Experimental and Simulation Study for Commercial Time Transfer Service over Geostationary Satellite

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Abstract—Time transfer over satellite links has been explored since the satellite era began. Currently, TWSTFT is routinely used between national timing laboratories to align national timing standards and the GPS provides precise timing signals in addition to its more familiar navigation solution. For many years, the possibility of a one-way timing service over satellite has been explored but apart from the GPS a commercial timing service product of this kind is not yet available. This paper reports on an approach to timing signal transfer from a precision reference clock over commercial satellite links with a specified low level of jitter at the receiving stations, making use only of the projected ephemeris information provided by the satellite operator. An initial experiment, reported here, showed that with one master station, measuring aggregate extraneous delays and transmitting positioning and delay data plus a correction factor to the slave stations, allowed transfer of a PPS timing signal with jitter standard deviation of 72ns-98ns and peak-to-peak of around 500ns-600ns, measured against a GPS reference. Subsequent analysis of the experiment uncovered some issues with the implementation which suggested that these results could be substantially improved upon. Furthermore, simulation of the one master station system modeling the aggregate extraneous delays as random white noise plus wander can produce similar results to those obtained in the experiment. Finally, we report on the ongoing development and simulation of a system with three master stations with the desired goal of no more than 100ns of jitter peak-to-peak. Simulations show that obtaining such performance with three master stations for satellite positioning will be highly dependent on the statistics of the noise due to the aggregate extraneous delays.

Key words:* *time dissemination, timing, jitter, simulation, satellites, delay effects, propagation

I. INTRODUCTION

When a local clock needs to be synchronized to a more accurate clock located remotely from the local clock, it is necessary to perform time and/or frequency transfer. Time and frequency transfer methods fall into three different categories: one-way methods, two-way methods and common view methods. The simplest approach to time transfer is the one-way method, where the user requires only a receiver and there is a master clock source which may be transmitted to many such receiving stations. For this approach to be successful, a good estimate of the delay from transmitter to receiver must be available [1]. In two-way time transfer, the delay is estimated, usually concurrently with the transfer, based on measured round-trip delays between two stations. In the ideal case, the delay is symmetrical and can then be eliminated entirely [2]. In common view approaches, several receiving stations measure the arrival time of a master timing signal from a common source then compare their measurements by subtracting them. To the extent that path delays and path delay fluctuations are common between the different paths, they will cancel out, reducing the error in the time transfer [1].

Time transfer over satellite links has been explored since the satellite era began. One-way approaches began in the 1970s with investigation of the transmission of a highly accurate master clock to other stations over the newly available satellites [3], [4]. To be able to make use of the received timing signal, the delays between master and slave stations via the satellite have to be known very accurately. The main problem is the continuous variation in the satellite position over time. These two papers represent early attempts to quantify the uncertainty in the received timing signal. In [3], the position of the satellite is estimated from six orbital elements which are provided by the satellite operators and the delays thus calculated are compared with measured delays. In [4], the approach used is three station trilateration of the satellite position while simultaneously synchronizing the clocks.

Currently, the most common one-way time transfer implementation using satellites is the Global Positioning System (GPS) [5], [6] in which the remote master device is a high-precision clock located on board the navigation satellite. The delay from a GPS satellite to a receiver is about 65ms but the uncertainty in the delay, computed by the receiver using ephemeris information sent by the satellite, is only nanoseconds and the other components of the delay uncertainty become just as important, although their individual absolute amounts may be quite small, because the uncertainties in either measuring these or estimating these from models are larger [1].

Two-way time transfer over satellite offers potential precision on the order of nanoseconds, because the path and equipment delays cancel out [2]. Originally there were also significant disadvantages as it was expensive, both stations needing to transmit as well as receive, and it was more difficult to set up as a point-to-point procedure requiring calibration of equipment and careful measurement of delay components. However, it is today used extensively and routinely in TWSTT (two-way satellite time transfer) and TWSTFT (two-way satellite time and frequency transfer) for comparing reference clocks and time scales between national timing laboratories [7].

For many years, the possibility of a commercial one-way timing service over satellite has been explored but apart from the GPS a commercial timing service product of this kind is not yet available. GPS provides excellent accuracy but from some points of view, it remains a technical and geopolitical risk that the system is managed by the defense department of a single country. These risks have been historically confirmed, for example, in the use of Selective Availability [8]. Consequently, as alternatives to GPS, there are similar projects under development, such as Galileo (EU), GLONASS (Russia), COMPASS (China) and IRNSS (India). All of these systems, despite their enormous potential, are still not available as an alternative, and most likely will not even be fully operational for several more years. More recently, real concern has arisen over episodes of deliberate jamming of the GPS signal, usually in an attempt to block location information, sometimes with criminal intent [9]. In the current situation, if the quality of the GPS signal deteriorates, some of the main information and communications channels would not be usable in many countries, causing a wide range of problems.

This paper reports on the development of a proposal for timing signal transfer from a precision reference clock over commercial satellite links with a specified low level of jitter at the receiving stations, making use only of the projected ephemeris information provided by the satellite operator. In the fully realized system, with a number of master stations using TWSTFT and exchanging timing information via satellite to track the satellite position, information transmitted concurrently with the reference timing signal will allow slave stations to adjust the timing signal compensating for the satellite motion. The paper is structured as follows: in Section II, we present an overview of the time transfer system proposed by Mixed Processing Ltd and of the experiment conducted as a proof of concept and demonstration of the system. In Section II, the analysis of the experiment and its results are also discussed. In Section III, results of the simulations of the experimental system and the development of a simulation of a full system are presented. Finally, in Section IV we present our conclusions and a brief outline of the future development plans.

II. THE MIXED PROCESSING TIME TRANSFER SYSTEM

The time transfer system [10] now being developed by Mixed Processing Ltd is to provide a complete off-the-shelf system for providing precision time transfer over satellite. The full system, shown schematically in Figure 1, would consist of three master stations in order to be able to fix the satellite position. The master stations would communicate with each other and with the receive-only slave stations using bandwidth rented from a commercial satellite provider, such as Intelsat [11] or Eutelsat [12]. One master station will have a high precision clock such as a Cesium atomic clock and two sub-master stations will have precision clocks with a high holdover capability e.g. Rubidium clocks. Each of the master stations, whether master or sub-master, will have a bi-directional link to the satellite. Finally, there are slave or receive-only stations which have a unidirectional (receive) link with the satellite. Mixed Processing Ltd has developed the satellite modem for the system using an FPGA with a soft-core microprocessor. The RF transceiver functions in the L-Band and is two-way only for the master stations, whereas it is configured as receive-only for the slave stations.

