Experimental and Simulation Study for a Time Transfer Service via a Commercial Geostationary Satellite

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Abstract: Time transfer over satellite links has been explored since the satellite era began. Currently, Two Way Satellite Time and Frequency Transfer (TWSTFT) is routinely used between national timing laboratories to align national timing standards, and the Global Positioning System (GPS) provides accurate timing signals in addition to its more familiar navigation solution. This paper reports on a method for transferring time from a reference clock over commercial geostationary satellite links with a specified low level of uncertainty at the receiving stations, using only the 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 1 pps (pulse per second) timing signal with a standard deviation of 72 to 98 ns and peak-to-peak variations of 500 to 600 ns, when measured against a GPS reference. Subsequent analysis of the experiment uncovered some issues with the implementation, suggesting that these results could be substantially improved upon. Furthermore, a simulation of the system that modeled the extraneous delays produced results similar to those obtained in the experiment.

1. Introduction

Time and frequency transfer is used to provide accurate time signals, synchronized to a reference clock, to locations distributed across a territory. The requirements of the implementation vary depending upon whether the need is to transfer time or frequency. For accurate transfer of time from a remote reference clock to a local clock, the path delay of the time signal must be known as accurately as possible, whereas for frequency transfer, the goal is to minimize the variation in the path delay [1]. Time and frequency transfer methods fall into three different categories: one-way methods, two-way methods and common-view methods. In two-way time transfer, the delay is estimated based on measured round-trip delays between two stations. In two-way time transfer, the path delay in each direction can be eliminated entirely in the two-way difference if the paths between the two stations are symmetrical [2]. In common-view approaches, two or more 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 variations are common between the different paths, they will cancel out in the difference of two measurements, reducing the error in the time transfer [1].

Two-way time transfers over satellite links offer uncertainties on the order of nanoseconds, because most of the path delay cancels out [2]. Originally there were also significant disadvantages to this approach 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 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 [3].

The simplest approach to time and frequency transfer might appear to be the one-way method, where the user requires only a receiver, and a master clock signal can be transmitted to many such receiving stations. However, for this approach to be successful, a good estimate of the delay and delay variation from transmitter to receiver must be available [1]. One-way time transfer over geostationary satellite links has been explored since the satellite era began [4], [5]. However a geostationary satellite is not completely stationary but has a small, continuous variation in its position. References [4] and [5] represent early attempts to quantify the uncertainty in the received timing signal due to the resulting variation in the path delay between the sending and receiving stations. In [4], 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 [5], the approach used is three station trilateration of the satellite position while simultaneously manually synchronizing the clocks.

A one-way time transfer approach which makes use of an existing signal, in this case a line in a standard television signal, was introduced in [6]. For time transfer between a reference station and a user station, the differential delay between the satellite and the two stations needed to be known as accurately as possible, and the uncertainty due to the variation in the satellite position was estimated at 2 to 3 µs. Improvements to this approach were further described in [7], [8] where averaging was used to remove periodic components of the satellite motion and the geometry of a known reference link was used to correct for the longitudinal drift. An alternative approach of fixing the position of the satellite was also described, although this required four stations as it used the differential delays.

The broadcast of UTC (NPLI) using the INSAT geostationary satellite system to receiving stations in India is described in [9]. In this system, the satellite position was calculated based on the six orbital elements received from the satellite operator once every seven to ten days. The results for the timing data showed a distinct diurnal variation and, in the absence of the orbital corrections, an increasing error up to ±20 µs, which is reduced every time the orbital elements are updated by new information. In [10] a differential approach for reduction of diurnal residuals to within one microsecond accuracy is described. Another system that required differential measurements from four stations for input into an extended Kalman filter (EKF) to apply a dynamic model of the geostationary satellite orbit was claimed to improve the accuracy to within

±0.025 μs across the Korean peninsula [11]. In [12], frequency transfer using a geostationary satellite was described. The approach required four reference stations with synchronized frequencies in order to determine the velocity vector of the satellite motion, and to provide a correction for the Doppler shift on the frequency at the receiver stations.

Currently, the most common one-way time transfer implementation using satellites is the Global Positioning System (GPS) [13], [14] 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 large, about 65 ms, but the uncertainty in the delay, computed by the receiver using ephemeris information sent by the satellite, is only nanoseconds. However, components other than path delay uncertainty become just as important. Even though their individual absolute amounts may be quite small, the uncertainties involved in their estimates or measurements can still be significant [1].

