

A Distributed Time Synchronization Strategy for LEO PNT Constellations Supported by Optical Links

By Vinicius FERREIRA NERY,¹⁾ Shunichiro NOMURA,¹⁾ Takayuki HOSONUMA,¹⁾ Satoshi IKARI,¹⁾ and Shinichi NAKASUKA¹⁾

¹⁾The University of Tokyo, Japan

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This work extends a prior proposal for optical-link–assisted LEO PNT by developing a fully distributed time-synchronization strategy. Building on the idea of using a ground optical clock as a high-precision reference, we assume free-space optical links (supplemented by RF) deliver picosecond-level time differences when available. Intra-orbit synchronization is achieved by fusing pairwise measurements into an implicit ensemble mean and steering each onboard oscillator toward that mean. Plane times and uncertainties are then exchanged among neighboring planes via a weighted consensus update to form a common constellation timescale. When a satellite passes over a ground station, a feedforward estimator uses the ground optical clock to correct the constellation time, binding it to UTC. Simulations of two Walker Delta constellations demonstrate that the intra orbit filter converges to sub nanosecond alignment with one second updates, and an investigation of ground link availability under stochastic cloud models underscores topology limitations that will inform future ground-filter design. Remaining drift among plane times highlights the role of the inter-plane and ground layers introduced here.

Key Words: LEO PNT, Optical Communications, Time Transfer, Clock Synchronization, Laser link

Nomenclature

p	: pseudorange measurement, m
ρ	: relative radial distance, m
c	: speed of light, m/s
dt	: clock offset, s
D_T	: Delay by troposphere, s
D_I	: Delay by ionosphere, s
e	: additional errors, s
x_{1i}	: time deviation of clock i , s
x_{2i}	: frequency deviation of clock i
w_i	: weight of index i
x_{ij}	: time difference between clock i and j , s
γ	: Lorentz factor
v	: velocity, m/s
$\mathbf{x}$	: clock state
y_{ij}	: time measurement between i and j , s
V	: gravity potential, m^2/s^2
q	: clock model noise parameter
T_s	: sampling time, s
ξ	: gaussian process
A	: state transition matrix
B	: control matrix
$\mathbf{w}$	: process noise vector
$\mathbf{v}$	: measurement noise vector
$\mathbf{u}$	: control input vector
C	: measurement matrix
Σ	: diagonal noise covariance matrix
P	: estimation error covariance
$\mathcal{N}$	: neighbor set
T_{plane}	: plane time
$T_{\text{constellation}}$	: constellation time
$Z_{ol,i}$	: deviation of i to optical clock l
U_{ol}	: feedforward cumulated control action
K	: gain

Subscripts

i	: element of index i
r	: received
e	: ensemble
LQR	: of the linear quadratic regulator

Superscripts

s	: sent
i	: orbital plane i

1. Background

Satellite systems have transformed global timekeeping and distribution. Today's GNSS constellations carry highly stable atomic clocks onboard medium-Earth-orbit satellites, enabling positioning, navigation and timing (PNT) at the global scale.¹⁾ Recently, there has been growing interest in extending PNT capabilities by deploying constellations of low-Earth-orbit (LEO) satellites. LEO satellites, orbiting much closer to Earth, deliver stronger signals and faster update rates than traditional GNSS. As a result, they can improve coverage in polar regions, dense urban canyons, and even indoor environments.^{11,12)} Continuous global coverage with LEO requires hundreds of satellites instead of the few dozen used in GNSS. This dramatic increase places stringent size, mass, and power constraints on each satellite.

A principal challenge for LEO PNT is clock performance. Conventional space-qualified clocks—cesium, rubidium, or hydrogen-maser standards—remain too large and power-hungry to deploy in large numbers. Chip-scale atomic clocks (CSACs) offer a far smaller form factor but exhibit lower stability, leading to increased time and frequency errors unless corrected frequently.^{7,18)} In contrast, optical atomic clocks on the ground, such as lattice clocks, achieve two orders of magnitude better fractional frequency stability than microwave standards.⁸⁾ Although these optical clocks are too large and delicate

to operate in orbit, their high-precision output can be transferred to orbit via free-space optical links.

To make use of ground optical clocks, two-way optical time and frequency transfer (OTWTFT) has demonstrated femtosecond-level synchronization over turbulent free-space channels.^{5,19)} These optical links, enabled by frequency combs, bridge ground clocks and satellite CSACs.^{4,6)} When optical links are unavailable, traditional RF-based TWSTFT provides a nanosecond-level fallback.¹⁾

A LEO constellation equipped with both RF and optical inter-satellite links, together with occasional optical passes to ground stations, can form a distributed clock network.²³⁾ Each satellite exchanges time-difference measurements with its neighbors, when in view of a ground station, receives a correction from the ground optical clock. By fusing these measurements, the constellation can approximate a single high-stability timescale without requiring every satellite to carry a high-performance clock.^{7,9,10)}

Therefore, this paper focuses on the time-synchronization strategy for such an optical-link-assisted LEO PNT system. Building on existing two-state clock models and Kalman-LQR steering techniques,^{13,15,16)} we introduce a three-layer, distributed filtering architecture. While the inter-plane consensus and ground correction filters are described briefly, our analysis centers on the first layer, which equalizes clocks within each orbital plane using replicated-fusion filtering. In this work, we demonstrate via simulation that the intra-plane filter alone can reach sub-nanosecond alignment under realistic link delays and noise, laying the groundwork for end-to-end constellation timing.

The remainder of this paper is structured as follows: Section 2. presents the problem description, detailing timing requirements, clock instabilities, and link intermittency in LEO PNT. Section 3. introduces the single-clock model and its dynamics. Section 4. extends that model to multiple clocks and describes time-difference measurements, Kalman-filter estimation, and LQR-based control. Section 5. presents the distributed synchronization strategy, including the intra-plane, inter-plane, and constellation-ground filters. Section 6. reports simulation results and discusses the performance of the intra-plane filter under realistic noise, update-interval, and link-dropout conditions. Finally, Section 7. summarizes the work, outlines next steps, and suggests paths for future research.

2. Problem Description

Because chip-scale atomic clocks (CSACs) drift rapidly and LEO links drop out frequently, sub-nanosecond alignment is difficult. Our objective is to synchronize all onboard clocks in a LEO PNT constellation to a common timescale with sub-nanosecond accuracy, despite each satellite carrying only a modestly stable chip-scale atomic clock (CSAC). Precise clock alignment is essential because any clock offset directly degrades range measurements. For example, a simplified pseudorange measurement is given by

$$p_r^s = \rho_r^s + c(dt_r - dt^s) + D_{T_r}^s + D_{I_r}^s + e_r^s, \quad (1)$$

where ρ_r^s is the geometric distance between receiver r and satellite s , dt_r and dt^s are the receiver and satellite clock offsets from

system time, $D_{T_r}^s$ and $D_{I_r}^s$ denote tropospheric and ionospheric delays, c is the speed of light, and e_r^s collects remaining errors.¹⁾ A clock error of 1 ns, therefore, induces about 0.3 m of range error, which is unacceptable for many LEO PNT applications.