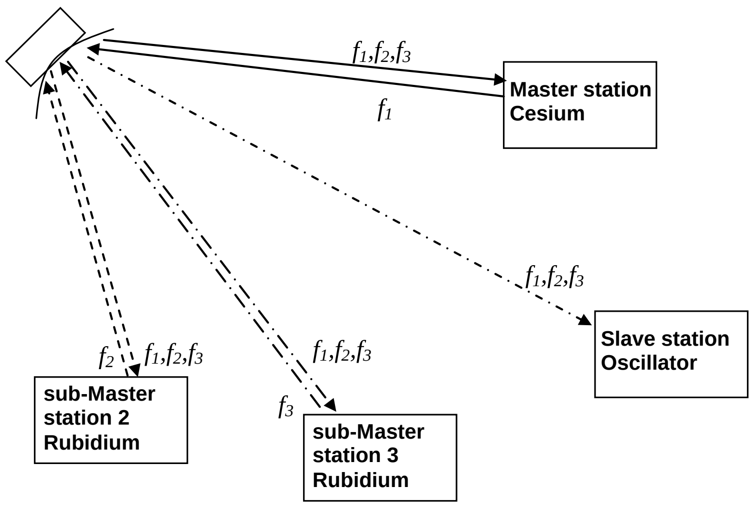

Figure 1. Proposed system for time transfer over satellite.

In order to determine accurately the propagation time of signals between the master station and the slave stations it will be necessary to consider and correct errors due to:

- Errors in the satellite ephemeris.
- Relativistic effects, including the Sagnac effect.
- Delay variation due to the interaction of the signals and the troposphere and the ionosphere. At the transmission frequencies to be used of between 12 and 14.2 GHz, the effect of the ionosphere can largely be neglected [13].
- Errors caused by the resolution of the transmitter and receiver system and by the noise of the PLL (Phase Locked Loop) and DLL (Delay Locked Loop).
- Temperature induced variation (diurnal wander) in cables and particularly outdoor equipment.
- Generic statistical errors regarding the evaluation of distances and ground station position.

A. Proof of Concept Experiment

An experiment was conducted as a proof of concept of the system with a single master station broadcasting a PPS timing signal to three slave stations. The experiment also provided an opportunity to demonstrate the system to potential customers. Satellite ephemeris data for Eurobird 3 (now known as Eutelsat E33A) was obtained from the satellite operator [12]. The master station measured the round-trip time to the satellite and broadcast the satellite co-ordinates, transmission delay information, and a correction factor to the slave stations so that they could adjust their expected arrival time of the PPS. As this was an initial experiment with such a system, a GPS PPS signal, which was readily available from the equipment used, was used as a reference to measure the jitter on the satellite transmitted PPS timing from the master station to the slaves.

The experiment was conducted in Italy with the master station located at Bresso, Lombardia, and the three slave stations at Asti, Piemonte, Treviso, Veneto, and Palermo, Sicilia. As the master station was the furthest north, the PPS actually arrived sooner at the slave stations than its time of return to the master station. The PPS timings were processed centrally at the master station equipment and stored in a Microsoft Excel spreadsheet for subsequent analysis of the experiment.

The procedure carried out by the equipment at the master station is illustrated in Figure 2 and is as follows:

- Use the master station co-ordinates and the satellite co-ordinates to calculate the transmission delay master-to-satellite.
- Measure e1PPSDelay: the time between the GPS PPS reference at the master station and the time the PPS is received back at the master station following a round-trip via the satellite.
- Calculate a correction factor – the difference between the predicted round-trip time and the actual round-trip time.
- Send the satellite co-ordinates, transmission delay and the correction factor to the slave stations.

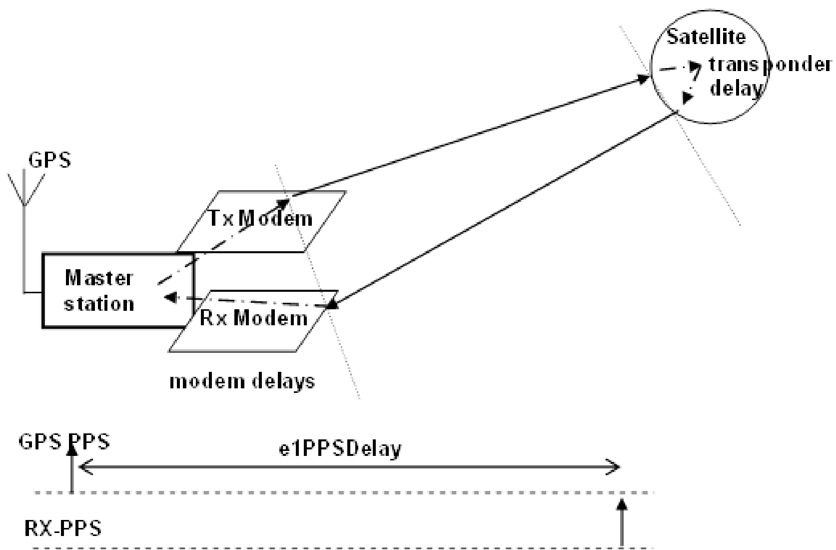

Figure 2. Diagram of procedure and measurements at master station.

From Figure 2 and the sequence of events described above performed at the master station, it can be seen that the calculation of the difference between the estimated round-trip delay between master station and satellite and the actual measured delay will include all the extraneous delays including the uplink and downlink satellite transponder delays, the delays through the ground equipment and cables and atmospheric effects.

The procedure carried out by the equipment in the slave stations and illustrated in Figure 3 below, is as follows:

- Receive the satellite co-ordinates, transmission delay and the correction factor from the master station together with the PPS signal.
- Calculate the expected one-way delay between slave station and satellite using the known position of the slave station and the satellite co-ordinates.

- Calculate the expected one-way path-only receive delay from master to satellite to slave.
- Incorporate the correction factor and thus calculate the expected delay (e1PPSOffset) at the slave station for the PPS.
- e1PPSDelay is the error or the time difference between the PPS received over the satellite link from the master and the GPS PPS delayed by e1PPSOffset which has been placed in a delay line as shown in Figure 4.

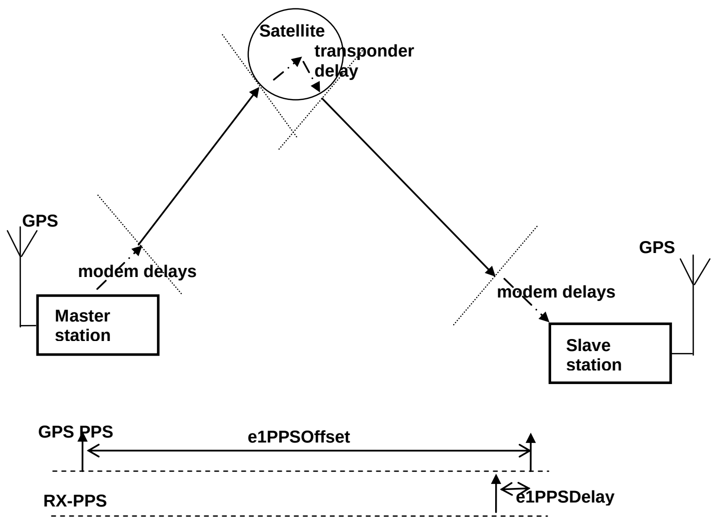

Figure 3. Diagram of procedure and measurements at slave station.