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 because the system is managed by the defense department of a single country, the United States. These risks have been historically confirmed, for example, in the use of Selective Availability [15] where the system accuracy was intentionally degraded until the program was discontinued in May 2000. Consequently, as alternatives to GPS, there are similar projects under development, such as Galileo (EU), GLONASS (Russia), COMPASS (China) and IRNSS (India). Only one of these systems (GLONASS) is currently fully available as an alternative with the other systems projected to become operational progressively during the next decade. 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 0. 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 0.

This paper reports on the development of a system for time signal transfer from a reference clock over commercial satellite links. The system will aim to provide a specified low level of timing uncertainty of ±50 ns 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 to compensate for satellite motion. The paper is structured as follows: in Section 2, 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 a demonstration of the system. The analysis of the experiment and its results are also discussed. In Section 3, the development of a simulation of the experimental system and its results are presented. Finally, in Section 4 we present conclusions and a brief outline of the future development plans.

2. **The Mixed Processing Time Transfer System**

The time transfer system 0 now being developed by Mixed Processing Ltd. can provide a complete off-the-shelf system for transferring accurate time via satellite. The full system, shown schematically in Fig. 1, consists of three master stations used to fix the satellite position using triangulation, with the possibility of up to three more master stations for redundancy and failover. 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 [19] or Eutelsat [20]. One master station will have a high performance clock, such as a Cesium atomic clock. The two sub-master stations will have stable atomic clocks of lower performance, such as rubidium clocks. The master stations will align their clocks using TWSTFT and exchange satellite ranging data to allow the master station to send real-time satellite ephemeris data to the slave stations. Each of the master stations, whether master or sub-master, will have a bi-directional link to the satellite. Finally, slave or receive-only stations will require only a unidirectional (receive-only) link with the satellite. Mixed Processing Ltd. has developed the satellite modem for the system using an field-programmable gate array (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 may be configured as receive-only for the slave stations. The satellite links are in the Ku-Band.

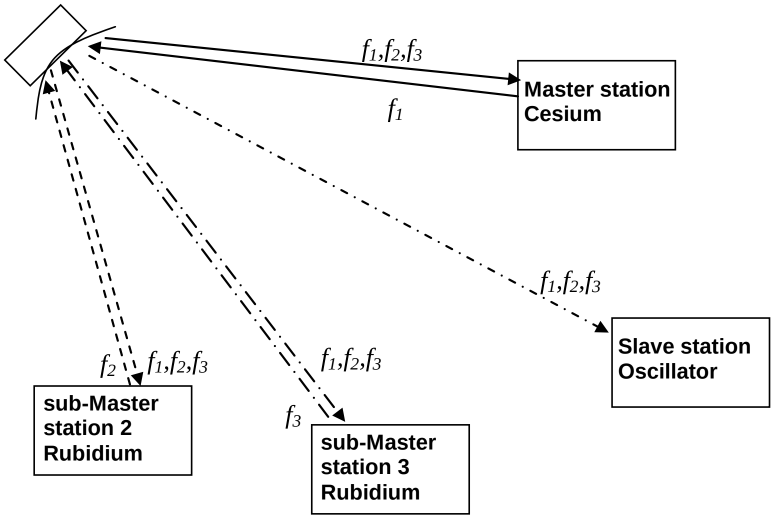

Figure 1. Proposed system for time transfer over satellite.

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 with the troposphere and the ionosphere.
- 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 variations in cables and particularly in outdoor equipment.

- Generic statistical errors regarding the evaluation of distances and ground station position.

2.1 Proof of Concept Experiment

An experiment was conducted as a proof of concept of the system with a single master station broadcasting a 1 pps timing signal to three slave stations. The experiment was conducted in Italy with the master station located at Bresso, Lombardia and the three slave stations located at Asti, Piemonte, Treviso, Veneto and Palermo, Sicilia. Satellite ephemeris data for Eurobird 3 (now known as Eutelsat E33A), a satellite used for the transmission of television signals, was obtained from the satellite operator [20]. The master station measured the round-trip time to the satellite and broadcast the satellite coordinates, transmission delay information, and a correction factor to the slave stations so that they could adjust their expected arrival time of the 1 pps signal. Commercially available satellite modems (Comtech CDM570 L band) were used at the stations and proprietary multi-source time and frequency equipment was used to provide a GPS 1 pps reference for the experiment and to implement the experimental algorithms. The GPS receiver in the equipment was a single frequency C/A code receiver and the uncertainty of the GPS 1 pps was ±50 ns. The 1 pps was encoded as the LSB in channel 2 (Frame 0, Time Slot 1) of the multiframe E1 signal. As this was an initial experiment with such a system, the GPS 1 pps signal available at each station was used as a reference to measure the 1 pps timing signals transmitted from the master station to the slaves. The measurements were processed centrally at the master station equipment and stored in a spreadsheet for subsequent analysis.

