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Improving time transfer performance for low earth orbit satellites

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***Abstract*—Low earth orbit (LEO) provides closer satellites with lower transmission losses and delays while struggling with a smaller field of view (FoV) and larger drag. The related works have been developed in the past utilising LEO satellites for positioning by relaying the signal from GNSS to the ground station. The following work addresses the timing aspect along with satellite positioning through ranging and limiting the position and velocity errors to provide control over the timing bias and drift errors.**

Using real-time two-line element (TLE) ephemeris data from a LEO satellite, the solution incorporates a linear Kalman filter to obtain predictions by updating the algorithm with a multilateration dataset from four known ground stations. The simulation dataset for satellite orbit propagation is used as ground truth to compare with the predictions and obtain position and velocity errors, leading to timing bias and drift. An error reduction of nearly 70 % was observed for position estimation, while an error reduction of nearly 30 % was found for the timing bias. The obtained value is within 0.5 ns of the "LEO satellite positioning through the GNSS" technique. The proposed solution contributes to the evolving landscape of LEO navigation, improving positioning and timing measurement accuracy for satellite-based services.

***Index Terms*—Multilateration; Kalman filter; low earth orbit (LEO); ephemeris; positioning; timing error.**

I. INTRODUCTION

Satellite navigation from LEO is an expanding field due to lower deployment costs, reduced radiation effects, and lower signal delay. The instruments deployed in the current GNSS technology are state-of-the-art, providing precise timing and position information. The technology leads to lower signal attenuation and improved S/N ratio, requiring less power for transmission. Yet, challenges for navigation in the LEO environment, including atmospheric drag, limited field of view, shorter stationary periods, and the earth's gravitational perturbations, pose obstacles to obtaining precise measurements. These propagation effects, perturbations, and disturbances disrupt the accuracy achievable from the instrumentation and measurement devices employed. Addressing these issues becomes essential for engaging LEO to host navigation satellites.

The hardware aspect of the timing and navigation instruments on-board and on-ground provide highly precise output. However, the underlying issue remains within the signal transmission. Due to various external influences, the signal is delayed, distorted or attenuated. To correct these issues within the communication link of the satellite and ground station, the software aspect needs to bring adequate correcting factors into the solution programme. This will enable the extraction of the optimal performance from the instrumentation devices of the satellite and the ones on-ground.

The measurements are commonly extracted from two-line element (TLE) files. It focuses on identifying the measurement errors in timing signals and developing a precise satellite positioning method to improve the time transfer performance by controlling the errors.

The satellite's position is determined using periodic TLE data corrected using a linear prediction technique, while a high precision orbit propagator (HPOP) software is used to generate ground truth for the orbit. The updated predictions yield the orbit and the errors encountered in the recorded measurements.

The proposed solution uses data from multilateration to update the obtained periodic TLE data using a linear Kalman filter technique and compares it with the ground truth to evaluate the performance by position, velocity, and timing errors. The obtained error results are compared to the performance of the existing technology. The paper also discusses the effect of elevation change on the timing error values pertaining to the elevation angle from the horizon.

Section II discusses the existing alternate methods, their effectiveness and limitations. Section III describes the project's methodology of the proposed solution. The results are discussed in section IV, followed by the work's conclusions and future potential works in section V.

II. RELATED WORKS

Since the 1950s, technological strides to achieve the accuracy of sub-nanosecond levels have drastically improved the performance of satellite timing and navigation and widened their possible applications [1]. [1], [2] discuss the hardware

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technologies deployed in the past for accurate time dissemination for precise timing and position measurements. Crystal oscillators provide an accuracy of 10^{-6} to 10^{-4}. Atomic clock accuracy is in the 10^{-10} range, such as for a Rubidium clock. Caesium clocks achieve the accuracy of 10^{-12} with a skew of about 1 μs per day. Hydrogen Maser (H-Maser) clocks can provide an accuracy of 10^{-15} seconds per day. These alternatives for on-board instrumentation are likeable for applications in satellites with navigation payloads [1]. Although highly efficient in recording and disseminating the time, these hardware devices are susceptible to external environmental influences during a mission.