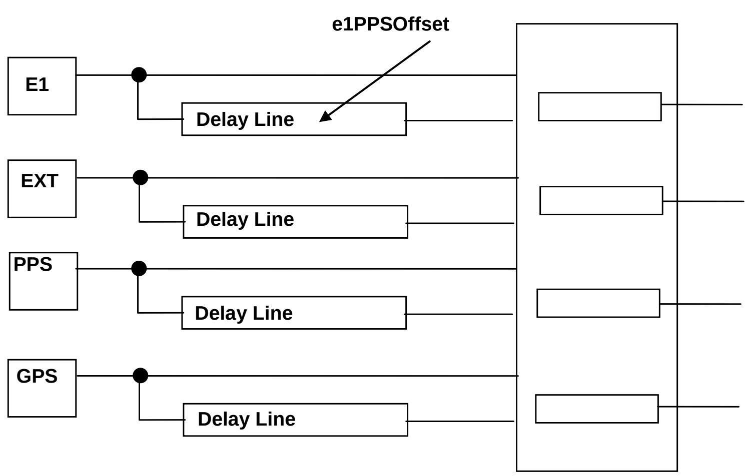

Figure 4. Schematic of timing signal regeneration using delay line.

B. Experimental Results

The initial experiment demonstrated that even with the simple protocol presented above, it was possible to transmit the PPS timing signal from a master station to slave stations dispersed over a large territory using a commercial geostationary satellite link with an accuracy of at worst 1µs. For this accuracy to be achieved, satellite ephemeris data from the satellite operator was interpolated to one second intervals and sent to the slave stations along with the one-way transmit master to satellite delay calculated from the ephemeris data plus a correction factor accounting for all the extraneous delays estimated from the measured round-trip delay. At this level, the experiment did not use the measured round-trip delay to improve the estimate of the satellite position because this is not possible without more master stations, e.g. using trilateration.

A number of problems arose in the initial experiment. These will be briefly described first and then the impact of each will be evaluated. The first issue was the intermittent failure of the satellite modem used (not one developed by Mixed Processing Ltd) which necessitated an occasional reset of the satellite link and is the cause of the vertical "jumps" in the e1PPSDelay data as seen in Figure 5. A second issue connected with this and having implications for the analysis of the experimental results, is that the data recovered from the experiment are not continuous and have timeline interruptions of varying duration. A third issue was the use of ground station position co-ordinates from the GPS function of the equipment used in the experiment, as a result of which the ground station co-ordinates used for calculations were time-varying. A fourth issue was the programming into the equipment of an incorrect earth radius value which affected the calculation of the path delays involved.

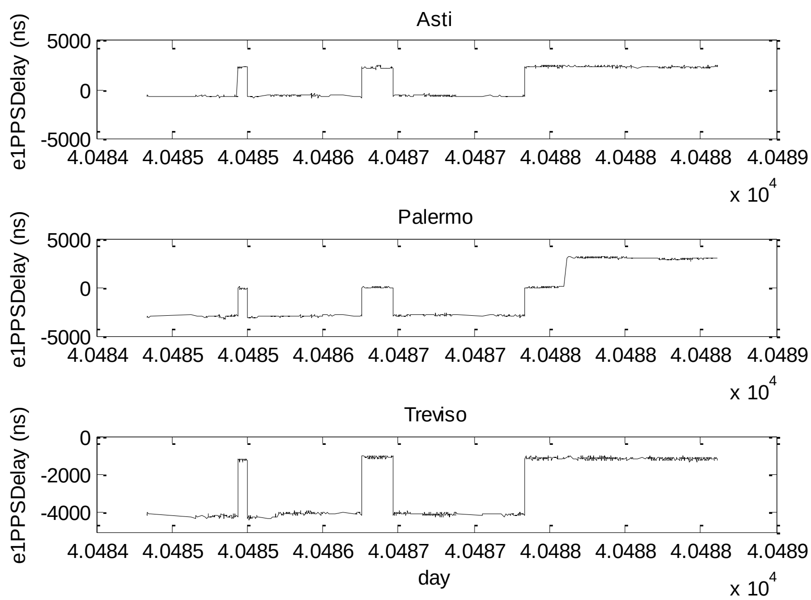

Figure 5. e1PPSDelay – the measured error at the three slave stations.

The e1PPSDelay is the timing jitter on the received PPS signal measured relative to the GPS PPS. In the evaluation of the e1PPSDelay, the 'jumps' in the data, as seen in Figure 5, obscure the size and character of the jitter on the e1PPSDelay. Thus, in the analysis of the experiment, the jumps, which were artifacts of resetting the communications link, were removed from the e1PPSDelay without shifting the data with respect to the time of day (horizontal) axis and the data were re-plotted. The re-plotted e1PPSDelay data (called "adjusted e1PPSDelay") for the three different slave stations are shown in Figure 6.

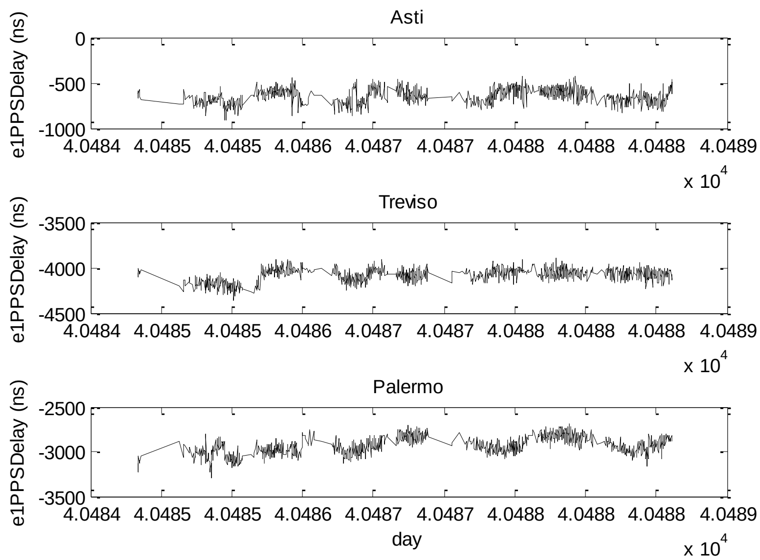

Figure 6. Adjusted e1PPSDelay at the three slave stations.