In terrestrial GNSS, each satellite's clock data are sent to ground control, where a real-time, weighted ensemble timescale is formed, similar to International Atomic Time (TAI) or UTC, via

$$x_e(t) = \sum_{i=1}^N w_i(t), [x_i(t) - \hat{x}_{ie}(t)], \quad (2)$$

with $x_i(t)$ the reading of clock i , $\hat{x}_{ie}(t)$ its predicted deviation, and $w_i(t)$ its weight based on performance.²⁾ In a LEO PNT constellation, however, each orbital plane completes a revolution in 90–120 minutes, inter-plane visibility windows often last only tens of seconds, and ground-station passes remain brief and weather-dependent.^{11,12)} Consequently, no single master clock can be broadcast continuously to all satellites, and a decentralized synchronization strategy becomes necessary.

Each CSAC exhibits two-state stochastic noise (white frequency and random walk) that yields fractional frequency instability on the order of $10^{-11}/\tau^{1/2}$.¹³⁾ Without frequent corrections, these instabilities produce tens of nanoseconds of error within minutes. In contrast, optical clocks on the ground achieve fractional frequency instability of $2 \times 10^{-16}/\tau^{1/2}$,⁸⁾ suggesting that periodic transfer of optical-clock reference into orbit could dramatically reduce timing errors.

An optical communication-assisted LEO PNT concept was previously proposed:²³⁾ when a satellite is in view of an optical ground station (OGS), two-way optical time transfer (OTWTFT) using frequency combs provides a high-precision time difference, and inter-satellite laser and RF links then distribute that reference throughout the constellation. This approach leverages the superior stability of ground optical clocks without requiring every satellite to carry a laboratory-grade clock.

Because every time-difference measurement, whether obtained via OTWTFT or via RF, must traverse moving platforms, it is subject to Doppler and relativistic biases. In particular, relative velocities of several kilometers per second among satellites and between satellites and ground introduce significant Doppler shifts and relativistic effects. Any two-way time-difference measurement y_{ij} between satellites i and j must account for geometric delays and first-order Doppler, for example:

$$y_{ij} = [x_i(t) - x_j(t - \Delta t_{ij})](1 - v_{ij}/c) + \delta_{\text{rel}} + \eta_{ij}, \quad (3)$$

where Δt_{ij} is the light-time, v_{ij} the line-of-sight relative velocity, δ_{rel} the combined gravitational and kinematic relativistic correction, and η_{ij} measurement noise.

More elaborate relativistic corrections may consider coordinate transformations from the proper time (the local oscillator's physical time) to a coordinate time, which depends on the choice of spacetime coordinate system.²⁴⁾ The transformation consists in computing the rate of a clock with respect to a Earth-centered inertial (ECI) spacetime reference with time component set at infinity. Using the Schwarzschild metric, one can derive the rate of such clock with respect to coordinate time:

$$\frac{d\tau}{dt} \approx 1 + \frac{V(\mathbf{r})}{c^2} - \frac{v^2}{2c^2} \quad (4)$$

where $V(\mathbf{r})$ is the gravitational potential at position $\mathbf{r}$ (approximated by Earth's potential expanded to third-order multipoles) and v is the clock's velocity in ECI coordinates. A proper timestamp τ is transformed into coordinate time $t(\tau)$ via

$$t(\tau) = t_0 + \int_{\tau_0}^{\tau} \left(\frac{d\tau}{dt} \right)^{-1} d\tau. \quad (5)$$

Thanks to approximate knowledge of each satellite's position and velocity, the integral in (5) can be evaluated in real time: even with kilometer-scale errors in $\mathbf{r}$ and meter-per-second errors in v , coordinate-time estimates remain accurate to the picosecond level over one-second intervals.²⁴⁾ Henceforth, all time measurements assume that these relativistic corrections have been applied and may be omitted from further discussion.

In this work, a multi-layer, distributed filtering architecture is proposed to handle intermittent links between orbital planes and to ground stations. At the first layer (intra-plane), pairwise time differences are fused into an implicit ensemble mean (IEM), and each CSAC is steered toward that mean to achieve sub-nanosecond alignment despite measurement noise and Doppler/relativistic biases. At the second layer (inter-plane), each orbital plane exchanges its IEM and associated uncertainty with neighboring planes via a weighted consensus update, driving all plane times toward a common constellation timescale. At the third layer (constellation-ground), whenever a satellite passes an OGS, a feedforward estimator uses the high-precision optical clock reference to correct the constellation timescale, binding it to UTC(k) despite realistic cloud coverage and turbulence.

3. Clock Model and Dynamics

3.1. Stochastic Clock Model

Consider a two-state atomic clock model to describe the dynamics of the phase and frequency deviations from a ideal time reference. The clock reading deviation the reference for the two-state atomic clock can be heuristically modeled by the integral stochastic equation described in Eq. (6).¹³⁾

$$h(t) = x_0 + y_0 t + \int_0^t \xi_1(\tau_1) d\tau_1 + \int_0^t \int_0^{\tau_2} \xi_2(\tau_2) d\tau_2 d\tau_1. \quad (6)$$

Here, x_0 and y_0 are constants that represent the initial phase and frequency deviations from the ideal time, ξ_1 is a Gaussian process with variance q_1 corresponding to white frequency noise, and ξ_2 is a second Gaussian process with variance q_2 that characterizes the random frequency walk.