The Rubidium atomic clock on-board BDS-3 experiences a2-drift variations in the form of random run frequency modulation and random walk frequency modulation [3]. The long-term fluctuations in broadcast clock parameters and increased Hadamard deviation are caused by a2-drift variations, resulting in GPS Rbs maintaining a magnitude of 10^{-14} and BeiDou-3 Rbs deteriorating to a magnitude of 10^{-13} when the averaging time is 10^6 s.

Satellite ephemeris error (including position, velocity and timing data) is the inaccuracy between the calculated and actual satellite positions. Ionospheric delays occur due to the free electrons concentration in the ionosphere due to wind and solar influence. Local temperature, pressure, relative humidity, and elevation angle of the satellite dictate the tropospheric delay. Multipath effects lead to signal dispersion due to geometric obstacles that disturb the signal's path to the receiver end. The receiver itself suffers from signal reflections [2]. Errors may also originate from the hardware instrumentation on-board or at the ground station. They may be affected by the operating environment without a consistent deviation. Hence, a software model needs to be generated to account for these measurement errors in the instruments.

To understand the signal transmission link, [4] describes an approach for two-way satellite and frequency transfer (TWSTFT) with an asymmetric delay compensation model applied and discussed over BeiDou navigation satellite system-3 (BDS-3) radio determination satellite service (RDSS). The approach identifies the asymmetric sources in the instrumentation and measurement devices and the signal transmission. The standard time deviation (STD) of 1.7 to 2.6 ns is achieved. Although the hardware delays are treated as constants, and the measurements are calibrated beforehand, the space environment, temperatures, and diurnal variations create errors in the device measurement outputs.

TLE data is crucial in procuring satellite position data to provide orbital information. The measurements made from the SpaceTrack website for the selected OneWeb Gen-1 satellites offer a resolution of 1 microsecond in UTC data [5]. A combination of multiple TLEs and modelling techniques like batch least-squares differential correction and high-precision numerical propagators (TLE-OD/OP) improve the accuracy and reliability of the TLE data [6]. TLE is inherent to significant flaws in the magnitude of kilometres, making them erroneous for precise localisation. Securing greater accuracy and denser distribution of the orbital measurement data is a long-term process [6].

Timing measurement and calibration systems on LEO communication satellites can utilise signals of opportunity to generate precise timing. These signals can also be used to estimate the satellite's position by TDOA calculations. With such a calibration system, LEO communication satellites can provide users with precise and robust timing solutions. [7], [8]. [9] discusses the use of Doppler measurements of Iridium satellites to achieve high-precision differential positioning and the relation between the mean-variance of the baseline and the equivalent Doppler residual in the Iridium's Doppler differential positioning system (DDPS). The positioning error recorded from the zero baseline DDPS was 1.9 m, while the single station value without difference was 235 m in 3D resultant form. Thus, the paper presents a valid alternative for high-accuracy positioning and timing and studies the impact of the direction and length of the baselines on the presented Doppler residual.

A state-of-the-art method is to relay the LEO satellites to the MEO GNSS satellites. The GNSS then communicates with the ground station. This approach provides positioning and timing reference with respect to the GNSS [10]. Based on a continuous 2-week data arc processing, a 0.9 ns precision of the receiver time alignment relative to the GPS-based timescale was obtained [10]. [11] describes developing a LEO/GNSS integrated positioning model exploiting the precise point positioning - real-time kinematics (PPP-RTK) technique, simulated for over 100s of LEO satellites. This work provides rapid positioning with centimetre-level accuracy for a large coverage area. With a sampling time of 5 seconds and the ionospheric delay in a random noise level range of 2.2 cm for 400-km spaced networks, the positioning accuracy for the horizontal plane is within 10 cm. The accuracy is improved by incorporating more LEO satellites in the 400 space network. [12] uses a combination of GPS and Galileo as a dual-constellation cross-check algorithm to detect a constellation-wide error affecting several satellites using the Galileo-GPS time offset (GGTO). From the experiments performed in [12], the errors due to GPS were recorded in the range of 0 to 100 μs. [13] discusses the development of a laser time synchronisation system based on satellite laser ranging (SLR) for precise geodetic measurement to control the firing time of the pulse laser so that each pulse reaches a target satellite exactly on a specified epoch within 100 ns. The achieved timing stability is of the order of 10 ns, while the jitter is reduced from 10 ns to 40 μs. The geometric dilution of precision (GDOP) recorded from the GDOP-based node placement experiment conducted in [14] for about 250 different position measurements ranges from 2 to 12 mm. The paper discusses timing measurements and satellite links for estimating the distance between a reference position and an anchor in 2-D and 3-D case scenarios. [15] discusses an ultra wide-band (UWB) real-time locating system (RTLS) that uses a one-way communication link for timing synchronisation at a reduced cost and complexity. With the implemented solution with the TDOA algorithm and custom hardware, a localisation

