportation Systems Center (US), Jan. 2021.

[ii] Jiménez-López, F. Girela-López, J. López-Jiménez, E. Marín-López, R. Rodríguez and J. Díaz, "10 Gigabit White Rabbit: Sub-Nanosecond Timing and Data Distribution," in IEEE Access, vol. 8, pp. 92999-93010, 2020.

[iii] V. L. Knoop, P. F. de Bakker, C. C. Tiberius, and B. van Arem, "Lane determination with GPS precise point positioning," IEEE T. on ITS,

vol. 18(9), pp. 2503–2513, 2017.

[iv] P. S. Henkel, "Tightly coupled precise point positioning and attitude determination," IEEE T.-AES, vol. 51(4), pp. 3182–3197, 2015.

[v] Alarifi, Abdulrahman, AbdulMalik Al-Salman, Mansour Alsaleh, Ahmad Alnafessah, Suheer Al-Hadhrami, Mai A. Al-Ammar, and Hend S. Al-Khalifa. "Ultra wideband indoor positioning technologies: Analysis and recent advances." Sensors 16, no. 5 (2016): 707.

[vi] Diouf, Cherif, Han Dun, Tarik Kazaz, Gerard Janssen, and Christian Tiberius. "Demonstration of a decimeter-level accurate hybrid optical-wireless terrestrial positioning system." In Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), pp. 2220-2228. 2020.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions

- The abstract and introduction are appropriate and clear. In the "Compatibility with telecommunication infrastructure" I would add for completeness the alignment of the proposed system with current and evolving standards such as 3GPP 36.305 and 38.305 for 4G and 5G.

R2.11 – This is a useful suggestion. We have modified the text in this subsection as follows:

In addition, the OFDM modulation format is similar to that used in 4G and 5G radio access networks as well as Wi-Fi networks, suggesting that the OFDM PNT signals may be transmitted by present-day mobile base stations (in line with current and evolving standards such as 3GPP 36.305 for 4G and 38.305 for 5G) and Wi-Fi access points […]

- The experimental findings and the conclusions, even though adequate as described in point E., are spread throughout the manuscript. I suggest putting the analysis of findings and conclusions together in a "Discussion" section.

R2.12 – We agree with referee #2 that the findings are spread out over the manuscript (this seems the case in particular for the results concerning the positioning and timing performance). The reason for the spread is that positioning and timing are rather different aspects of the system, for each of which we need to provide some context. We have considered adding a separate Discussion section, but we came to the conclusion that it would duplicate much from the aforementioned context, and make us run into the space limits of a *Nature* article. Instead, we decided to add a new table (Table 1) to provide the reader with an overview of all positioning and timing uncertainties for our TNPS testbed, for the various methods described in the main text. Table 1 is called several times from the main text, in subsection 'Positioning and timing performance'. For completeness, we show Table 1 also below:

Table 1|Positioning and timing uncertainty

Positioning method	**RMSE (cm)**	
	East	**North**
Time-delay positioning (full band)	10.2	7.4
Time-delay positioning (sparse band)	9.4	8.4
Carrier-phase positioning (float, full band)	3.7	4.5
Carrier-phase positioning (fixed, full band)	2.2	4.1
Timing method	**Standard uncertainty (ns)**	
WR TN time synchronisation at TGV (fibre-optic)	<0.5	
Rx clock relative to WR time base (wireless)	0.6	
Rx clock relative to UTC(VSL) (wireless/fibre-optic)	50	

Positioning RMSEs correspond to the data shown in Fig. 3c, and include the 2.5-cm RMSE of the ground-truth system. Residual time offsets of the WR TNs were calibrated to within 0.1 ns in the laboratory prior to installation, and verified on-site with 0.5 ns uncertainty after installation at TGV.

Christos Laoudias

Response to referee #3

Referee #3 (Remarks to the Author):

We thank referee #3 for the time and effort spent on reviewing our manuscript. We are also grateful for the kind words, the interesting papers [1-5] pointed out by the referee, and the valuable suggestions for improvement. Please see our responses below.

This work presents a decimeter-level accuracy terrestrial networked positioning system (TNPS), and performance is evaluated via experimental tests. However, there have been many TDOA-based and OFDM-based positioning systems, e.g., [1-5]. I see this work as a successful project but has limited contribution in localization regarding the system deployment, signal design, and localization algorithms.