The state-space representation of the system is obtained by considering the follow transformation:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t) + \xi_1(t) \\ \dot{x}_2(t) &= \xi_2(t) \\ h(t) &= x_1(t) \end{aligned} \quad (7)$$

Which yields

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \xi_1(t) \\ \xi_2(t) \end{bmatrix}. \quad (8)$$

3.2. Discrete Atomic Clock Model

The continuous model presented in Eq. (8) can be discretized at a sampling time T_s . The discrete clock dynamics resulting from an increment at time step kT_s with $k \in \mathbb{Z}$ is given as in Eq. (9).

$$\mathbf{x}[k+1] = \begin{bmatrix} x_1[k+1] \\ x_2[k+1] \end{bmatrix} = \mathbf{A}\mathbf{x}[k] + \mathbf{w}[k] \quad (9)$$

Where $k+1 := (k+1)T_s$, and $\mathbf{w}[k]$ is a two-dimensional Gaussian noise with zero mean and covariance matrix $\mathbf{Q}$. The matrices $\mathbf{A}$ and $\mathbf{Q}$ are given as follows:

$$\mathbf{A} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} q_1 T_s + q_2 \frac{T_s^3}{3} & q_2 \frac{T_s^2}{2} \\ q_2 \frac{T_s^2}{2} & q_2 T_s \end{bmatrix}.$$

The model given in Eq. (9) can be modified to include a control input to enable periodic adjustments to the clock frequency. Since the phase is coupled to the frequency, periodic frequency adjustments are sufficient to control the phase deviation of the clock as well. The discrete state-space model including a scalar control input $u[k]$ is given in Eq. (10).

$$\mathbf{x}[k+1] = \mathbf{A}\mathbf{x}[k] + \mathbf{B}u[k] + \mathbf{w}[k] \quad (10)$$

With $\mathbf{B}$ matrix given by

$$\mathbf{B} = \begin{bmatrix} T_s \\ 1 \end{bmatrix}.$$

4. Clock State Estimation and Control

4.1. Time Differences Between Clocks

In the previous sections, we defined the clock reading deviation from an ideal time reference as the first state x_1 of the two-state model defined by Eqs. 8, 9 and 10. This quantity is by definition immeasurable because the ideal time reference is unknown. However, time exchanges between different clocks are measurable quantities that are independent of the ideal time reference and can be used to infer the real clock state vector $\mathbf{x}[k]$.

Consider, for example, two clocks with real readings $t_i[k]$ and $t_j[k]$, with $i \neq j$. If the true time reference $t_0[k]$ was known in the absence of measurement noise, each time deviation from the ideal time could be expressed as $x_{1i}[k] = t_i[k] - t_0[k]$, for $i \in \{i, j\}$. Therefore, as shown in Eq. (11), the time difference $y_{ij}[k] = t_i[k] - t_j[k]$ between the real clock readings is independent of the ideal time reference and corresponds, aside from noise, to the difference between the states in our model.

$$y_{ij}[k] = x_{1i}[k] + t_0[k] - x_{1j}[k] - t_0[k] = x_{1i}[k] - x_{1j}[k] \quad (11)$$

4.2. Space-State Representation for Multiple Clocks

For a set of N clocks, we form the general state vector $\mathbf{x}$, which contains the phases and frequency deviations from the ideal time for all clocks. Based on Eq. (10) and Eq. (11) the system equations can be expressed as in Eq. (12).

$$\begin{cases} \mathbf{x}[k+1] = \mathbf{A}^* \mathbf{x}[k] + \mathbf{B}^* \mathbf{u}[k] + \mathbf{w}[k] \\ \mathbf{y}[k] = \mathbf{C} \mathbf{x}[k] + \mathbf{v}[k] \end{cases} \quad (12)$$

Here, the state vector $\mathbf{x}$ is constructed by stacking all the phase deviation states x_{1i} followed by all the frequency states x_{2j} for $i, j \in 1, \dots, N$. The control input vector, on the

other hand, $\mathbf{u}[k]$ simply contains all the scalar inputs $u_i[k]$ for each clock i . The state and control vectors are expressed as $\mathbf{x}[k] = [x_{11}[k] \ \dots \ x_{1N}[k] \ x_{21}[k] \ \dots \ x_{2N}[k]]^\top$ and $\mathbf{u}[k] = [u_1[k] \ \dots \ u_N[k]]^\top$, respectively.

As a result of this choice, the state transition matrix A^* and control matrix B^* are modified from the original A and B matrices in Eq. (10) as follows:

$$\begin{aligned} A^* &= A \otimes I_N \\ B^* &= B \otimes I_N \end{aligned}$$

where the symbol $\otimes$ represents the Kronecker delta operator and I_N is the $N \times N$ identity matrix.

The measurement equation in Eq. (12) represents the time difference measurements described in section 4.1, with the addition of noise. The time difference measurement y_{ij} between clocks i and j with clock i as the reference and measurement noise v_{ij} is defined as:

$$y_{ij}[k] = x_{1j}[k] - x_{1i}[k] + v_{ij}[k]. \quad (13)$$

The $N-1 \times 2N$ matrix C in Eq. (12) considering the first clock as the reference clock is given by:

$$C = \begin{bmatrix} -1 & 1 & 0 & 0 & \dots & 0 & 0 \\ -1 & 0 & 1 & 0 & \dots & 0 & 0 \\ -1 & 0 & 0 & 1 & \dots & 0 & 0 \\ -1 & 0 & 0 & 0 & \dots & 0 & 0 \end{bmatrix}$$

And the measurement noise vector $\mathbf{v}[k] := [v_{12} \ v_{13} \ \dots \ v_{1N-1} \ v_{1N}]^\top$ is modeled as a zero-mean Gaussian distribution with variance matrix $R := \text{diag}(r_{12}, \dots, r_{1N})$ in which r_{ij} represents the measurement variance at measurement y_{ij} , for $i, j \in \{1, \dots, N\}$.

It is also worth mentioning that the noise vector $\mathbf{w}[k]$ is an extended version from the noise in Eq. (10) in the sense that it incorporates the noise characteristics of all clocks. Considering the state representation choice for the general state vector $\mathbf{x}[k]$, the covariance Q of $\mathbf{w}[k]$ is given by:

$$Q = \begin{bmatrix} \Sigma_1 T_s + \Sigma_2 \frac{T_s^3}{3} & \Sigma_2 \frac{T_s^2}{2} \\ \Sigma_2 \frac{T_s^2}{2} & \Sigma_2 T_s \end{bmatrix}$$

In which $\Sigma_1 := \text{diag}(q_{11}, \dots, q_{1N})$ and $\Sigma_2 := \text{diag}(q_{21}, \dots, q_{2N})$.