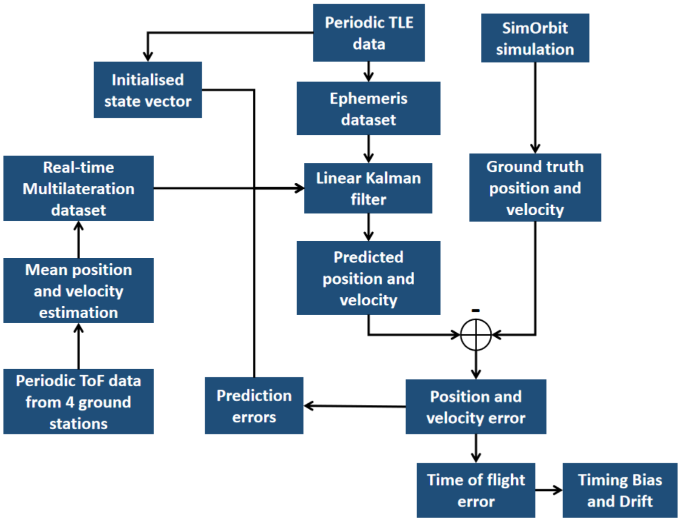

Fig. 1. Solution methodology overview

accuracy of 10 cm was achieved.

Another methodology is to use multilateration, with multiple ground stations, to locate and communicate with the satellite. The scope for multilateration in the current research adheres to obtaining precise fix for the location to improve the achievable measurement accuracy. Therefore, Bancroft's algorithm for multilateration is utilised [16]. It is an alternative to the least squares algorithm to obtain a solution from the time difference of arrival (TDOA) equations [17]. However, the method has shortcomings when it can produce no unique solution for the target object lying in the unfavourable regions. If there is more than one possible solution to the multilateration, other means are required to resolve the ambiguity [17].

So, multilateration is an attractive solution, but the method cannot provide unique solutions at every point. So, a post-processing software algorithm must be deployed to predict an optimal estimate for the position using the collected data and fit for the error variation. Such a solution is proposed in the current work.

III. PROPOSED SOLUTION

A linear clock model is assumed for the research. The resulting timing bias and timing drift are majorly accounted for by the inaccuracies of the positioning data in a cartesian frame - position errors vary the unexpected delay in the signal, leading to bias; the satellite's velocity is compared at every instant to determine the error rate. This can be either positive, leading to instability and higher errors, or negative, leading to lower errors.

The model's final outputs will be position and velocity prediction, timing bias, and drift values.

For the paper, OneWeb Gen.1 satellites were selected due to their presence as a LEO satellite constellation with a communication payload for positioning. Currently operating 618 functional satellites [18] constellation in LEO, OneWeb works as a nongeostationary satellite orbit (NGSO) fixed satellite service (FSS) [19], [20].

A set of ephemeris data collected from periodic TLE data sources is passed through the Kalman filter to update the position and velocity predictions for the real-time case. This initial data set inputs the HPOP propagator in the simulation model. The data collected in real-time from multilateration using all 4 ground stations is used to update the predictions at each step. This provides the time of flight (TOF) data from the ground stations to calculate the position with respect to the ground stations and in the ECEF frame.

The initial reading is collected from periodic TLE data from the SpaceTrack source and put to form the initial state vector for the Kalman filter algorithm. The TWSTFT method is utilised to calculate the time of flight data from all 4 ground stations. This means the new position calculates the distance from respective ground stations and their TOF after predicting the position and velocity data. This value is doubled for the two-way transfer method; thus, the one-way error must be halved from the obtained value.