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

- The expected path delay between the station position and the satellite position was calculated, using the speed of light c, where the station position was that provided by the GPS receiver in the equipment and the satellite position was obtained from the operator provided ephemeris that had been interpolated to one second intervals.
- Measure e1PPSDelay: the time between the GPS PPS reference at the master station and the time the same 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.

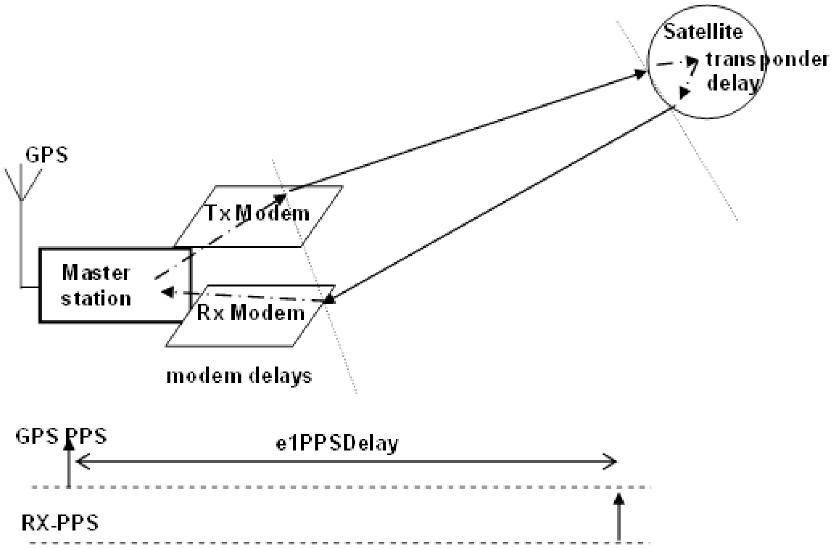

Figure 2. Diagram of procedure and measurements at master station.

From Fig. 2 and the sequence of steps 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 such as the uplink and downlink satellite transponder delays, the delays through the ground equipment and cables, and delays due to atmospheric effects. The components of the extraneous delay such as the equipment and cable delay were not determined separately. In future development of the system, it is expected that these components will be measured allowing for more accurate adjustment of the delay between stations.

The procedure carried out by the equipment in the slave stations (illustrated in Fig. 3), is as follows:

- Receive the satellite coordinates, transmission delay and the correction factor from the master station together with the 1 pps signal.
- Calculate the expected one-way delay between the slave station and the satellite using the known position of the slave station and the satellite coordinates.
- 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 1 pps signal.
- e1PPSDelay is the time difference between the 1 pps signal received over the satellite link from the master and the GPS 1 pps reference available independently at the slave station which has been delayed by the e1PPSOffset in a delay line as shown in Fig. 4.

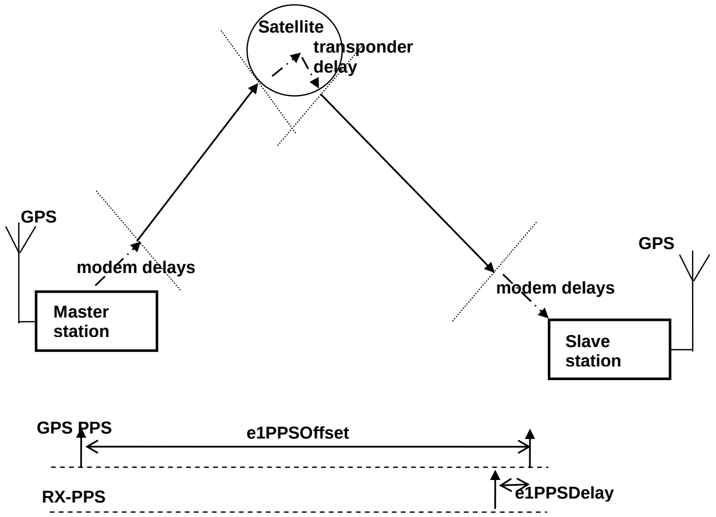

Figure 3. Diagram of procedure and measurements at slave station.