R3.1 – We thank referee #3 for raising this point and pointing out references [1-5]. Also after having reviewed these references, we stand by our claim that our TNPS radically advances the state of the art, enabling very accurate GNSS-independent positioning and timing, as well as possibilities for deep integration into existing wireless networks. We illustrate this claim for each of the references [1-5] individually below. It should be noted that we do not claim to be the first to use OFDM signals for positioning; this method has been around for many years (including in 4G LTE networks).

[1] This paper describes a TDoA localisation method in OFDM-based wireless metropolitan area networks (WMANs). The maximum available bandwidth is 100 MHz; the actual used bandwidth does not become clear. Since the used sample rate is 11.2 MHz, the signal bandwidth seems to be substantially smaller. The median range error of the implemented system is about 50 m, which is consistent with a rather narrowband signal. Such a range error is incomparable to the decimetre-level range errors reported for our OFDM-based TNPS. In addition, the authors of [1] leave undiscussed the timing uncertainty of their specific synchronization method (using the location servers as a timing reference). Given the low sample rate (bandwidth) and the many-metre errors, we suspect the timing errors of this synchronisation scheme to be 10-100 ns – incomparable to the sub-nanosecond uncertainty of our TNPS.

[2] This work considers TDoA-based positioning using LoRa signals. These are frequency chirps with different spreading factors (chirp rates). Since the bandwidth of LoRa signals is small (up to 500 kHz), time resolution is low. Time stamping of the gateways (receive locations) is done using GPS. Reported 90th percentile range errors are at multiple 100 m. Such performance is incomparable to that of our TNPS. The system also depends on GPS, limiting its use as a GNSS backup.

[3] This work considers a single Wi-Fi access point positioning system based on angle-of-arrival (AoA) and channel-state-information combined ranging. An OFDM signal is used in combination with an antenna array at the access point. The AoA of WiFi signals is inherently dependent on multipath, so the accuracy and applicability of AoA positioning in the presence of dense multipath will be limited. Notwithstanding the interest of the method, its performance (95th percentile errors of several metres) is incomparable to that of our TNPS.

[4] This article considers a positioning system using a master transmitter and a number of active reflectors (re-transmitters). Range measurements are thus achieved by two-way exchange of signals between the user equipment and the network infrastructure, which eliminates the need of time synchronisation of the network's base stations. The master signal is a sparse 80 MHz OFDM signal with

every Mth subcarrier occupied. The (M-1) retransmitted signals are frequency shifted such that all OFDM subcarriers become occupied. Standard WiFi training symbols are used for ToA/TDoA estimation. The achieved range accuracy is 0.2 m. The testbed is based on X310 USRPs.

This is a really original and interesting idea. Yet, our TNPS offers a number of features that this method does not provide. First, the sub-nanosecond synchronisation of the base stations our TNPS enables time transfer and wireless synchronization of stand-alone equipment. Time synchronisation is essential for vital infrastructure, and it currently relies strongly on GNSS timing. TNPS can overcome this overreliance, whereas the method of [4] cannot (since it intentionally employs two-way ranging to avoid the need for a time synchronisation system). Second, two-way ranging protocols like that of [4] are inherently non-private (as also mentioned in the manuscript), whereas our TNPS allows private, anonymous positioning, as do GNSS. Third, two-way methods scale less favourably with the number of users of the system, since for each user a two-way connection needs to be established (as opposed to our TNPS, which employs downlink transmissions only, and therefore can accommodate an arbitrary number of users).

We nonetheless find reference [4] inspiring as it could form a means to synchronise stand-alone base stations that are not connected to the WR network. We therefore included this reference as follows in the revised text (subsection ‘Compatibility with telecommunication infrastructure’):

(assuming these are synchronised using WR or similar protocols through the optical network, or over the air through two-way OFDM signal exchange[35] with nearby TNPS reference transmitters).

[5] This paper considers ranging/positioning using WLAN IEEE802.11b (an outdated DS-SS WiFi standard) with a 22 MHz bandwidth. This paper focusses only on accurate time stamping, for which a relative timing precision below 1 ns is achieved under favourable conditions (and 10 ns or worse under less favourable conditions). The authors suggest that this should enable a ranging precision of 1 to 3 metres, but they do not substantiate this with simulations or experimental data. The performance is incomparable to that of our TNPS.

This work is technically sound, and the results are reasonable. However, I would like to see more about the compatibility with different types of receivers, scalability with multiple user equipment, the robustness of the system dealing with blockage and multipath, and the system costs for a specific application scenario. This information is crucial to evaluate the utility of the system.