The adjusted e1PPSDelay values appear to show some quasi-periodic jitter. This jitter is unfortunately still obscured by the interruptions to the timeline of data collection which resulted from the modem faults, but is clearly present. It is seen most strongly in the Palermo data and least in the Treviso data. There is also random jitter present on the signal. Histograms of the e1PPSDelay distributions are shown in Figure 7 and suggest an approximately normal distribution of the e1PPSDelay, with the station at Asti having the most normal distribution and the station at Treviso the least. The normal probability plots of the e1PPSDelay data (not shown) suggest that the major component of the e1PPSDelay is normally distributed random error due to a variety of causes probably including equipment noise, the path delay errors caused by using the time-varying GPS station location co-ordinates, and the impact of factors not used explicitly in the delay calculations such as atmospheric effects. However, there is some curvature in the normal probability plot suggesting that there are other sources of noise in the e1PPSDelay data, in particular a quasi-sinusoidal variation (wander) due to the satellite motion plus diurnal wander in cables.

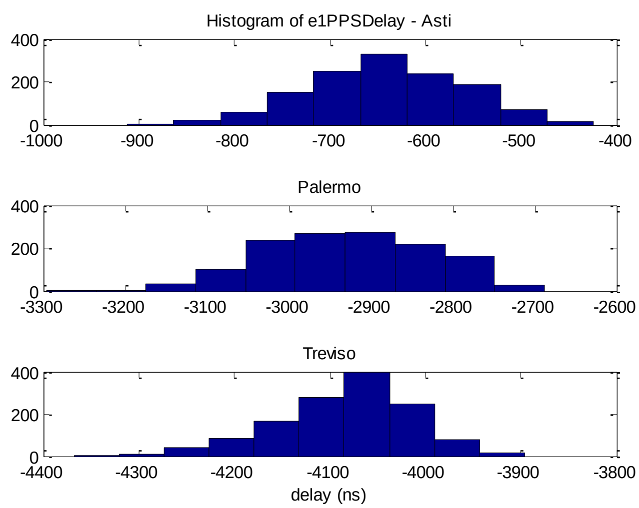

Figure 7. Histograms of e1PPSDelay (adjusted).

Descriptive statistics were also calculated for the adjusted e1PPSDelay. The results are summarized in Table 1 below, where the range characterizes the peak-to-peak of the quasi-periodic jitter and the standard deviation the rms of the random jitter (although its value is also influenced by the presence of the quasi-periodic jitter). Thus, the range gives an estimate of the peak-to-peak quasi-periodic jitter due predominantly to the satellite motion. Note that the range of the quasi-periodic jitter is largest at Palermo, the station which is the furthest from the master station.

Table 1. Descriptive statistics for e1PPSDelay at slave stations.

	Asti (ns)	**Palermo (ns)**	**Treviso (ns)**
mean	-642.5	-2927	-4083.4
standard deviation	78.5	98.6	71.99
median	-648	-2928	-3896
range	488	608	472

C. Sources of Error in the Experiment

Apart from the issues with the modem discussed above, a further potential source of error in the experiment was that in the calculations of path delay, time-varying station position co-ordinates provided by the GPS portion of the equipment were used. Clearly, the ground station antenna position is not really varying and thus using time-varying co-ordinates would be a source of error in the satellite path delay calculation and thus of random jitter on the received timing signal. It has been noted by several authors in reports of time transfer over satellite experiments that errors in the antenna co-ordinates can be the cause of delay discrepancies and closing errors [6], [14].

The analysis of the effect of using the varying ground station co-ordinates showed that it was not large. A comparison was made between the satellite ranges and range delays calculated using the time-varying station data and those that would have been calculated using a fixed value. The average of the time-varying positions was used as the fixed value for this comparison. The error plots for the range and delay resulting from using time-varying ground station positions are shown in Figure 8, where it can be seen that the maximum absolute range error is approximately ± 25m and the maximum absolute delay error is approximately ± 100ns. Thus, the inadvertent use of a time-varying satellite position contributes to the random jitter seen on the output value of e1PPSDelay at the slave stations.

A potentially more serious issue was an error in the mean earth radius value programmed into the software used to calculate the station to satellite ranges. Once this issue was discovered, extensive analysis was carried out investigating the effect of the error. The experiment was effectively re-run within a computer reconstructing the range and delay values using the satellite ephemeris data for the time period in question available from the satellite operator's archive [12]. These values were used to replicate the experiment results using the available measurement data, i.e. the actual measured master-to-satellite round-trip delays from the experiment for comparison with the experimental results. As a result of the analysis, it was established that the incorrect value used meant that the equipment consistently estimated the satellite as further away than it actually was. The net effect of the error was simply an additional delay with only a sub-nanosecond variation in that delay as shown in Figure 9.

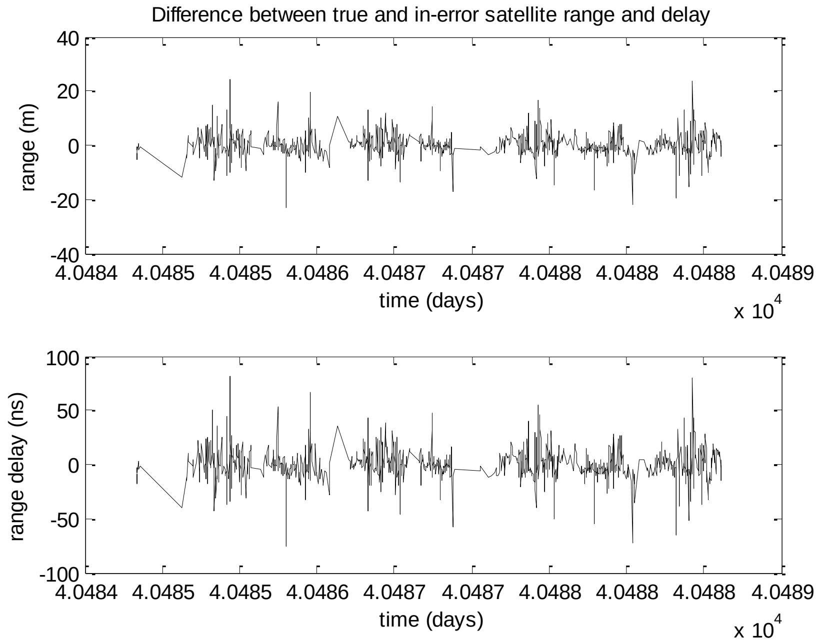

Figure 8. Range and delay variation due to time-varying satellite position.