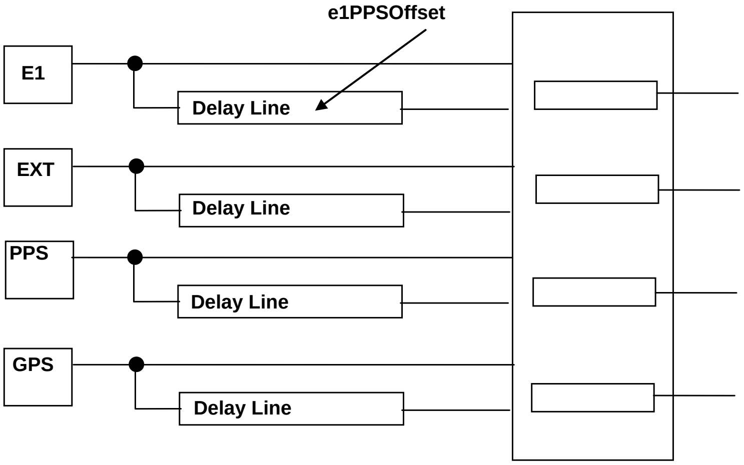

Figure 4. Schematic of timing signal regeneration using delay line.

2.2 Experimental Results

The initial experiment demonstrated that, even with the simple protocol presented above, it was possible to transmit a 1 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 1 µs. 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 and a correction factor that accounts for all extraneous delays estimated from the measured round-trip delay. At this initial stage of the project, 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, for example, 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 occasional malfunctioning of the satellite modem used (not one developed by Mixed Processing Ltd) three times at the master station and once at the Palermo slave station where an interruption to the 1 pps transmission appears to have caused a phenomenon similar to a cycle slip and is the cause of the phase steps in the e1PPSDelay data seen in Fig. 5. A second issue is that the data recovered from the experiment are not continuous and have interruptions of varying duration. A third issue was that the ground station position coordinates obtained from the GPS equipment varied over time, affecting the calculations. A fourth issue was that an incorrect earth radius value was used which affected the calculation of the station to satellite path delays.

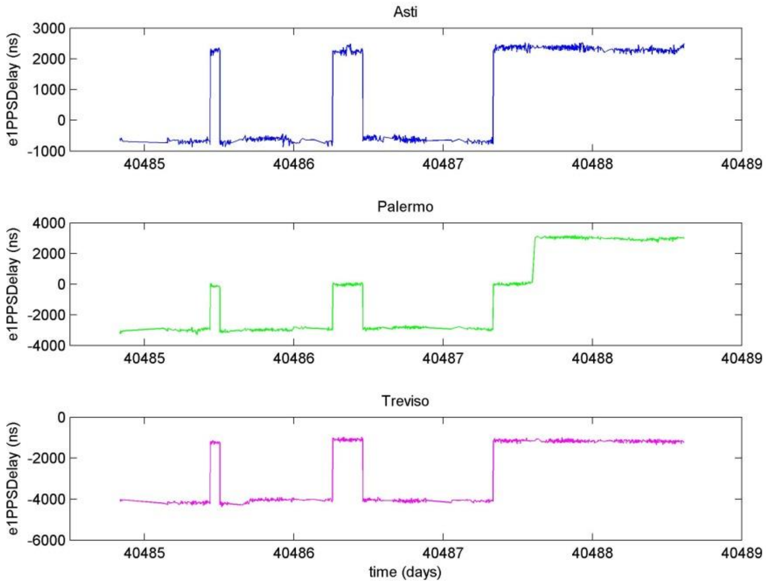

Figure 5. The measured time differences (e1PPSDelay) at the three slave stations.

The e1PPSDelay was measured relative to the GPS 1 pps signal. In the evaluation of the e1PPSDelay, the phase steps in the data (Fig. 5) made it difficult to analyze the data. Thus, the phase steps, which were caused by resetting the communications link, were removed from the e1PPSDelay without shifting the data with respect to the x-axis (time of day) and the data were replotted. The results (called ‘adjusted e1PPSDelay’) for the three different slave stations are shown in Fig. 6. Note that in all figures showing data from the experiments, the horizontal axis shows time in days represented as sequential date numbers in Excel format.

