

Fluid Antennas for LEO Channel Stationarization: An Ephemeris-Driven Approach

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Abstract—The orbital motion of low-Earth-orbit (LEO) satellites changes the line-of-sight direction seen by a ground array, requiring continuous spatial-channel tracking. This letter counteracts this variation physically with ephemeris-driven fluid antennas (FAs). From a Keplerian orbital–electromagnetic model, we derive a necessary and sufficient condition for an exactly time-invariant array response, closed-form FA counter-motion laws, aperture, spacing, and speed requirements, and an error bound under discrete ports, finite speed, and pointing and positioning errors. At 20 GHz, few-mm/s FA motion preserves the full coherent gain with a phase-shifter-free combiner, whereas a fixed array averages 0.21, and a $\lambda/16$ port pitch matches 4-bit electronic beam steering.

Index Terms—Fluid antennas, movable antennas, LEO satellite, orbital dynamics, channel stationarization, beam tracking.

I. INTRODUCTION

LOW-Earth-orbit (LEO) satellite networks are a key component of future non-terrestrial networks owing to their global coverage and low latency [1], [2]. Their high orbital velocity, however, makes the line-of-sight (LoS) direction seen by a terrestrial array change continuously, even though the LoS channel itself is fully predictable, so that the array response drifts and must be tracked, especially at Ka-band and above, where a small angular change produces a large phase change across the aperture. Ground terminals cope with this either mechanically, following the ephemeris-predicted direction with bulky, slow, and wear-prone gimbals, or electronically, with a phase shifter per element and either ephemeris-based pointing or pilot-assisted beam tracking whose overhead grows with the satellite angular rate; in both cases the spatial channel still varies over time. Statistical-CSI designs [3] reduce the feedback burden by exploiting slowly varying angular parameters, but the array response itself remains time varying.

Fluid antenna systems (FASs) and movable antennas (MAs) add a spatial degree of freedom by reconfiguring the antenna positions within a prescribed region [4]–[7], which has been exploited for diversity and outage [7], capacity [6], and beamforming and null steering [8]. In all these works the positions are optimized for a channel snapshot, so the optimization must be repeated at the coherence rate with up-to-date channel state information (CSI). Closer to this work, FA mobility has been used to render mobility-induced terrestrial channels approximately static [9], for statistically described multipath channels and with estimated CSI. In satellite communications,

MA positions have been optimized for dynamic beam coverage [10] and jointly with ground-station beamforming [11], again numerically and per snapshot.

An important gap therefore remains. LEO mobility is highly structured: the satellite position, velocity, and apparent LoS direction follow from its orbital state, known in advance from the ephemeris. None of the above schemes exploits this determinism at the antenna level: tracking is reactive rather than predictive, it needs per-element phase shifters or repeated numerical optimization, and antenna positions are re-optimized rather than used to remove the variation altogether. To the best of our knowledge, making the array response of a LEO link, i.e., the inter-element phase structure of the spatial channel, *exactly* time invariant by design, from the ephemeris alone, has not been addressed.

This letter answers this question affirmatively by introducing *orbital channel stationarization*: rather than re-optimizing an FA configuration for the instantaneous channel, the FA geometry is made to *counter-move with the orbital channel itself*, so that the normalized LoS spatial channel is exactly time invariant throughout the pass. Only the inter-element phase structure is frozen: the path gain is untouched and still improves toward culmination, while the full array gain is collected at every instant without tracking. The main contributions are as follows.

- From a Keplerian orbital–electromagnetic model including Earth rotation, we derive a necessary and sufficient geometric condition for exact channel invariance.
- We convert it into closed-form minimum-displacement and minimum-speed FA counter-motion laws, and prove that the phase-neutral collinear configuration is the only one feasible within a finite aperture over a complete pass and is aperture and speed optimal.
- We derive an explicit orbital upper bound on the required FA speed in terms of the satellite angular rate, which shows that sub-mm/s to few-mm/s motion suffices.
- We incorporate discrete ports, finite actuation speed, and pointing and positioning errors, with an analytical error bound.
- We validate the framework against a fixed array and ephemeris-driven electronic beam steering of equal hardware resolution.

Throughout, the FA motion compensates only the *spatial* variation of the channel; the range-rate term, i.e., the Doppler shift $f_D(t)$ and its phase ramp, is likewise predictable from the ephemeris and is removed by conventional Doppler pre-compensation at the transmitter or post-compensation at the

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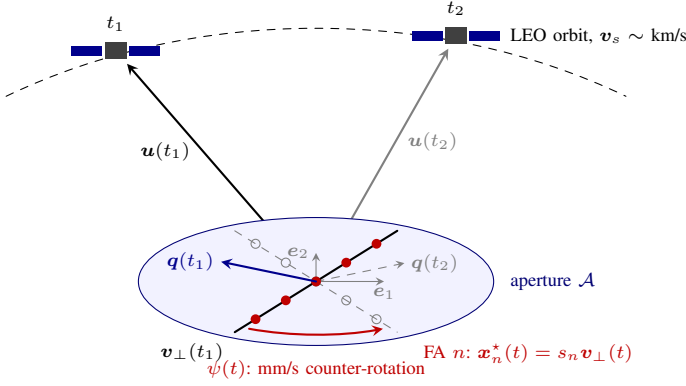


Fig. 1. Geometry of orbital channel stationarization: as the satellite moves from t_1 to t_2 , the projected LoS direction $\mathbf{q}(t)$ rotates in the aperture plane, and the N FAs, kept on the iso-phase line $\mathbf{v}_\perp(t) \perp \mathbf{q}(t)$, counter-rotate at mm/s speeds so that the array response is time invariant.

receiver. Mechanically compensating the several-km/s radial motion of a LEO satellite is infeasible, whereas compensating the angular evolution of the spatial channel requires only slow local FA motion, as quantified in Section V¹.