4.3. Kalman Filter

State estimates are obtained with a discrete-time, linear, minimum-variance Kalman filter applied to the multi-clock model of Eq. (12). Let the a-priori (predicted) and a-posteriori (updated) state estimates be denoted by $\hat{\mathbf{x}}[k|k-1]$ and $\hat{\mathbf{x}}[k|k]$, respectively, and let $P[k|k-1]$ and $P[k|k]$ be the corresponding error-covariance matrices. With an initial guess $\hat{\mathbf{x}}[0|0] = \hat{\mathbf{x}}_0$ and $P[0|0] = P_0 \geq 0$, one recursion of the filter proceeds as follows:

Prediction (time-update)

$$\hat{\mathbf{x}}[k|k-1] = A^* \hat{\mathbf{x}}[k-1|k-1] + B^* \mathbf{u}[k-1], \quad (14)$$

$$P[k|k-1] = A^* P[k-1|k-1] A^{*\top} + Q. \quad (15)$$

Innovation

$$\tilde{\mathbf{y}}[k] = \mathbf{y}[k] - C \hat{\mathbf{x}}[k|k-1], \quad (16)$$

$$S[k] = C P[k|k-1] C^\top + R. \quad (17)$$

Measurement-update (correction)

$$K[k] = P[k|k-1] C^\top S[k]^{-1}, \quad (18)$$

$$\hat{\mathbf{x}}[k|k] = \hat{\mathbf{x}}[k|k-1] + K[k] \tilde{\mathbf{y}}[k], \quad (19)$$

$$P[k|k] = (I - K[k] C) P[k|k-1]. \quad (20)$$

Equations (14)–(20) constitute the standard Kalman recursion, specialized here to the clock estimation problem. The process-noise covariance Q and measurement-noise covariance R were derived in Section 4.2. Their diagonal structure reflects the assumption that the stochastic errors of different clocks and of different pairwise measurements are mutually uncorrelated.

When only a subset of time-difference measurements is available at an epoch, the corresponding rows of C and entries of R can be removed, and the filter remains valid. Similarly, control inputs $\mathbf{u}[k]$ may be set to zero for free-running (uncontrolled) clocks or updated periodically to realize steering strategies such as disciplined frequency offsets.¹⁴⁾

4.4. Clock Synchronization

In order to synchronize multiple clocks, each clock is steered towards the same reference so the time and frequency differences between clocks are minimized. Here, steering refers to the process of injecting a small frequency correction $u = \Delta f$ into an oscillator in order to adjust its phase and frequency as introduced in Eq.(10).

For a control period T_u , the control input $u_i[kT_u]$, $i = 1, \dots, N$, is obtained so that the difference between the current state of clock i and the desired reference state is a zero-mean Gaussian process with bounded variance. A feedback law of the form $\mathbf{u}[k] = -K\hat{\mathbf{x}}$ with gain K such that the poles of the eigenvalues of the system described by Eq.(12) remain within the unit circle.

The adequate control gain K can be obtained using modern control techniques such as pole placement,^{14,18)} or the linear quadratic regulator (LQR).¹⁴⁾ In this work, we adopt the LQR for determining the control gain matrix K_{LQR} which is briefly introduced as follows.

Let the quadratic performance index over an infinite horizon be

$$J = \mathbb{E} \left\{ \sum_{k=0}^{\infty} (\mathbf{x}[k]^\top Q_{LQR} \mathbf{x}[k] + \mathbf{u}[k]^\top R_{LQR} \mathbf{u}[k]) \right\}, \quad (21)$$

where $Q_{LQR} \geq 0$ weights the phase/frequency errors and $R > 0$ penalizes the actuator effort (frequency steps). Solving the discrete Riccati equation

$$S = A^{*\top} S A^* - A^{*\top} S B^* (R_{LQR} + B^{*\top} S B^*)^{-1} B^{*\top} S A^* + Q_{LQR}$$

yields the optimal LQR gain

$$K_{LQR} = (R_{LQR} + B^{*\top} S B^*)^{-1} B^{*\top} S A^*. \quad (22)$$

Combining the Kalman estimator of Section 4.3. with the feedback law $\mathbf{u}[k] = -K_{LQR} \hat{\mathbf{x}}[k|k]$ gives a discrete linear-quadratic-Gaussian controller that is optimal for the stochastic model.^{15,16)} Because the estimator and regulator are designed from independent Riccati equations, the separation principle applies, and the closed loop remains stable, provided both Riccati solutions exist.

5. Distributed Layered Synchronization Strategy

To synchronize time without a single master clock, we adopt a layered approach. The problem is decomposed into three layers: intra-plane, inter-plane, and constellation-ground. The first layer aligns all on-board clocks within a single orbital plane. In that scenario, the relative velocities and angular velocities are small, and inter-satellite optical links can be maintained for long periods of time consistently. Once an orbit is internally aligned, it realizes a plane time $T_{\text{plane},i}$. The second layer exchanges these plane times to generate a constellation time $T_{\text{constellation}}$. Finally, opportunistic satellite-ground links tie $T_{\text{constellation}}$ to UTC(k), bounding long term drift. In this work, we focus on the first layer (intra-plane) while briefly introducing the other two layers, which will be further explored in a future work.

5.1. Replicated Fusion intra-plane Filter

Let s_j^i represent the j -th satellite in orbit $i \in \mathcal{O}$ in which $\mathcal{O}$ represents the set of all orbits in the constellation. Considering that each orbit contains N satellites, s_j^i has a leading satellite $s_{(j+1) \bmod N}^i$ and a trailing satellite $s_{(j-1+N) \bmod N}^i$ that comprise the orbit neighbors of s_j^i hereafter represented as $\mathcal{N}_j^i$. Whenever an optical communication link is available, the time difference measurement is obtained via optical time transfer; otherwise, the same two-way routine is performed over the redundant RF link.

Since data can also be transferred via optical or RF links, the time difference measurements, as presented in Eq.(13), are shared between nodes. Therefore, at time K , s_j^i has its local measurements $y_{ji}^1[k]$ with $s_j^i \in \mathcal{N}_j^i$, its neighbors' measurements $y_{ij}^1[k]$, and other shared measurements, which will be used to derive the time difference between s_j^i and $s_p^i \notin \mathcal{N}_j^i$.

With relative time differences to all satellites on the same orbital plane, each satellite can feed the measurements to its local Kalman filter consisting of $2N$ states to be estimated. The filters are equivalent, as they estimate the same states under the same dynamics; however, each local measurement has independent measurement noise realizations. To create proper replicas, or copies, we perform the following transformation of each measurement value $y_{mn}^i[k]$ and covariance r_{mn} :

$$\begin{aligned} y_{mn}^i[k] &= \frac{y_{mn}^i[k] - y_{nm}^i[k]}{2} \\ r_{mn} &= \frac{r_{mn} + r_{nm}}{4} \end{aligned} \quad (23)$$

with $n, m \in \{1, \dots, N\}$ with $n \neq m$, and the value of r_{mn} and r_{nm} being determined by the measurement method.

With the new measurements and covariances, the new estimated state vector $\hat{\mathbf{x}}_j^i[k]$ for satellite s_j^i is obtained using the Kalman filter step defined in equations (14)–(20), and its ensemble mean for satellite s_j^i is calculated as shown in Eq.(24).

$$x_{ej}^i[k] = \left[\begin{array}{c} \sum_{n=1}^N \Sigma_{1,n} (x_{1n}[k] - \hat{x}_{1nj}[k]) \\ \sum_{n=1}^N \Sigma_{2,n} (x_{2n}[k] - \hat{x}_{2nj}[k]) \end{array} \right] \quad (24)$$

With Σ_1 and Σ_2 defined as in Sec.4.. The local plane time for satellite s_j^i is defined as $T_{\text{plane},ij}[k] := \begin{bmatrix} 1 & 0 \end{bmatrix} x_{ej}^i[k]$.