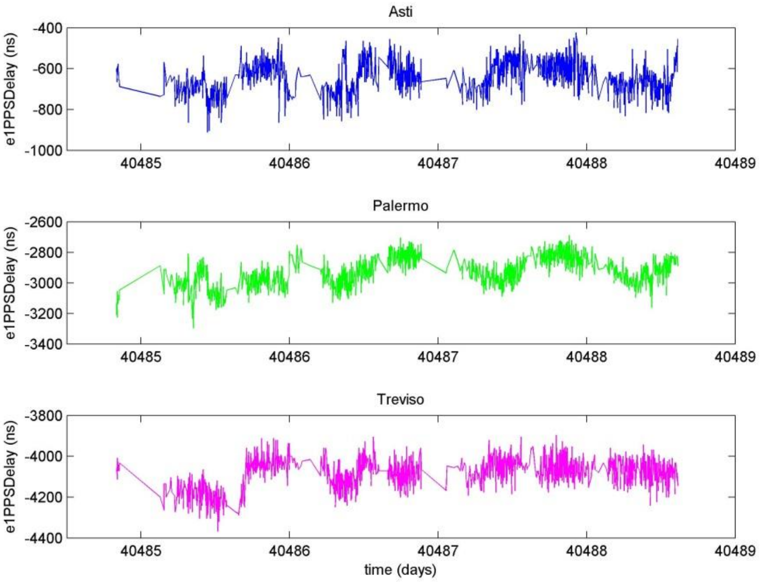

Figure 6. Adjusted e1PPSDelay at the three slave stations.

The adjusted e1PPSDelay values appear to show some quasi-periodic phase noise that is still somewhat obscured by the interruptions in the data collection, but is clearly present. It is seen most strongly in the Palermo data and least in the Treviso data. Histograms of the e1PPSDelay distributions are shown in Fig. 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. Normal probability plots of the e1PPSDelay data (not shown) suggest that the major component of the e1PPSDelay is normally distributed phase noise due to a variety of causes including equipment noise, the path delay errors caused by using the time-varying GPS station location coordinates, 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.

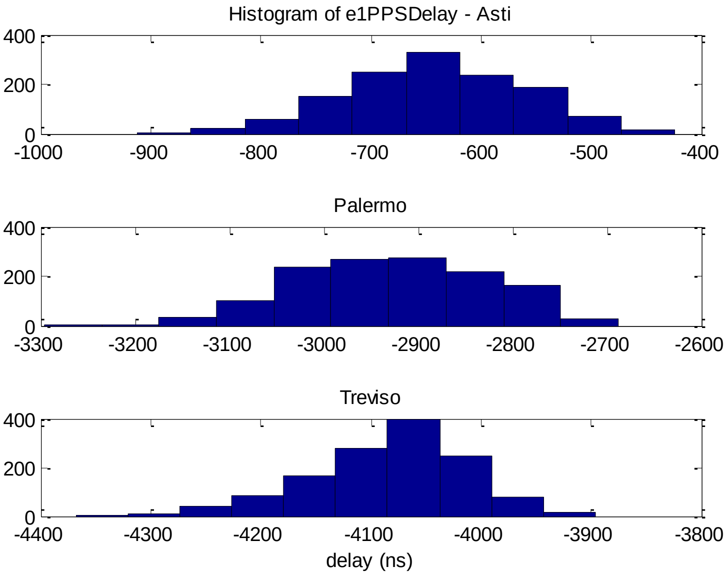

Figure 7. Histograms of adjusted e1PPSDelay.

Descriptive statistics were also calculated for the adjusted e1PPSDelay. The results are summarized in Table 1, where the range characterizes the peak-to-peak variation of the time differences. The table also shows the mean, standard deviation, and median of the time differences. The range is due predominantly to the satellite motion and is largest at Palermo, the station which is the furthest distance from the master station.

	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

Table 1. Descriptive statistics for e1PPSDelay at slave stations.

2.3 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 coordinates 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 coordinates would be a uncertainty in the satellite path delay calculation and would add additional phase noise to the received timing signal. Errors in antenna coordinates are a common source of uncertainty in satellite time transfer measurements [8], [14] and the experience of the experiment highlights the importance of determining these as precisely as possible using a geodetic GPS receiver.

Even so, the analysis of the effect of using the varying ground station coordinates showed that it was not especially large. A comparison was made between the satellite ranges and range delays calculated using the time-varying position 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 Fig. 8, where it can be seen that the maximum absolute range error is approximately ± 25 m and the maximum absolute delay error was less than 100 ns and the average delay was less than 10 ns.

A potentially more serious issue was that an error in the mean earth radius value was 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 [20]. 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 Fig. 9.