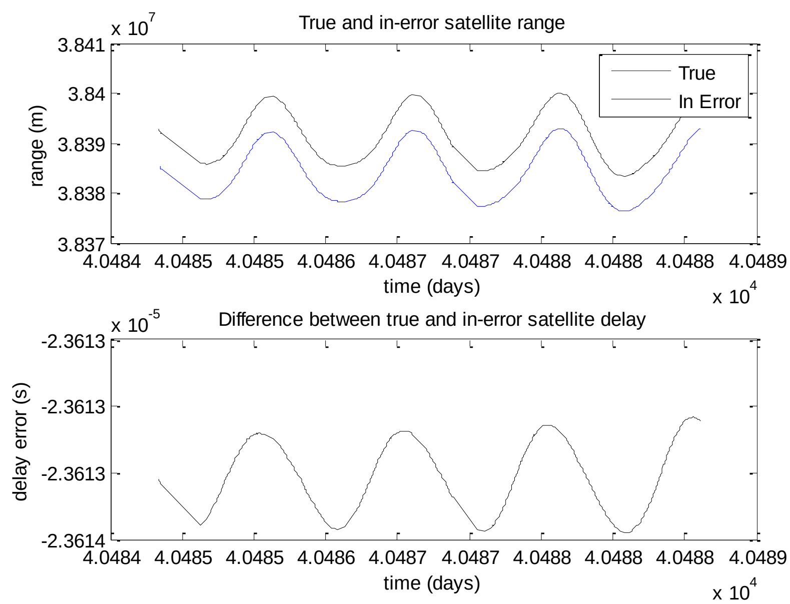

Figure 9. Difference in range and delay due to radius error.

III. SIMULATIONS

A. Simulation of a System with One Master Station

A simulation of the experiment using only one master station and one slave station was developed. The master station was placed at Bresso and the slave station at Palermo. As the goal was to reproduce the results of the experiment, the satellite ephemeris data was downloaded as ECEF Cartesian co-ordinates for the period covering the dates of the experiment from the satellite operator archive [12]. The satellite ephemeris data (available at 30 minute intervals) was interpolated to one second intervals. Using the station co-ordinates (average of the time-varying co-ordinates from the experimental data) and the interpolated satellite co-ordinates range and range delay values were calculated for the master and slave stations.

Weather data was downloaded for the two locations from the historical weather data archive for Italy provided by ilMeteo.it [15] and used to estimate the 90% of the troposphere delay due to the dry component using the dry model of Saastamoinen [16] for which barometric pressure is required. Where a barometric pressure reading for a day was missing (which occurred in 1-3 places within each file), it was replaced by the median value for the month. The dry component model value is also used as the station estimate of the mean troposphere delay. To add some uncertainty into the troposphere delay model, given that the stations would not be able to model the troposphere delay perfectly, the final value of the troposphere delay used in calculating the measured travel times of the signal also includes a random noise of average magnitude of 10% of the troposphere delay due to the wet component. The variation in delay due respectively to refraction and dispersion by the ionosphere is generally negligible at the frequencies to be used (12-14 GHz) [13] and is not modeled. Satellite transponder delays are not included in the simulation calculations as no information was available to characterize these. The Sagnac effect is also not included in the simulation as it can easily be calculated and removed in practice.

A set of measured master to slave delays was generated by combining the calculated master to satellite and slave to satellite delays with the modeled troposphere delay and a model for the overall equipment delay. The simulation records the received PPS from the master at the slave by adding the measured master to slave path delay to an "ideal" clock. Then following the procedure in the experiment, an estimate for the arrival time of the PPS at the slave is calculated (called PPSOffset in the experiment) using the estimated path delays plus the station's estimates of the troposphere delay and the equipment delay. The PPSOffset is subtracted from the jittered PPS which "arrives" at the slave station to generate the equivalent of the e1PPSDelay value in the experiment. In the simulation, a slave PPS is also reconstructed after subtracting the estimated path delays (master to satellite and satellite to slave) and the station's estimates of the troposphere delay and correction factor values. The jitter on the resulting period of this regenerated version of the PPS signal can then be calculated. Note that this signal was not produced in the experiment.

B. Equipment Delay Modeling and Simulation Versions

Two different approaches to modeling the equipment delay were used in the simulation. In the first version, the equipment delay was modeled on the correction factor data from the actual experiments using a normal distribution based on the statistics of the experimental data. It was not possible to use the actual correction factor values because they are not available at one second intervals. In analysis of the experimental data, the correction factor values were found to be of bimodal or trimodal (Palermo station) distribution, but approximately normally distributed around each modal value. These distributions probably occurred due to the problems with modem functioning experienced during the experiments: after each reset of the modem, a different mean delay was established. Of course, it was not necessary to model bimodal or trimodal distributions because these likely only arose due to the modem resets. Modeling the equipment delay from the experimental data was also difficult because the correction factor data effectively included all extraneous delays in addition to the path delay. Data sets of independent, normally distributed delays were generated for each mean and standard deviation value for each station and then these were combined by averaging (of two data sets for Bresso and three data sets for Palermo). In order to prevent the increase in variance caused by the summation of n independent random variables, the standard deviation was then adjusted by multiplying by $1/\sqrt{n}$. The modeled correction factors were then further adjusted by subtracting the daily estimate of the mean troposphere delay (applied identically to every second of data for a given day).

1) Version 1 – modeling equipment delay using experimentally derived statistics: In the version 1 of the simulation, the results are not as good as they were in reality because the noise produced by the model of the correction factor is too large. The standard deviation of the jitter on the received PPS at the slave station as well as the simulated e1PPSDelay at the slave is 0.4 µs. This means that the range of the jitter on the received PPS as well on the simulated e1PPSDelay is generally within 3µs, i.e. ±1.5µs as shown by the plot in Figure 10. The poor performance of the system in simulation in reducing the jitter can be explained mainly by the difficulty of modeling the correction factor. The amount of jitter on the PPS signal is very dependent on the standard deviation used in the model. The standard deviation value is based on the original experimental data but it is likely to be an overly pessimistic estimate because of the bimodal and trimodal distributions and the effect of the sinusoidal variation in the correction factor on its value.