For each on-board clock, the LQR controlled actuator considers only two states, which represent the deviation in phase and frequency from the local clock to its local ensemble mean. Steering then applies a feedback law

$$u_j^i[k] = K_{LQR}(x_{ej}^i[k] - \hat{x}_j^i[k]), \quad (25)$$

which completes the intra-plane filter step.

5.2. Consensus Based inter-plane Filter

Although the number of satellites per orbital plane remains moderate even for large constellations such as Starlink,⁽²¹⁾ the presence of many planes and only intermittent inter-plane links makes constellation-scale filtering challenging. Having achieved intra-plane synchronization at the first layer, each satellite holds a local copy of its plane's time, which we denote by

$$T_{\text{plane},p}[k], \quad p \in \{1, \dots, P\},$$

where p indexes the orbital plane and k is the epoch counter.

When a satellite s_j^p in plane p establishes an inter-plane link with satellite s_k^q in plane q , it transmits its current plane time $T_{\text{plane},p}[k]$ and an associated scalar uncertainty $P_{\text{orbit},p}[k]$ (the variance of the intra-plane ensemble time). Likewise, the peer sends $T_{\text{plane},q}[k]$ and $P_{\text{orbit},q}[k]$. From these two scalars one forms the relative measurement

$$Z_{pq}[k] = T_{\text{plane},p}[k] - T_{\text{plane},q}[k] + v_{pq}[k], \quad (26)$$

where $v_{pq}[k]$ is zero-mean Gaussian with variance

$$R_{pq}[k] = P_{\text{orbit},p}[k] + P_{\text{orbit},q}[k] + r_{pq},$$

and r_{pq} models any additive link jitter or time-transfer error.

To drive all orbital plane times toward a common constellation time, each plane p applies a scalar consensus update whenever it receives a measurement from some neighbor plane q . Fixing plane p , let its set of currently visible neighbor planes be $\mathcal{N}_p$. Then the update for plane p is

$$\begin{aligned} T_{\text{plane},p}[k^+] &= T_{\text{plane},p}[k] + \sum_{q \in \mathcal{N}_p} \alpha_{pq}[k] Z_{pq}[k], \\ \alpha_{pq}[k] &= \frac{1/R_{pq}[k]}{\sum_{\ell \in \mathcal{N}_p} 1/R_{p\ell}[k]}. \end{aligned} \quad (27)$$

Because each plane normalizes by $\sum_{\ell \in \mathcal{N}_p} 1/R_{p\ell}$, the weights α_{pq} sum to one over $q \in \mathcal{N}_p$. In practice, if only a single neighbor q is visible at epoch k , the sum reduces to $\alpha_{pq} = 1$ and

$$T_{\text{plane},p}[k^+] = T_{\text{plane},p}[k] + Z_{pq}[k].$$

After updating $T_{\text{plane},p}$, plane p revises its own uncertainty via the standard scalar-fusion rule:

$$P_{\text{orbit},p}[k^+] = \left(P_{\text{orbit},p}[k]^{-1} + \sum_{q \in \mathcal{N}_p} 1/R_{pq}[k] \right)^{-1}. \quad (28)$$

Each plane then broadcasts its updated pair $(T_{\text{plane},p}[k^+], P_{\text{orbit},p}[k^+])$ to all satellites in that orbit. Those satellites update their steer targets with the corrections, thereby driving every satellite in plane p toward the consensus result. Iterating across all visible neighbors ensures that, over time, every plane's time converges to a common constellation time.

5.3. Feedforward Constellation–Ground Filter

The ground filter estimates the difference between the ground optical clock state $X_{ol}[k]$ and the satellite plane–time state $x_i[k]$. We define

$$Z_{ol,i}[k] := X_{ol}[k] - x_i[k]. \quad (29)$$

When constellation synchronization is achieved, $x_i[k]$ already represents the common plane–time or constellation–time, so $Z_{ol,i}[k]$ captures the offset between the ground reference and that common time.

Let $\hat{Z}_{ol,i}[k]$ be the ground’s estimate of $Z_{ol,i}[k]$ at the last pass, with covariance $P_{ol,i}[k]$. Between passes, plane i applies a series of ℓ control inputs $u_i[k], u_i[k+1], \dots, u_i[k+\ell-1]$ that were broadcast by the satellites. Just before the next contact at epoch $k+\ell$, the ground filter predicts the state according to

$$\hat{Z}_{ol,i}[k+\ell] = A_g^\ell \hat{Z}_{ol,i}[k] + U_{ol,i}[k+\ell], \quad (30)$$

$$P_{ol,i}[k+\ell] = P_{ol,i}[k] + Q_{ol,i}(\ell), \quad (31)$$

where

$$U_{ol,i}[k+\ell] = \sum_{m=0}^{\ell-1} A_g^{\ell-1-m} B u_i[k+m], \quad (32)$$

and $Q_{ol,i}(\ell)$ is the integrated process noise of the ground–satellite relative dynamics over ℓ discrete steps. In these equations, A_g and B are the discrete-time state and input matrices from Eq. (10), specialized to the ground–satellite relative motion, and $u_i[k+m]$ denotes the scalar correction issued by plane i at epoch $k+m$.

At epoch $k+\ell$, the ground terminal obtains a new measurement of the offset:

$$Y_{ol,i}[k+\ell] = Z_{ol,i}[k+\ell] + v_{ol,i}[k+\ell], \quad (33)$$

where $v_{ol,i}[k+\ell]$ is zero-mean Gaussian measurement noise with variance $R_{ol,i}$. Since $Z_{ol,i}[k+\ell] = X_{ol}[k+\ell] - x_i[k+\ell]$, the terminal computes $Y_{ol,i}[k+\ell]$ by subtracting the satellite-reported plane–time $x_i[k+\ell]$ from the ground optical clock reading $X_{ol}[k+\ell]$.