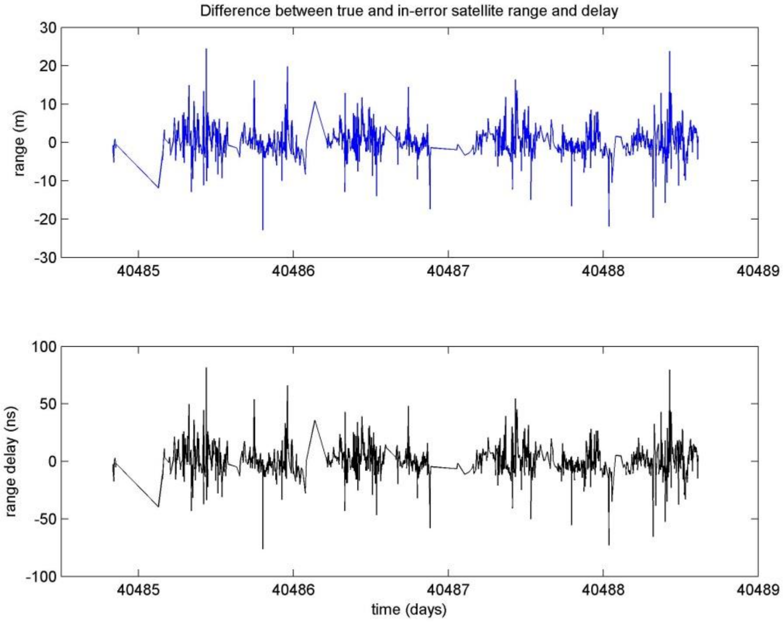

Figure 8. Range and delay variation due to time-varying satellite position.

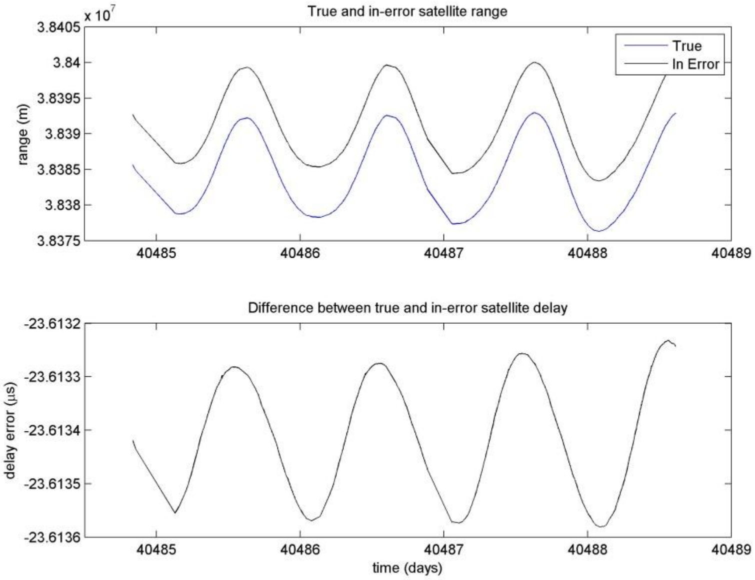

Figure 9. Difference in range and path delay due to radius error.

3. **Simulation**

A simulation of the experiment using one master station and only one slave station was conducted. The aim of the simulation was to improve understanding of the limitations of the experiment by reproducing the transmission of the 1 pps signal from master to slave station. This was done by generating a ‘ground truth’ record of the satellite position and thus generating a set of measurements of the overall delay for the transmission of the 1 pps signal from master to slave. The second step of the simulation was to reproduce the processing carried out at the master and slave stations in order to simulate the measurement of the difference (e1PPSDelay) between the GPS 1 pps and the received 1 pps sent over satellite.

In the simulation, the master station was placed at Bresso, as in the experiment, and the single slave station at Palermo. The satellite ephemeris data was downloaded as earth-centered earth-fixed (ECEF) Cartesian coordinates for the period covering the dates of the experiment from the satellite operator archive [20]. As it was archived satellite data, potentially corrected after observation of the satellite by the operator, it may be more accurate than the projected satellite ephemeris originally available at the time of the experiment, which makes it suitable for generating the ground truth track of the satellite for the simulation. However, the archived satellite ephemeris data is still available only at 30 minute intervals and had to be interpolated to one second intervals using splines as was done in the experiment. Using the station coordinates and the interpolated satellite coordinates, ground truth path delay values were calculated for the master and slave stations.