R3.2 – We thank referee #3 for this very useful suggestion. We now have added information regarding most of these items. Addressing each item mentioned by referee #3 separately:

- *Compatibility with different types of receivers*: the presented TNPS is a prototype based on an OFDM receiver implemented in a USRP. It will certainly be interesting to define generic receiver requirements and evaluate the compatibility of e.g. present 4G and 5G user equipment. However, we consider this an avenue for future research
- *Scalability with multiple user equipment*: the synchronisation of the TNPS base stations facilitates anonymous positioning of user equipment, using downlink communication only (like GNSS). No multiple access techniques are required, and there is no restriction on the number of users. This is reflected by the newly added line in the main text (‘Alternative timing and positioning infrastructure’):

[…] which is less privacy-friendly than the use of downlink-only (silent) GNSS receivers. Downlink-only positioning methods, like GNSS, also scale more favourably than two-way methods, for which the network overhead increases with the number of users.

- *Robustness of the system dealing with blockage and multipath*: we addressed these aspects in our responses to referees #1 and #2, who made similar comments; see responses R1.1 and R2.3 and the accompanying changes in the revised manuscript (Main text, Extended Data Fig. 5 and Extended Data Tables 1, 2). The reduced sensitivity to multipath of TNPS in comparison to GNSS is discussed in the main text, section 'Positioning and timing performance', supported by results shown in Figs. 4a,b
- *System costs for a specific application scenario*: a similar request was made by referee #2, see our response R2.4. Estimating the system cost, which encompasses both hardware and installation costs, is a challenging task. On the one hand, there are strong indications that a TNPS system will be very cost effective: based on the expertise of the first author, who is co-founder and former CTO of WR-provider OPNT, we project that current FPGA-based WR hardware prices (ranging from several hundred euro for a WR node to a few thousand euros for a WR switch) are expected to drop by one order of magnitude when ASIC-based WR devices become available, while WR payload data capacity would increase by a similar factor to 10-25 Gb/s. Time distribution is also efficient in terms of transport capacity: not only can existing fibre-optic connections be used, time can also be locally regenerated and distributed to as many downstream nodes and users as needed (i.e. no bigger upstream 'data pipes' are needed to transport time to more downstream users). And thanks to the OFDM structure of the PNT signals demonstrated here, we expect that the PNT radio signal modulation and transmission can be done through present-day 4G base stations and Wi-Fi access points with minimal hardware modifications, and mostly software modifications (see also below).

  On the other hand, hardware prices are subject to fluctuations that depend on the nature and size of the installation (e.g. volume discounts), component shortages (like the current COVID-19 induced shortage of integrated circuits), the negotiation power of the customer, the presence of auxiliary infrastructure (the cost for a TNPS will be significantly lower for a customer who already has secured access to rooftop installations and cell towers), the cost of local labor force for installation, et cetera. An even more important unknown in cost estimates will be the level of integration of WR equipment and TNPS transmitters in telecommunication hardware, and opportunities for dual use: for example, WR hardware could simultaneously be used as a time-distribution system and a Gigabit Ethernet optical supervisory channel (see e.g. US Patent 9331844 B2), adding perhaps a marginal amount of 100 euro to the cost of a DWDM network node (>>10,000 euro). Likewise, TNPS transmitters might be fully integrated in 5G base stations and/or Wi-Fi access points, so that the additional cost covers only that what is required to achieve deterministic OFDM PNT transmissions with 0.1 ns jitter, and to synchronize to the WR network. We believe that any attempt to estimate the system cost will be handwaving at best. In our humble opinion such information might also be considered to fall outside the scope of this type of article in *Nature* (although it might be suitable for a Perspective article at a later time). At the same time, we do believe that our results – even without a cost estimate – will provide a strong impetus to developments towards further integration of TNPS-like components into telecom equipment.

Some comments on the paper:

Page 3, Line 4: 'The systems rely on two-way communication' is not necessarily true. If the pilot signals and transmission schemes are predefined, positioning and can be done with only uplink or downlink communication.

R3.3 – The referee's statement in the second sentence is correct. However, the statement in the referee's first sentence does not entirely reflect what we wrote in the original manuscript:

However, these systems rely on two-way communication *or* radio transmissions from the mobile transceiver to a sensor infrastructure.

Our statement is valid for the systems we referred to in the preceding sentences (described in Refs. 14,18,20). We agree with referee #3 that positioning can be done using only uplink or downlink communication, but in both cases the nodes of the fixed infrastructure should be time-synchronised (this is an essential ingredient of the 'predefined transmission schemes' mentioned by referee #3). Moreover, the uplink-only case is not anonymous like GNSS, and – from the viewpoint of the network operator – scales less favourably with the number of mobile user devices.