The ground filter then updates its estimate via a standard Kalman correction:

$$\hat{Z}_{ol,i}[k+\ell] = \hat{Z}_{ol,i}[k+\ell] + K_{ol,i}(Y_{ol,i}[k+\ell] - C \hat{Z}_{ol,i}[k+\ell]), \quad (34)$$

$$P_{ol,i}[k+\ell] = (I - K_{ol,i}C)P_{ol,i}[k+\ell], \quad (35)$$

where C is the measurement matrix from Eq. (12). The gain $K_{ol,i}$ is the steady-state Kalman gain found by solving the Riccati equation in Section 4, replacing the state transition matrix and the covariance matrices accordingly. It should be noted that the resulting process noise is the one-step process noise of the ground optical clock $Q_{ol,i}(1)$ and the one-step process noise of the satellite clock $Q_i(1)$.

Once $\hat{Z}_{ol,i}[k+\ell]$ is available, the ground filter computes a ground-correction command:

$$u_{\text{ground},i}[k+\ell] = K_{\text{ground},i}(\hat{Z}_{ol,i}[k+\ell] - \hat{Z}_{ol,i}^s[k+\ell]), \quad (36)$$

where $\hat{Z}_{ol,i}^s[k+\ell]$ is the satellite’s own estimate of $Z_{ol,i}[k+\ell]$ transmitted during the pass, and $K_{\text{ground},i}$ is the LQR gain for the ground correction as described in Section 4. The scalar

$u_{\text{ground},i}[k+\ell]$ is broadcast to all satellites in plane i and applied as an additional term in their steering law at the next epoch. Since the intra- and inter-orbit filters have already equalized the plane times to within small bounds, this single feedforward correction from the ground suffices to pull the entire constellation back toward UTC(k).

6. Simulation Results & Discussion

The first layer of the distribution strategy proposed in Section 5, is critically important for constellation-wide time synchronization. Given the dynamic topology of the constellation, intra-plane links have the highest availability, and the corresponding filters perform most of the clock steering. Therefore, our initial simulation study focuses on this first layer and evaluates intra-plane time synchronization.

Two constellations are considered: a Walker-Delta 60°: 144/12/1 and a Walker-Delta 60°: 360/18/1, using Walker’s notation.²²⁾ The first constellation is depicted in figure 1.

For these Walker geometries, the average distance between satellites in the same orbital plane is 3800 km in the smaller constellation and 2300 km in the larger one. The corresponding one-way signal travel times are approximately 12 ms and 7.7 ms, respectively. Taking into account processing and communication overhead, the topology supports about 39 hops/s in the small constellation and 65 hops/s in the larger one. That is sufficient to support a 1 s filter update interval for the replicated-fusion estimator. Thus, by the time of the next filter update, each satellite has received all peer measurements and can perform a complete Kalman step.

6.1. Constellation and Ground Topology

As discussed earlier, changes in constellation topology determine which links are available for time measurements. Since this work focuses on intra-orbit filters, we also examine each orbital plane’s link availability to ground stations over a 70-minute interval. Figure 1 shows the eight ground stations selected across multiple continents. Figures 2 and 3 plot results for an ideal (no-cloud) scenario and for a scenario with cloud blockage, respectively.

In the ideal scenario (Figure 2), most orbital planes achieve more than 40% ground connectivity, and plane 12 is in contact with the ground 80.38% of the time. However, our ground-station layout leaves plane 10 with no ground visibility; satellites in that plane must rely solely on inter-plane comparisons to synchronize with the constellation. For planes with ground visibility, the average contact duration exceeds 12 minutes per pass, which is ample time for multiple time comparisons between satellites and ground.

When cloud blockage is included, both metrics degrade sharply. In terms of ground connectivity, figure 3 shows that no orbit was able to achieve a ground-connectivity percentage of 10% with values averaging 4.3%. The average connection duration also was severely affected, dropping from more than 12 min on average in the ideal case to under 12 seconds when in the presence of clouds. Even though the ideal case is not a realistic scenario as it is highly unlikely to have a complete absence of clouds at all ground stations at all times, the simulated cloud interference is also not on par with reality. Here we con-

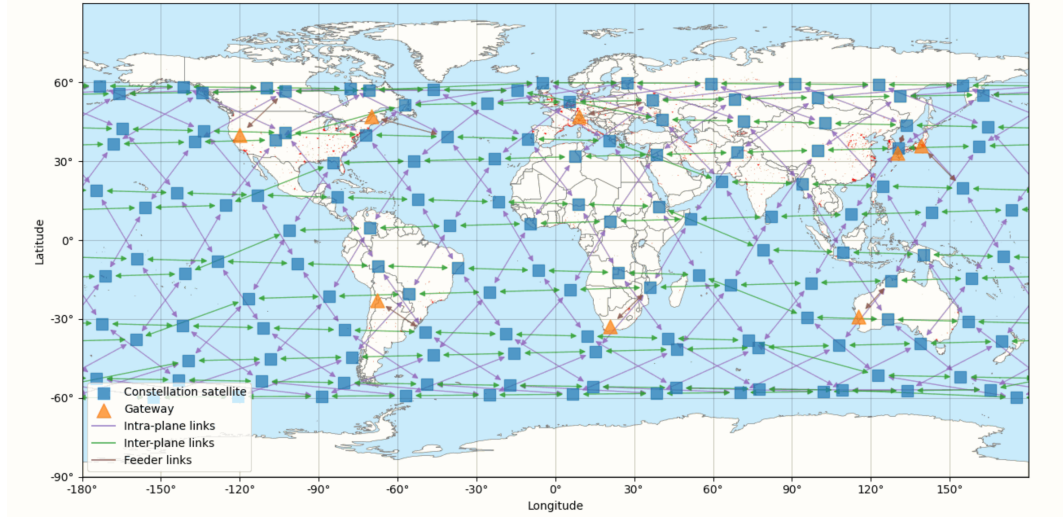


Fig. 1. Walker-Delta 60°: 144/12/1 constellation consisting of 144 satellites over 12 planes.

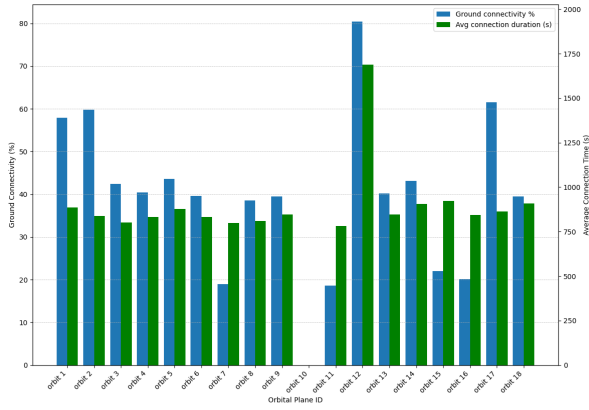


Fig. 2. Ground connectivity percentage over simulation time and average connection time (seconds) for each orbit in ideal weather conditions.