After attaining the position and velocity predictions, these values are compared with the simulated ephemeris data (ground truth) to obtain the position and velocity errors. These errors, in turn, provide the time of flight error compared to the case without the predicted values. This data is then used to obtain the timing bias and drift values at every timestep and as the mean value.

To analyse the effect of elevation angle on the position and timing measurement errors, the TLE data of the satellite is collected at different times in its orbit. The process was performed multiple times, recording the elevation angle and the respective measurement performance from the on-board timing instruments.

A timing error comparison was drawn from the obtained timing errors, comparing the performance of the proposed solution to the state-of-the-art methodology already in place. The effects of atmospheric delays, delays due to earth tides, and instrumental delays were assumed to be symmetric and are not presented in the budget table. A brief discussion of the implemented solution segments is presented below.

A. Simulation Model: SimOrbit

This section describes the propagation model developed for orbit simulations. The propagation model was simulated on SimOrbit to collect ground truth ephemeris data propagated through the simulation time of 1 solar day. These data are then exported to Matlab for Kalman filter implementation. The position of the 4 known ground stations is tabulated in table I. The ground stations are directly linked with the satellites in orbit within the UK mainland. This way, the satellite ephemeris data can be directly collected from these stations without connecting a new ground station and can easily be sourced within the UK.

SimOrbit is a sophisticated software developed by Spirent Communications PLC with SpacePNT for real-time modelling and simulation of satellite orbits [21]. Simulations of a satellite

TABLE I
POSITION OF THE 4 KNOWN GROUND STATIONS IN THE UK. SOURCE: SATELLITE APPLICATIONS CATAPULT [7]

Ground station number	Ground station name	Latitude (degrees)	Longitude (degrees)	Altitude (meters from MSL)
L1	Westcott (1)	51.8433	-0.9715	81.59
L2	Westcott (2)	51.8435	-0.9716	82.70
L3	Southampton	50.9377	-1.4698	29.20
L4	Goonhilly	50.0484	-5.1784	111.00

were run in low earth orbit for a given duration to collect the ephemeris data at each timestep. This data is used as the ground truth to compare the data of the predicted position and velocity of the satellite.

The selected orbit is the sun-synchronous orbit for the satellite constellation at an altitude of 1200 km. The position for satellite and ground stations is expressed in the earth-centred earth fixed (ECEF) frame.

The satellite TLE data from the SpaceTrack application and the known ground station location from I are used for initialisation. The satellite is simulated in 2 different cases. The first is a single isolated satellite in orbit. The software overburdens and crashes with 400 satellites. So, based on the software's performance, 10 satellites were simulated. Similar to the Iridium constellation [2], the minimum elevation angle for the line of sight is 10 degrees.

After initialising, the software prepares a specific simulation file to define the parameters. This includes the timesteps taken as 0.01 seconds and the leap seconds count, which, as of August 2023, is 27 seconds [22].

As the satellite travels in orbit at low elevation angles, it is captured by one of the ground stations. After a short duration, all the ground stations are in the satellite's FoV. The maximum duration of access of 1195.12 seconds ($\sim$ 20 minutes) in the current simulation case provides an ample set of simulation position and velocity data. From the simulation performed, the 20-minute window during which the satellite is within the FoV of the ground station is clipped, and the ephemeris data for this duration is exported.

B. Multilateration algorithm

By leveraging the satellite's distances from the ground stations, a set of equations is constructed within the pertinent reference frame (ECEF) to obtain the object's position. The algorithm is based on the linear algebraic method and has low computational complexity [23].

To simplify the multilateration model, the atomic timing clocks on the 4 ground stations are assumed to be synchronised. This indicates that the time of flight data simulation does not require additional corrections or post-processing due to the asynchronised clocks.

C. Selection of prediction algorithm technique

In the research preceding the paper, an initial study was conducted on different linear and nonlinear solvers. As for the current model, the initial state vector is the only real-time data given as an input; the linear solvers become more adept at adequately modelling the problem. With respect to this, linear solvers such as linear regression and the least squares method were employed to obtain predictions for the position and velocity data of the satellite.