It was not possible to use the recorded correction factors from the experiment to simulate the measurements, because the correction factors are not available at one second intervals. Hence, an alternative approach was required to estimate the extraneous delays, providing us with the opportunity to use the simulation to determine how much these contributed to the observed results of the experiment. Two alternative approaches were used. In the first approach, the extraneous delays were modeled based on the statistics of the correction factor data from the experiment. In the second approach, the extraneous delays were modeled as a sum of the troposphere delay estimated from weather data and overall equipment delay modeled as a sum of white noise and diurnal wander. 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 [21].

The simulation records the reception of the 1 pps signal from the master at the slave by adding the generated measured overall master to slave transmission delay to an 'ideal' clock (i.e. a sequence of integers simulating an ideal one second period). This matches the procedure in the experiment where the GPS 1 pps was used as a reference and was assumed to not contribute any noise to the measurement. Then, following the procedure in the experiment, an estimate for the arrival time of the 1 pps at the slave is calculated (called ePPSOffset in the experiment) using the estimated path delays plus the station's estimates of the correction factor. Again, as it was not possible to use the correction factor data from the experiments in the simulation, an alternative to the correction factor needed to be created for the simulation. The correction factor used in the simulation differed depending upon which approach was used to model the extraneous delays. The ePPSOffset is then subtracted from the 1 pps signal that 'arrives' at the slave station to generate the equivalent of the e1PPSDelay value in the experiment.

3.1 Modeling of Extraneous Delays

Two different approaches to modeling the extraneous delays were used in the simulation. In the first approach, the delays were modeled on the correction factor data from the actual measurements, by using a normal distribution based on the statistics of the collected data. In analysis of the measurement 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 the satellite modems, after each reset of the modem, a different mean delay was established. Thus, it was not necessary to model bimodal or trimodal distributions because these likely only arose due to the modem resets. 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). To prevent an increase in variance caused by the summation of n independent random variables, the standard deviation was then adjusted by multiplying by $1/\sqrt{n}$. Modeling the delays from the measurement data in this way means that the resulting values effectively include all extraneous delays, including atmospheric effects and the Sagnac effect, and that these delays do not have to be separately modeled.

When modeling equipment delay using data sets from the experimentally derived statistics, the results of the simulation were not as good as the actual measurements. In other words, the received 1 pps at the slave station was noisier in the simulation than it was during the actual measurement. The likely cause of this effect is that the noise produced by modeling the equipment delay based upon the statistics of the correction factor is too large. The standard deviation of the 1 pps signal received in the simulation at the slave station is 0.4 µs and that of the resulting simulated e1PPSDelay at the slave station is 0.3 µs. The peak-to-peak range of the simulated e1PPSDelay is ±1.5 µs as shown in Fig. 10. The apparent poor performance of the system in simulation can be explained mainly by the difficulty of modeling the delays based on the correction factor statistics. The standard deviation used in the model based on the correction factor statistics is likely to be an overly pessimistic estimate, because of the bimodal and trimodal distributions and the effect of the problems experienced with the modem that occurred during the actual measurements.

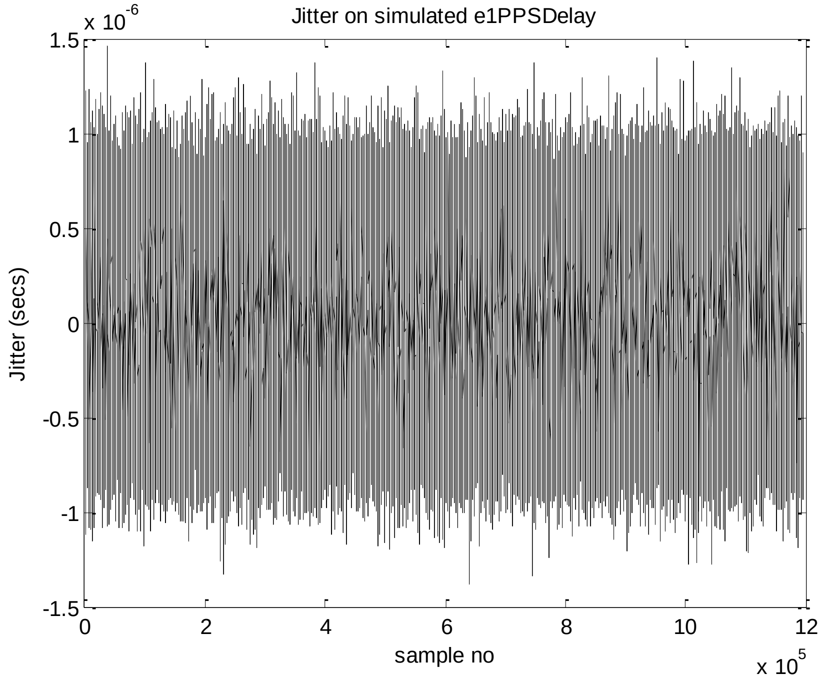

Figure 10. Simulation with equipment delay modeled using experimental statistics.