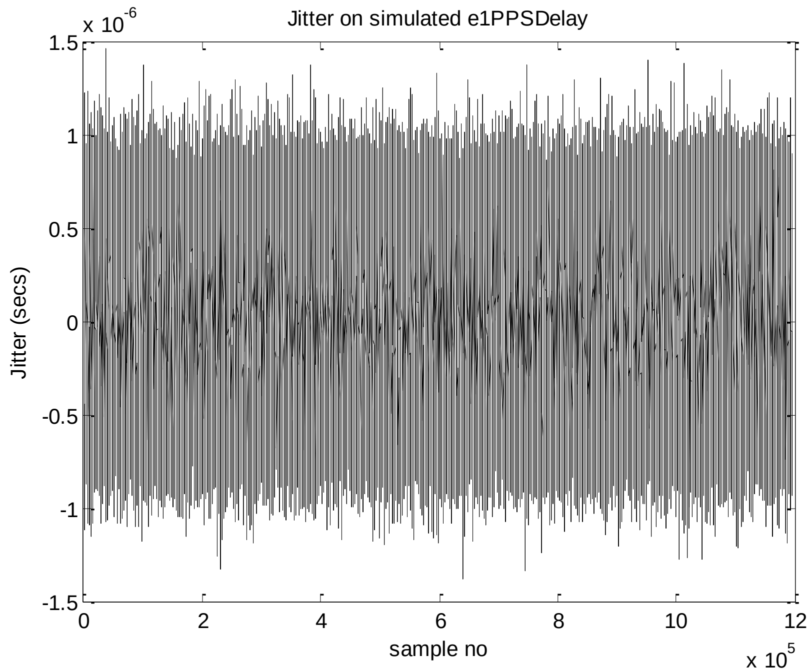

Figure 10. Simulation version 1: Jitter on simulated e1PPSDelay at the slave station.

2) Version 2 – modeling equipment delay as wander plus random noise: In the second approach, the equipment delay is modeled directly as a mean value plus a variation which is a sum of a sinusoidal variation, modeling satellite motion plus diurnal wander which will occur in cables and in equipment exposed to daily temperature variations, and random white noise. The values for the standard deviation of the Gaussian noise component and the wander amplitude were chosen by trial and error so that the simulation could reproduce the jitter on the e1PPSDelay signal that was observed in the experiment. The final standard deviation values used were 45-50 ns and the diurnal wander amplitude was around 30 ns. For example, as shown in Figure 11, these values generated a simulated e1PPSDelay signal with a peak-to-peak variation of around 500-600 ns and a standard deviation of 84 ns, comparable to the values found experimentally and shown in Table 1. The standard deviation of the jitter on the received PPS period after adjustment using knowledge of the path delays and estimates of the equipment delay and mean troposphere delay is 0.1µs and the range of the jitter on the received PPS period after adjustment is within 1.0µs.

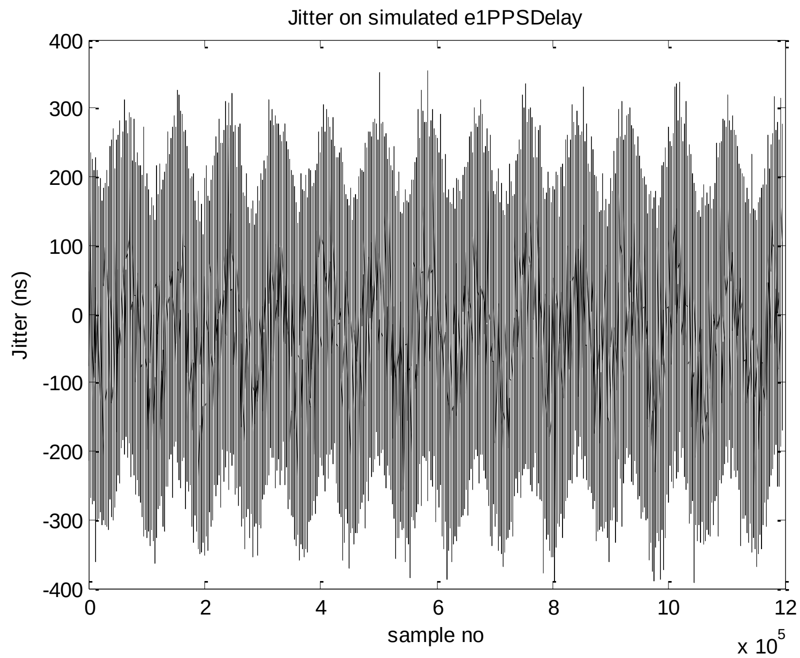

Figure 11. Simulation version 2: Jitter on simulated e1PPSDelay at the slave station.

C. Simulation of Complete System with Three Master Stations

A detailed simulation of the system involving three master stations is under development. Building on the previous simulation and experimental work, the locations of the master stations were chosen as Bresso (master 1), Asti (master 2) and Treviso (master 3). The satellite chosen for the simulation was the Eutelsat E33A so that available archived satellite data could be used. As in the previous simulation, a ground truth satellite track was generated by interpolation and used to simulate the delay measurements made by the stations. Interpolation of ephemeris data was used rather than using a detailed physical model for a number of reasons. Firstly, it was the basis for the initial system and experiment. Secondly, it is simpler and quicker to calculate, which is important because the final implementation will not have the capacity to make a lot of floating point calculations in near real-time. A disadvantage of using an interpolation approach is that it does make it difficult to implement, for example, a Kalman Filter approach to refine the satellite path prediction [17].

The simulated measurements of the transmitted signal include models of troposphere delay and equipment delay. Troposphere delay was modeled in the same way as described for the single master station simulation. As before, satellite transponder delays are not included in the simulation calculations as no information is available to characterize these. The Sagnac effect is also not included in the simulation as in practice it can easily be calculated and removed. The equipment delay was modeled using a mean delay plus white Gaussian noise and/or as a diurnal wander plus a mean delay. Subsequently, the mean delay is used as the station's measurement of its equipment delay. The standard deviation of the white noise and/or the amplitude of the diurnal wander could be varied.

In the three station simulation the approach has been to simulate the satellite motion in enough detail to be able to make an estimate of the path delay to and from the satellite including the satellite motion during the travel time of the signal to the satellite. For the n^{th} one-second interpolated satellite position, the range and delay for the uplink is calculated. The uplink troposphere delay and the uplink equipment delay are added to the uplink path delay to produce the time of arrival at the satellite. To simulate satellite motion during the uplink delay to the satellite, which is of the order of one-eighth of a second, it is necessary to further interpolate the satellite position between the nth one-second point and the $(n+1)^{th}$ one-second point. This interpolation is done using a linear interpolation between the two successive satellite positions. The step size is given by the sum of the uplink path delay plus the troposphere delay and the equipment delay. Once the intermediate satellite position is found, the range and delay for the downlink back to the master station (for a round-trip) or to another master station can be determined. Finally, the total delays for the return paths are calculated by adding the troposphere delay and the equipment delay as appropriate for the station to which the signal is travelling.