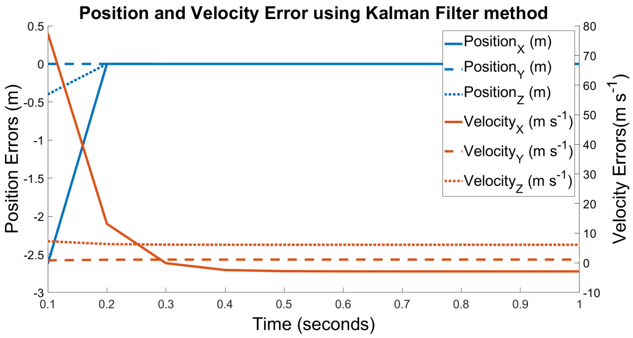

Fig. 2. Position and velocity prediction employing KF algorithm compared to the HPOP simulation from SimOrbit software for the same time frame.

However, these linear models do not consider the constantly varying prediction and measurement noise, rendering the problem in the nonlinear domain. Hence, the Kalman filter was selected for the discussed problem. The KF algorithm determines a system's state using observed data. It is a recursive filter utilised for estimating the internal state of a linear dynamic system from a series of noisy measurements [24]. This contains 2 primary segments: Prediction and Update. The Prediction segment entails calculating the state vector, process noise, and error covariance, while in the Update segment, calculation of Kalman gain, measuring noise, and updating the state vector and error covariance.

A linear Kalman filter is utilised in the current work to evaluate the method's performance. The filter algorithm was prepared in the Matlab model from the math described in [25]. The initial state vector for the filter was extracted from the TLE data from SpaceTrack and converted to a cartesian frame state vector. The initial parameters and error values were assumed to be zero and of the compatible size for 6 states (3 positions and velocities).

IV. RESULTS AND DISCUSSIONS

A. Positioning by Multilateration

The position estimates from the multilateration are the precise real-time position of the satellite based on the TOF for the satellite to send the communication data packet to the ground stations' receivers. Through multilateration, the distance measured between the predicted position of the satellite and the one generated from the ephemeris data is estimated to be 0.3 meters.

B. Measurement results from Linear Kalman filter technique

Figure 2 shows a plot highlighting the position and velocity errors in the 3 separate axes. The trend developed by this plot is that the filter rapidly converges for the position and velocity

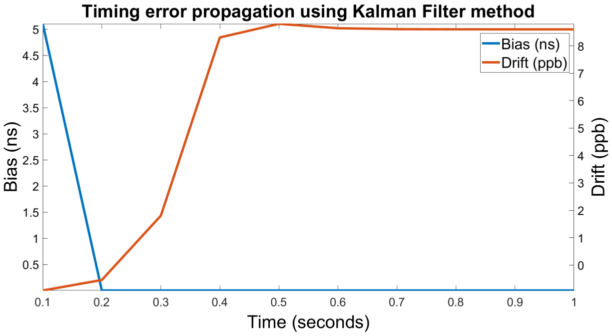

Fig. 3. Plot for timing errors derived from the position errors obtained by comparing the position and velocity prediction to the ground truth from the HPOP simulation on SimOrbit software for the same time frame.

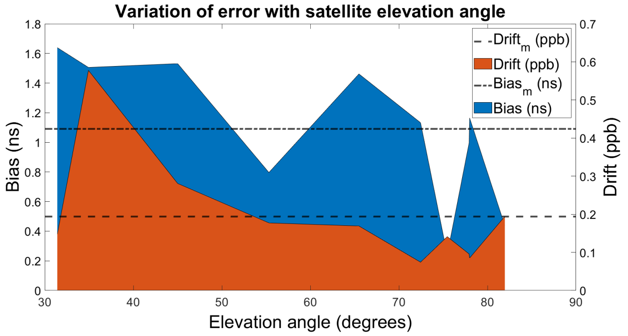

Fig. 4. Mean Timing error with the elevation angle measured in degrees. Bias is measured in ns, while drift is measured in ns per second.

TABLE II
TIMING ERRORS FOR THE NETWORK IMPLEMENTING THE PROPOSED SOLUTION COMPARED TO THE STATE-OF-THE-ART METHOD.