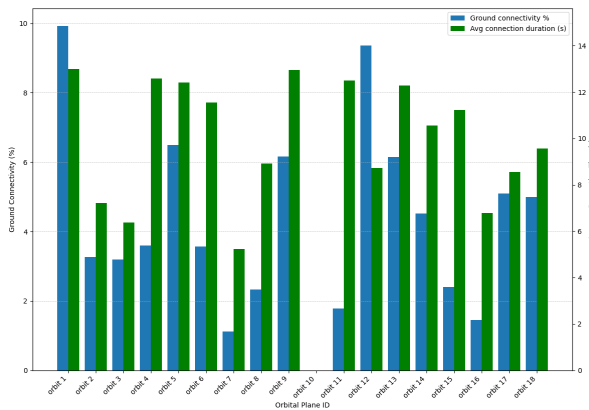


Fig. 3. Ground connectivity percentage over simulation time and average connection time (seconds) for each orbit in cloudy conditions.

sidered a two-state Markov chain model with the two states being "cloudy" and "clear" and transition probabilities from cloudy state (1) to clear state (0) and vice versa were set at $p_{10} = 0.01$ and $p_{01} = 0.1$, respectively. A proper tuning of transition proba-

bility values to accurately describe each ground node is planned for future investigations.

6.2. Intra-plane Filter Performance

To validate the proposed intra-plane clock synchronization method, for each satellite in the topology, we select a random clock model from the CSAC models described in table 1. The scale of parameters q_1 and q_2 was chosen based on literature values on similar atomic clock synchronization researches for ground networks.¹⁹⁾

Table 1. CSAC model parameters.

Clock Type	q_1	q_2	T_s
CSAC 1	1×10^{-20}	1×10^{-26}	1
CSAC 2	2×10^{-20}	1.5×10^{-26}	1
CSAC 3	5×10^{-20}	1×10^{-26}	1
CSAC 4	3.5×10^{-20}	5×10^{-26}	1

Each clock evolves according to the discrete model in Equation (10) with $T_s = 1s$. We model optical time transfer with a measurement-noise variance of 10^{-24} (ps-level) and TWSTT with 10^{-18} (ns-level), consistent with ground experiments.^{7,19)} Each local Kalman filter uses the state-space model of Equation (12) and updates every $T_u = 1s$, matching the 39–65 hops/s capability and ensuring that each satellite receives all peer measurements before the next update.

6.2.1. Satellite-to-satellite Synchronization

The phase difference between two random clocks in the same orbital plane on the smaller constellation is shown in Figure 4. The results indicate that the phase difference between the two clocks converges to a zero-mean signal with bounded variance, which agrees with the definition of synchronization described in Sec. 4. Furthermore, the standard deviation 1σ falls below a quarter of a nanosecond, demonstrating the sub-nanosecond capabilities of the combination of CSACs, optical and RF links, and the proposed synchronization strategy. The larger constellation also showed similar results and are displayed in Figure 5.

6.2.2. Plane time

According to the synchronization strategy proposed in Sec. 5., the satellites in each orbital plane are synchronized via the

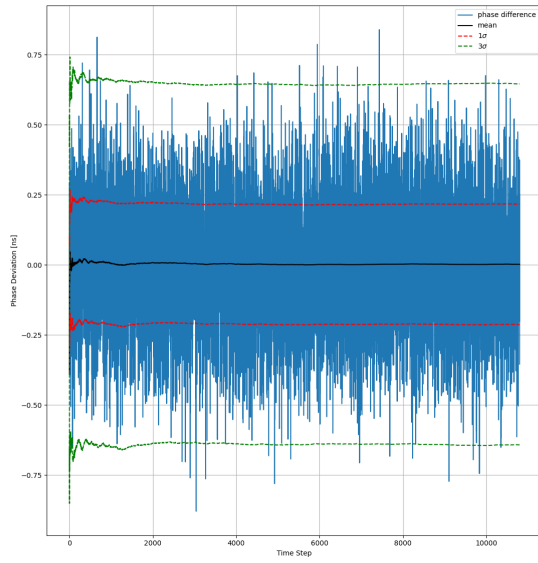


Fig. 4. Phase difference between two random clocks on the same orbit over time for the Walker-Delta 60°: 144/12/1 constellation.

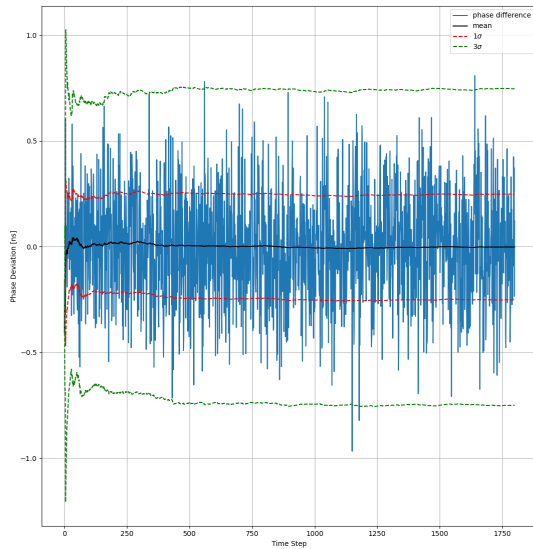


Fig. 5. Phase difference between two random clocks on the same orbit over time for the Walker-Delta 60°: 360/18/1 constellation.

intra-plane filters. The phase of each controlled clock for constellation Walker-Delta 60°: 360/18/1 is presented in Figure 6. From the figure, 18 lines are noticeable. Those correspond to the T_{plane_i} for $i = 1, \dots, 18$ discussed in Sec. 5. Figure 6 also provides a closer look at the behavior of a group of clocks on the same orbit. The close tracking of their ensemble value validates the expected behavior of the algorithm.

However, as described in Sec. 5., the clocks of each orbit, even though synchronized to each other, continue to deviate over time. That behavior motivates the use of the additional

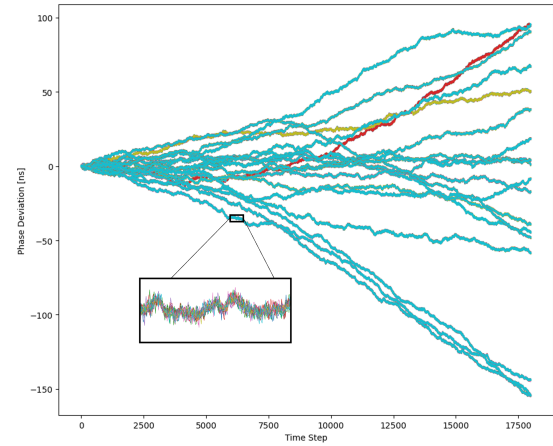


Fig. 6. Controlled clock phase for all clocks in constellation Walker-Delta 60°: 360/18/1 constellation with $Q_{LQR} = 10^5$ and $R_{LQR} = 10^2$.

filters proposed to achieve constellation-wide synchronization with bounded deviation from ground references.