Page 3, Line 9: It is true that GNSS outperforms existing mobile-network-based positioning methods (e.g., 4G signals). Nevertheless, the deployment of 5G systems has already been completed in some areas, and integrated communication, localization, and sensing are expected. What is the advantage of this TNPS system then? A dedicated designed positioning system for a specific scenario, what kind of scenario?

R3.4 – To our knowledge, neither 4G nor 5G networks currently provide positioning with uncertainties comparable to GNSS. To achieve such positioning, there is a need to synchronise 5G base stations at the 10 ns level, which is considered challenging even using GNSS timing receivers; see H. Li et al. Analysis of the synchronization requirements of 5G and corresponding solutions. *IEEE Comm. Stand. Mag.* March 2017, pp. 52-58. DOI: 10.1109/MCOMSTD.2017.1600768ST. The expectation put forward by referee #3 that 5G may provide GNSS-level positioning depends strongly on the capability to synchronise 5G base stations with GNSS-level accuracy (~10 ns), if not better. Even if this expectation is met, the performance would still not be at the decimetre level (as required by many applications) but rather at the metre level. Our TNPS shows that deep-subnanosecond synchronisation, as needed for decimetre-level positioning, is achievable using telecom fibre and a standardized timing protocol (WR, or the High Accuracy profile of the IEEE 1588 standard) that runs over Ethernet.

One might argue that 5G positioning could technically speaking be done using two-way ranging (as done in Ref. [4] pointed out by referee #3 above). In this way, the need for network synchronisation is avoided altogether. In this case, however, the user would not be able to extract precise time, since no precise time reference is present in the network. This would hamper the vast amount of existing applications that now use GNSS receivers for time synchronisation (and that often are in need of a timing back-up, for example base stations of mobile networks themselves), as well as emerging technologies (such as quantum communication) that require sub-nanosecond synchronisation. For that matter, our TNPS is not designed for a specific scenario, but rather a general-purpose system with a wide range of applications, both in positioning and timing, including in urban areas with dense multipath.

Regarding the expectations of 5G of '*integrated communication, localization, and sensing*', as alluded to by referee #3: in our manuscript, we make the case that our TNPS is highly compatible with telecommunication infrastructure, and that we anticipate that dm-level positioning and sub-ns timing will become an integral part of the services provided through future telecommunication networks (and we explicitly mention 5G networks in this context). As a matter of fact, we believe that our work lays a firm foundation for follow-up research and technology development that will ultimately enable dm-level positioning and sub-ns timing through future 5G and 6G networks.

Page 6, Line 7: Why sparse-band and full-band OFDM-TD positioning have similar performance, how similar it is. The performance can be easily analyzed theoretically (e.g., by CRLB), and it is not convincing to just mention 'we find'.

R3.5 – We agree with the referee. In fact, the CRLB was analysed by several of us in previous work, but the referee's comment kindly reminded us of the fact that we forgot to include references to this work. To fix this, the main text now reads:

We find that sparse-band and full-band OFDM-TD positioning have similar decimetre-level performance, as expected from the similar values for the theoretical Cramér-Rao lower bound (CRLB) for both methods[7,22].

The root-CRLB values for the two methods differ by about 1.3; see e.g. Fig. 5(a) of Ref. 22.

Page 7 Line 20: WR equipment has been commercially available for over one decade; what is the limitation that prevents the application of this technique in positioning. If this technique is mature, what is your contribution?

R3.6 – WR, as a time and frequency distribution system, has been available for over a decade as open-source, open-hardware devices, provided by a growing number of vendors (who now also sell proprietary WR equipment). WR has been used in many timing applications (see Ref. 29 of our manuscript for an overview). To our knowledge, however, WR has never been used to synchronise anchor stations for a terrestrial PNT network and demonstrate positioning. We can only speculate about the limitations that have prevented such a development, but one possible reason is the interdisciplinary nature of our TNPS (which involves a range of techniques, such as time keeping and time distribution, optical communication, wireless communication, electronics and electro-optics, as well as navigation and positioning), which required a multidisciplinary team in order to conceive, develop, and demonstrate the system.

So, the novelty of our work is not in improvement of WR per se. Rather, the novelty is in the first demonstration of positioning and (wireless) timing, based on a WR optical network, enabling high performance (robust decimetre-level positioning and subnanosecond timing) with an additional traceability to UTC, which make our system suitable as a back-up or replacement of GNSS.