The second approach of the simulation modeled the extraneous delays as a sum of troposphere delay and equipment delay. To model the troposphere delay, weather data were downloaded for the two locations from the historical weather data archive for Italy provided by ilMeteo.it [22] and used to estimate the 90 % of the troposphere delay due to the dry component using the dry model of Saastamoinen [23] for which barometric pressure is required. Where a barometric pressure reading for a day was missing (which occurred in one to three 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 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 to refraction and dispersion by the ionosphere is generally negligible at the frequencies used (uplink at 11.7 GHz, downlink at 14.4 GHz) [23] and is not modeled.

The equipment delay in this approach was modeled as a deterministic variation plus a random walk: a sum of a sinusoidal variation, modeling satellite motion and white noise. The values for the standard deviation of the Gaussian noise component and the random walk amplitude were then chosen by trial and error so that the simulation could reproduce the noise on the e1PPSDelay signal that was observed in the measurements. The final standard deviation values used were 45 to 55 ns and the amplitude of the diurnal variations was near 30 ns. For example, as shown in Fig. 11, these values generated a simulated e1PPSDelay signal with a peak-to-peak variation of about 500 to 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 received 1 pps signal after adjustment using knowledge of the path delays and estimates of the equipment delay and mean troposphere delay is 0.1 µs, and the peak-to-peak range of the signal is less than 1.0 µs.

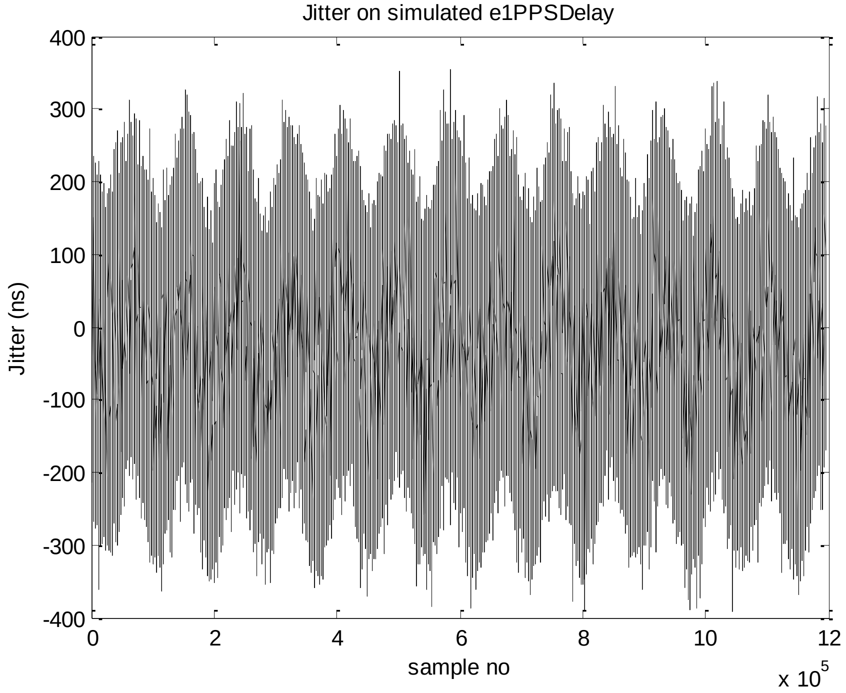

Figure 11. Simulation with equipment delay modeled using wander plus random noise.

4.Conclusion and Further Development

We have described a proposal by Mixed Processing Ltd. for an off-the-shelf system for transferring time signals via geostationary satellite. We have reported on the initial testing and simulation of the proposed system, which is under further development. Our experience has shown that developing such a system is within reach of a commercial operator but that careful attention must 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 1 pps timing signal across 900 km of territory (the baseline between Bresso and Palermo is approximately 889 km) with a peak-to-peak range of less than 1 µs. The 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. 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.

5. **References**

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