For the initial development of the simulation, it has been assumed that each master station will range the satellite and that the measurements will be communicated to the primary master station. To illustrate the notation to be used, the measured round-trip delay ΔT_{11}, for the first master station is given by:

$$\Delta T_{11} = \tau_1^{Tx} + \Delta_{1s}(n) + \tau_1^{SU} + \Delta_{s1}(n + dn) + \tau_1^{SD} + \tau_1^{Rx} + 2\tau_1^{TR}, \quad (1)$$

where τ_i^{Tx}, τ_i^{Rx} are the transmit and receive equipment delays for station i, $\Delta_{is}(n)$ is the path delay from station i to the satellite and $\Delta_{si}(n+dn)$ is the path delay from the satellite back to the station, τ_j^{SU}, τ_j^{SD} are the satellite transponder uplink and downlink delays at frequency j, and τ_i^{TR} is the delay from station i to the satellite due to the effect of the troposphere. The effect of the ionosphere is neglected as already noted. Each master station measures its round-trip delay and processes the measured round-trip delay by subtracting its estimates of the troposphere and equipment delays. This processed round-trip delay is denoted T_{ii} for the i^{th} master station and is given by, for example, for master station 1:

$$T_{11} = \Delta T_{11} - 2\bar{\tau}_1^{TR} - \bar{\tau}_1^{Tx} - \bar{\tau}_1^{Rx}, \quad (2)$$

where $\bar{\tau}_1^{TR}, \bar{\tau}_1^{Tx}, \bar{\tau}_1^{Rx}$ are these estimates represented by the mean of the modeled troposphere and equipment delays and, as in the single station simulation, the transponder delays will henceforth be neglected for the purposes of the simulation. The processed master round-trip delays are then used to generate range estimates which are used to recover the position of the satellite. To do this in real time obviously presents some difficulties as each processed delay could only be sent to the other stations after it had already been measured and processed and suggests that a predictive approach such as a Kalman filter will ultimately be required at the slave station.

D. Verification of Simulation Approach and Error Evaluation

To verify that the simulation was working correctly, it was first run across the set of satellite ephemeris data using only the mean troposphere and mean equipment delays. That is, it was assumed that the stations had perfect knowledge of the troposphere and equipment delays and there was no additional noise in the system. The only remaining errors between the "true" satellite track as calculated by the simulation and the measurements of the track would then be the satellite motion. To check this point, the difference between an estimated round-trip delay, $\hat{T}_{ii}$, made at each master station and the processed round-trip delay, T_{ii}, at that station was made. The estimated round-trip delay is given by $\hat{T}_{ii} = 2\Delta_{is}(n)$ assuming that a one second satellite ephemeris interpolation would be available at the station. Under the assumption of perfect knowledge, this quantity then includes only the error due to the satellite motion as shown in equation (3) and Figure 12.

$$\hat{T}_{11} - T_{11} = 2\Delta_{1s}(n) - \left(\Delta_{1s}(n) + \Delta_{s1}(n + dn)\right). \quad (3)$$

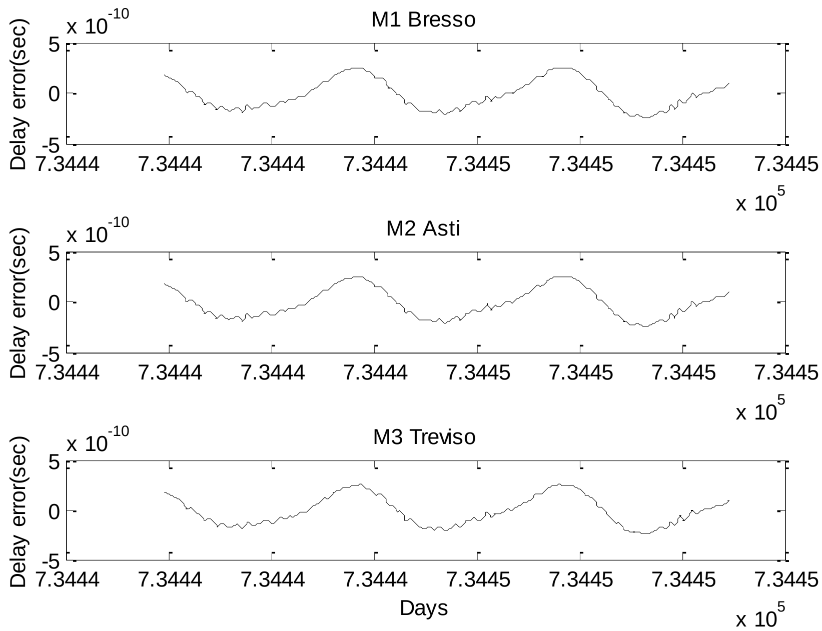

Figure 12. Delay error due to simulated satellite motion in a 3-station simulation.

In the second part of the simulation verification, the simulation is re-run with more realistic troposphere and equipment delays, i.e., adding some variation in the form of noise to these delays in the simulated measured delay data. The variation in the troposphere delay is estimated as white Gaussian noise of average magnitude of 10% of the dry component. The variation in the equipment delay is modeled as white Gaussian noise plus a diurnal wander.

Two error measures were calculated and plotted, the difference between an estimated round-trip delay, $\hat{T}_{ii}$, made at each master station (assuming that a one second satellite ephemeris interpolation would be available at the station) and the measured round-trip delay ΔT_{11} at that station:

$$\hat{T}_{11} - \Delta T_{11} = 2\Delta_{1s}(n) - (\Delta_{1s}(n) + \tau_1^{Tx} + \Delta_{s1}(n + dn) + 2\tau_1^{TR} + \tau_1^{Rx}), \qquad (4)$$

This quantity, shown in equation (4) above, includes all the extraneous delays and the error due to the satellite motion. The second error measure was the difference between the processed round-trip delay at each master station and the estimated round-trip delay at that station. This quantity, shown in equation (5), includes the error due to the satellite motion plus the error due to the imperfectly known troposphere and equipment delays.

$$\hat{T}_{11} - T_{11} = 2\Delta_{1s}(n) - \left(\Delta_{1s}(n) + \Delta_{s1}(n + dn)\right) + \tau_1^{Tx} - \bar{\tau}_1^{Tx} + 2\tau_1^{TR} - 2\bar{\tau}_1^{TR} + \tau_1^{Rx} - \bar{\tau}_1^{Rx} \qquad (5)$$

A set of typical results for the quantity in equation (5) is shown in Figure 13 representing about 2.77 days where the variation in the equipment delay was modeled as white Gaussian noise with a standard deviation of about 1.5 ns (compared with a mean delay of about 1000 ns) plus a wander with an amplitude of about 1.5 ns. Note that the quantity in equation (4) has an essentially similar appearance and size. It can be seen in Figure 13, that the resulting error on the range delay is +/- 20 ns and the effect of the white noise is quite prominent, although the periodic jitter due to the satellite motion is also visible. The step change in delay error in the plots is due to a change in the mean troposphere value from one day to the next which appears in the processed round-trip delay but not in the estimated round-trip delay.