Page 8, Line 9: I am afraid the bandwidth scarcity issue can hardly be solved by the reported TNPS system. The mentioned 160 MHz bandwidth can be easily obtained by mmWave systems.

R3.7 – Notwithstanding the large bandwidths achievable with mmWave systems (and similar for existing microwave systems and free-space optical communication systems), we stand by our claim that the sparse-band approach may help creating a (virtual) wideband while circumventing the general bandwidth scarcity issue (specifically in the crowded UHF band), for example by choosing bands that coincide with the pieces of radio spectrum licensed to mobile network operators and license-free bands.

That said, we agree with referee #3 that mmWave systems can easily provide 160 MHz bandwidth (on account of the higher carrier frequencies of several tens of GHz), and indeed one could envision extending our TNPS with e.g. 5G mmWave gNodeB stations, synchronized through WR. At the same time, mmWave systems come with other challenges such as 100-fold increased free-space path loss, and the need for beamforming and dynamic tracking of moving user equipment (for multiple access and interference reduction). Such features imply some form of user access to the network in order to make PNT through mmWaves work. With omnidirectional mobile communication signals, like in our TNPS, such access is not required.

Moreover, it is not clear beforehand if mmWave stations are ready for deployment in an TNPS system. For example, research may have to be conducted about the effect of dynamic beam forming on transmission delays. It seems fair to assume that such possible technical obstacles will eventually be overcome. Even then, our sparse-band approach opens the door to complement positioning through wideband mmWave stations by PNT transmissions in virtual (ultra)wideband bands in the UHF range, where free-space path loss and beam forming and tracking are less of an issue.

Suggestions:

I would suggest this work be submitted to more technical journals (e.g., IEEE transactions) where more solid suggestions can be provided.

R3.8 – As a follow-up to the presently submitted manuscript, elaborate technical papers are in the making. We do believe, however, that the present work suits the scope of *Nature* and its broad readership. GNSS positioning and timing is crucial for society, but no back-up system is available, and even augmented GNSS receivers fail to provide the precision and reliability that will be needed in the immediate future. Our TNPS offers a GNSS-independent, more precise, and scalable system that may be integrated into existing and future telecom infrastructure. As such it presents and substantiates the vision of a telecom network that not only provides connectivity, but also positioning and timing beyond the limitations of GNSS.

Also from a technical point of view, we believe exposure to a wider audience is warranted. In our response R3.6 we already mentioned the multidisciplinary nature of the TNPS system. To stimulate further research in this direction, we seek to inform the broader community in physical sciences and engineering, rather than addressing e.g. only the time-keeping community through publication in a specialized journal.

[1] Ni, Hao, Guangliang Ren, and Yilin Chang. "A TDOA location scheme in OFDM based WMANs." IEEE Transactions on consumer electronics 54, no. 3 (2008): 1017-1021.

[2] Podevijn, Nico, David Plets, Jens Trogh, Luc Martens, Pieter Suanet, Kim Hendrikse, and Wout Joseph. "TDoA-based outdoor positioning with tracking algorithm in a public LoRa network." Wireless Communications and Mobile Computing 2018 (2018).

[3] Han, Shuai, Yi Li, Weixiao Meng, Cheng Li, Tianqi Liu, and Yanbo Zhang. "Indoor localization with a single Wi-Fi access point based on OFDM-MIMO." IEEE systems journal 13, no. 1 (2018): 964-972.

[4] Yang, Mingyu, Li-Xuan Chuo, Karan Suri, Lu Liu, Hao Zheng, and Hun-Seok Kim. "ilps: Local positioning system with simultaneous localization and wireless communication." In IEEE INFOCOM 2019-IEEE Conference on Computer Communications, pp. 379-387. IEEE, 2019.

[5] Exel, Reinhard, Georg Gaderer, and Patrick Loschmidt. "Localisation of wireless LAN nodes using accurate TDoA measurements." In 2010 IEEE Wireless Communication and Networking Conference, pp. 1-6. IEEE, 2010.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

The authors have satisfactorily addressed all of my concerns in their revised manuscript, which I believe is worthy of publishing in Nature.

Referee #2 (Remarks to the Author):

The authors have made a significant effort to address my comments and suggestions. Explanations, clarifications and some new results have been added. I am happy with the revised manuscript.

Christos Laoudias

Referee #3 (Remarks to the Author):

The response and actions look good, and I have no further comments.