6.3. Discussion

The ensemble time defined in Eq.(24) is the core of synchronization process. However, not only that value cannot be directly computed in the real scenario, requiring a separate oscillator to realize an ensemble based on the estimations of the intra-plane filter,^{14,18)} but also the clocks do not follow strictly the calculated ensemble value. There is a bias between the estimated state and the real clock state given the system is not fully observable. Since the error between the on-board clock and the obtained ensemble is used for clock correction, the bias is not included in the correction which results in increased fractional frequency instability. That behavior is observed in the Allan deviation plot in figure 7.

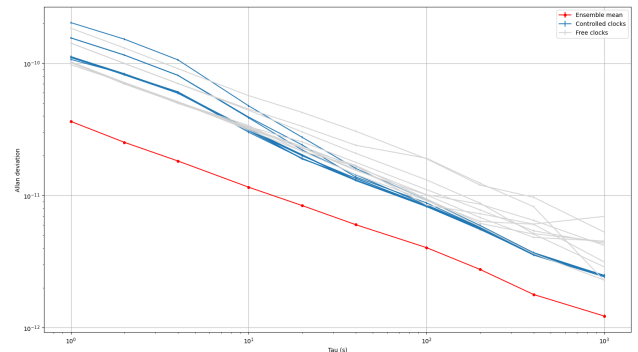


Fig. 7. Disparity between fractional frequency instability of corrected clocks and local ensemble.

This previous result elucidates that the local ensemble value of each satellite is not appropriate to represent the on-board clock state, as it includes the filter bias. To investigate the true fractional frequency instability of the ensemble of the controlled clock values, two combinations of controlled clock values are investigated. The first is a simple average of each controlled clock in orbit where the weighting factor is equal to all clocks and equal to $1/N$, with N as the number of satellites in the orbit of choice. The second is to consider the frequency drift noise characteristics of each clock Σ_i as the weighting factor of

each clock. Each average and controlled clock phase values are shown in figure 8, and the corresponding fractional frequency instabilities are shown in figure 9.

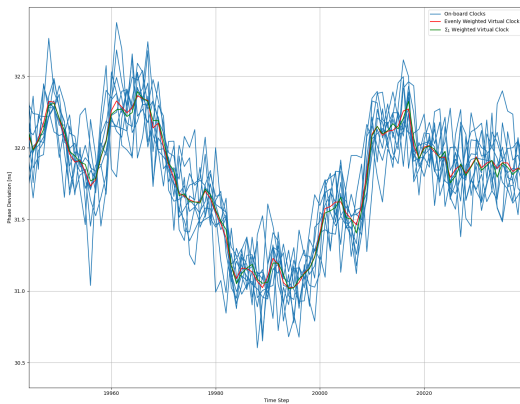


Fig. 8. Phase of controlled clocks of orbital plane 1, their average value (red), and their sum weighted by the frequency drift noise characteristics Σ_1 of each clock.

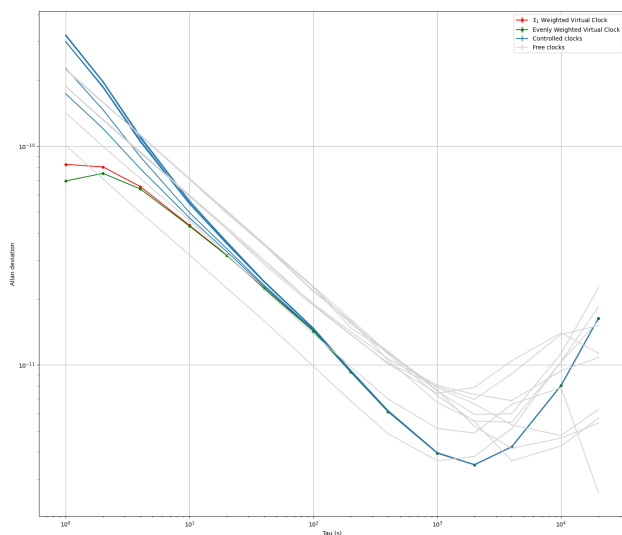


Fig. 9. Allan deviation of controlled clocks of orbital plane 1, their average value (red), and their sum weighted by the frequency drift noise characteristics Σ_1 of each clock.

It is noticeable that there is no appreciable difference between the considered averaging methods. One may consider either average to be used to represent the target steering value for the controlled clocks and, therefore, the plane time value T_{plane_i} of orbit i . However, it is important to remember that the states are not directly available, so such ensemble mean computation is restricted to simulation environments.

7. Conclusion & Future Works

This work has proposed a three-layer method for synchronizing time in LEO PNT constellations using optical links. Existing two-state clock models and standard Kalman-LQR steering were adopted from the literature, while free-space optical

two-way time and frequency transfer was considered to deliver picosecond-level measurements when links are available. The first layer aligns every clock in a single orbital plane by fusing pairwise time differences into an implicit ensemble mean and steering each onboard oscillator toward that mean. The second layer combines the ensemble times and uncertainties of all planes using a scalar consensus update, driving all plane times toward a common constellation time. The third layer compares the constellation time against a ground optical clock, predicts the ground-satellite offset over successive orbits, and issues a feed-forward correction to bind the overall timescale to UTC.

Simulations for two Walker-Delta configurations (144/12/1 and 360/18/1) show that each intra-plane filter converges to sub-nanosecond alignment within one-second update intervals, and that optical passes—when cloud coverage allows—provide valuable anchor updates to the ground layer. Even under a simple cloudy/clear model, the ensemble trajectories remain stable when planes have ground visibility. Phase-difference traces confirm that any two clocks in the same plane converge to zero-mean error with bounded variance, validating the intra-plane layer's ability to form a stable local timescale. At the same time, residual drift among different planes underscores the need for the inter-plane and ground layers.

Important topics for future investigation include a comprehensive study of constellation geometry and link availability, assessing how varying orbital layouts and station-keeping maneuvers affect convergence of the consensus update among plane times. The distributed consensus and feed-forward ground filters described here will need to be implemented in a full network simulator that incorporates realistic link delays, pointing errors, atmospheric turbulence and weather-dependent visibility. It will also be necessary to quantify how residual clock errors propagate into user positioning performance, for example by integrating the synchronized times into a pseudorange-based navigation solution. Finally, scaling analyses for larger constellations can reveal whether sparse cross-plane connectivity or temporary partitions might slow convergence, and to what extent the proposed three-layer approach remains effective as the number of satellites grows.

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