Timing errors	**Values from [10]**	**Values from proposed solution**	**% Δ**
Mean Timing Bias (ns)	0.90	1.16	28.9
Mean Timing Drift (parts per billion-ppb)	Not Available	1.945	-

of the satellite. The position errors' value is relatively small, within the sub-meter level. However, the velocity errors are quite significant initially but drop down rapidly.

A similar rapid response can be observed for the timing error plot varying across the whole simulation of orbit propagation. The bias and drift derived from the position and velocity errors are shown in figure 3. These errors provide an understanding of the timing inaccuracy present in the signal due to the sole effect of error in the ephemeris data.

In a general case of KF implementation, the real-time propagation data deviates from the expected ground truth uniquely, and the model corrects the prediction after each timestep. However, in the current research, the only real-time data available is from the Spacetrack ephemeris, which was used for model initialisation. The simulation files already have an in-built propagation model, but it is truncated to some level, and then KF is implemented. However, after certain timesteps of reducing the error variation, the model reaches a constant harmony with the simulation files that do not have any real-time error source. The error associated with the built model is from the same simulations and is purely computational. This means the solution must be verified with real-time data, which is suggested as future work.

C. *Timing error variation with elevation*

The error variation experienced with elevation angle constitutes one of the most significant factors in controlling the timing and position errors within the required set levels. Accordingly, the satellite was translated to various elevation angles at different positions in the sky view of the ground stations, and the results obtained for different elevation angles were cumulatively plotted for different positions of the satellite. The resulting plot is shown in figure 4.

The lower elevation corresponds to slightly higher timing errors, which corresponds to the real scenario, where the transmission signal is attenuated due to travelling a further distance in the dense atmosphere when close to the horizon compared to the overhead case of 90 degrees, yielding the lowest timing errors. For an observer on the ground, the satellite going overhead would traverse a parabola-like path. So, the worst bias is expected at lower elevations. Atmospheric effects would make the effect considerably worse as the signal slices through a thicker part of the atmosphere at lower elevations and has to deal with the dynamically varying atmospheric changes with a LEO satellite compared to a MEO satellite. The drift is also affected and can be regarded as a similar concept to the Doppler effect. The drift reduces while moving from a lower to a higher elevation and, conversely, from a higher to a lower elevation. It thus provides substantial results and determination of the timing error and timing performance across the range of elevation positions with respect to the ground stations.

D. *Timing error comparison with state-of-the-art*

From the implementation of the above methodology, the resulting reduction in the RMS value of positioning error due to gravitational perturbations was reduced from 4 meters to 1 meter. The timing errors are described in table II. The table indicates typical error values for the primary case with and without the solution implementation.

This indicates that the timing errors achieved for bias and drift are similar to the GNSS connecting link-based solution by implementing the proposed solution. Both methods differ by 0.5 ns, but the proposed solution has the advantage of independent operation from GNSS for positioning and timing.

V. CONCLUSIONS AND FUTURE WORKS

The paper identifies limitations in existing technologies for LEO satellite applications for positioning purposes. Based on a linear Bayesian approach, the method continuously refines position and timing information using simulated and actual satellite ephemeris data. The paper evaluates the timing accuracy of on-board clocks by correlating them with ground station clocks synchronised to UTC(k). Two primary sources of error, low elevation angles and inaccuracies in position and velocity data are analysed. A comparison with the industrial solution identifies the proposed solution as a strong contender with a 0.5 ns difference. The accuracy variation due to elevation angle is within very close limits of 1 ns.

A major challenge was procuring real-time data to feed into the KF model to estimate prediction for comparison with the ground truth. This led to the technique being dependent on the mock values from another software to assess its workability. An essential need would be to collect real-world data from satellites and use that data to obtain the correct predictions.

After defining the accurate model for the satellite's position, velocity, and timing data, the next step is to validate it with real-time data from existing satellites. Future work involves integrating the software with hardware for a comprehensive solution in deploying navigation satellites in low earth orbit. The research considered 4 ground stations in the UK mainland that can be modified to any other ground station to cover the globe for enhanced modelling and simulation. Nonetheless, the research holds high potential for current industrial applications and future research.

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