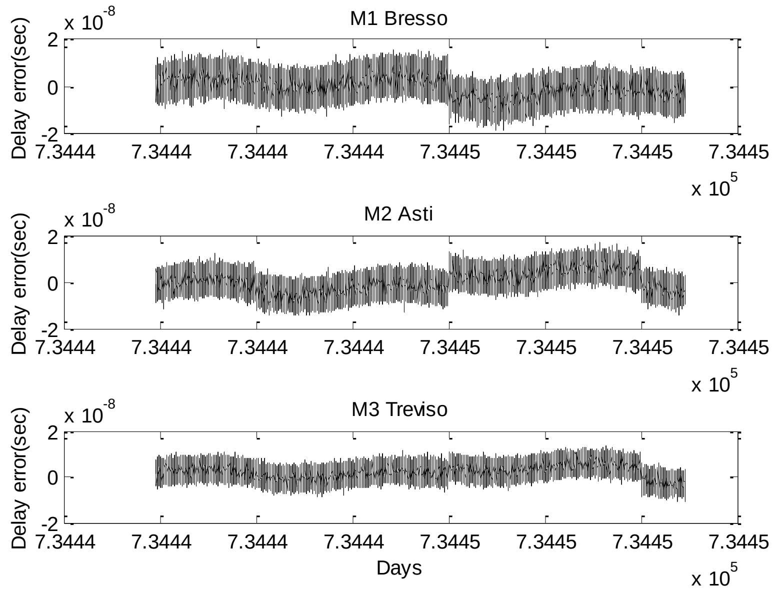

Figure 13. Three station simulation: Range delay error.

Currently, as in the single master station simulation, the three station simulation replicates the procedure of the experiment, recording the received PPS from the master at the slave by adding the measured master to slave path delay to an “ideal” clock. Then an estimate for the arrival time of the received PPS at the slave is calculated using the estimated path delays plus the station’s estimates of the troposphere delay and the equipment delay. However, in the three station simulation, the slave station generates its estimate using the recovered satellite position that has been provided by the master station. The estimated arrival time of the PPS at the slave station is subtracted from the jittered PPS which “arrive” at the slave station to generate the equivalent of the e1PPSDelay value in the experiment. In the simulation, a slave PPS is also regenerated after subtracting the estimated path delays (master to satellite and satellite to slave) and the slave station estimates of the troposphere delay and equipment delay. The jitter on the resulting period of this regenerated PPS signal can then be calculated.

Using the same parameters for the modeling of the equipment delay as were used to produce the plot in Figure 13, the jitter on the simulated e1PPSDelay is shown in Figure 14. The standard deviation of the jitter on the received PPS period after adjustment using knowledge of the path delays and estimates of the equipment delay and mean troposphere delay is 45ns and the standard deviation of the jitter on the regenerated PPS is 33ns.

The sensitivity of the satellite position tracking to noise and error on the path delay is demonstrated clearly with the three station simulation even with the relatively straightforward approach to simulation of the satellite motion which is employed. It must be noted that the results presented do not include any filtering or predictive tracking techniques and that these are under investigation and could be expected to improve the results. As an example, to generate the plot of jitter on the simulated e1PPSDelay signal shown in Figure 13 the standard deviation of the noise in the equipment delay model was an order of magnitude smaller than in the single master station simulation.

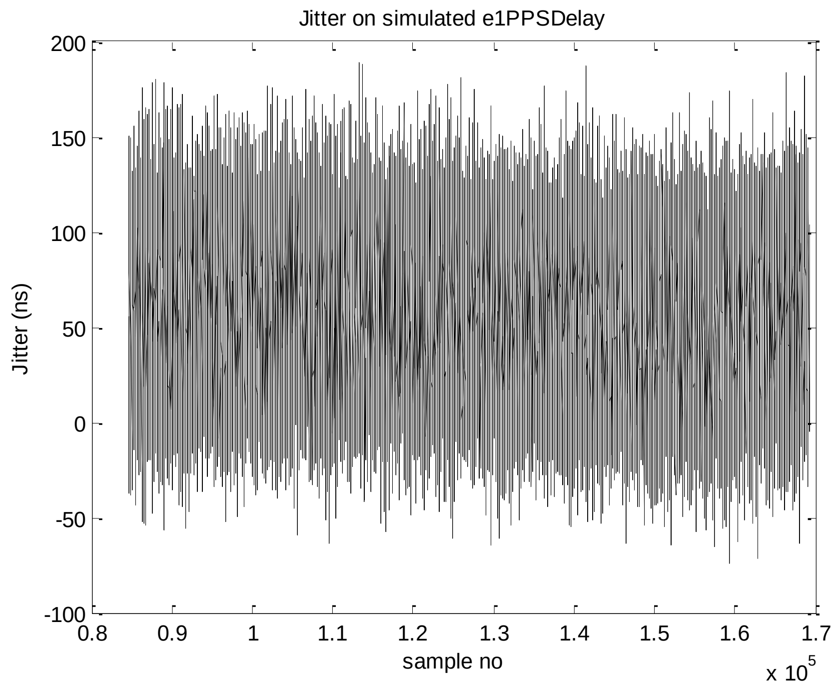

Figure 14. Three station simulation: Jitter on simulated e1PPSDelay at slave.

IV. CONCLUSION AND FURTHER DEVELOPMENT

We have described the proposal by Mixed Processing Ltd for an off-the-shelf system for timing signal transfer over geostationary satellite. We have reported on the initial testing and simulation of the proposed system, which is still under development. Our experience has shown that developing such a system is within reach of a commercial operator but that careful attention has to be paid to detail at every stage of development.

An initial experiment, reported here, was successful in demonstrating the feasibility of the service as it succeeded in distributing a PPS timing signal across 900 km of territory (the baseline distance between Bresso and Palermo is approximately 889 km) with less than 1μs of jitter. Analysis of the experiment uncovered key issues which may have affected the performance of the timing signal transfer, suggesting that the results could have been substantially better. Working with the University of Limerick, simulations were developed which were able to replicate and explain the experimental results and were instrumental in uncovering some of the problems experienced. The simulations of the three master station system show that obtaining such performance with three master stations for satellite positioning will be highly dependent on the statistics of the noise in the equipment and in the modelling and estimation of the correction factors applied in the recovery of the transmitted timing signal. Simulations of the complete system are under further development to assist with the deployment and testing of the next stage of the system which will incorporate a satellite modem designed and built by Mixed Processing Ltd to use TWSTFT over the bidirectional links between the master stations.

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