II. ORBITAL-ELECTROMAGNETIC CHANNEL MODEL

Consider a LEO satellite communicating with a ground terminal equipped with N independently reconfigurable FAs, as in Fig. 1. The scheme targets a compact user terminal or a small gateway antenna: at 20 GHz, $N = 8$ FAs with half-wavelength spacing fit in a disc of radius 30 mm, and the actuation power at mm/s speeds is negligible. The satellite orbit is described by the Keplerian elements $(a, e, i, \Omega, \omega, M_0)$, i.e., semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of periapsis, and initial mean anomaly [12]. At time t , the mean anomaly is $M(t) = M_0 + n_o(t - t_0)$ with $n_o = \sqrt{\mu/a^3}$, where μ is the Earth's gravitational parameter, and the eccentric anomaly $E(t)$ solves Kepler's equation $M(t) = E(t) - e \sin E(t)$. The satellite position in the perifocal frame is $\mathbf{r}_{\text{pf}}(t) = a[\cos E(t) - e, \sqrt{1 - e^2} \sin E(t), 0]^T$, its Earth-centered inertial (ECI) position is

$$\mathbf{r}_s(t) = \mathbf{R}_3(\Omega)\mathbf{R}_1(i)\mathbf{R}_3(\omega)\mathbf{r}_{\text{pf}}(t), \quad (1)$$

where $\mathbf{R}_1(\cdot)$ and $\mathbf{R}_3(\cdot)$ are elementary rotations about the first and third axes, and the velocity $\mathbf{v}_s(t)$ follows by differentiation. For a terminal with Earth-fixed position $\mathbf{r}_g^E$, Earth rotation gives

$$\mathbf{r}_g(t) = \mathbf{R}_3(\theta_0 + \omega_E t)\mathbf{r}_g^E, \quad \mathbf{v}_g(t) = \omega_E \times \mathbf{r}_g(t), \quad (2)$$

¹Notation: Bold lowercase and uppercase letters denote vectors and matrices; $(\cdot)^T$ and $(\cdot)^H$ denote transpose and conjugate transpose; $\|\cdot\|$ is the Euclidean norm; $\mathbb{Z}$ is the set of integers; $\mathbf{I}$ and $\mathbf{1}_N$ are the identity matrix and the all-ones vector; and $\text{wrap}(\cdot)$ maps its argument to $(-\pi, \pi]$ modulo 2π .

where θ_0 is the initial sidereal angle and $\omega_E = [0, 0, \omega_E]^T$ is the Earth's angular velocity. The satellite-to-terminal vector, range, and LoS direction are

$$\boldsymbol{\rho}(t) = \mathbf{r}_s(t) - \mathbf{r}_g(t), \quad \rho(t) = \|\boldsymbol{\rho}(t)\|, \quad \mathbf{u}(t) = \boldsymbol{\rho}(t)/\rho(t), \quad (3)$$

and the range rate and Doppler shift are $\dot{\rho}(t) = \mathbf{u}^T(t)[\mathbf{v}_s(t) - \mathbf{v}_g(t)]$ and $f_D(t) = -f_c \dot{\rho}(t)/c$, with f_c the carrier frequency and c the speed of light.

Let $\mathbf{x}_n(t) = [x_{n,1}(t), x_{n,2}(t)]^T \in \mathcal{A}$ denote the position of FA n within the local two-dimensional aperture $\mathcal{A}$, and let $\mathbf{B}_g(t) = [\mathbf{e}_1(t), \mathbf{e}_2(t)] \in \mathbb{R}^{3 \times 2}$ contain two orthonormal vectors spanning the aperture plane, expressed in the ECI frame as $\mathbf{B}_g(t) = \mathbf{R}_3(\theta_0 + \omega_E t)\mathbf{B}_g^E$ with $\mathbf{B}_g^E$ Earth fixed. The global position of FA n is $\mathbf{r}_n(t) = \mathbf{r}_g(t) + \mathbf{B}_g(t)\mathbf{x}_n(t)$, and its exact distance to the satellite is

$$d_n(t) = \|\boldsymbol{\rho}(t) - \mathbf{B}_g(t)\mathbf{x}_n(t)\|. \quad (4)$$

The LoS channel coefficient of FA n is $h_n(t) = \sqrt{\beta(t)} \exp(-j\kappa d_n(t))$, where $\beta(t)$ is the large-scale gain, $\kappa = 2\pi/\lambda$, and $\lambda = c/f_c$. Since the aperture is negligible compared with the range, the first-order expansion of (4) gives

$$d_n(t) \simeq \rho(t) - \mathbf{q}^T(t)\mathbf{x}_n(t), \quad \mathbf{q}(t) \triangleq \mathbf{B}_g^T(t)\mathbf{u}(t), \quad (5)$$

where $\mathbf{q}(t)$ is the projection of the LoS direction onto the aperture plane, with $\|\mathbf{q}(t)\| = \cos \theta_{\text{el}}(t) \leq 1$ for a horizontal aperture and elevation angle $\theta_{\text{el}}(t)$; the neglected term is bounded by $\kappa\|\mathbf{x}_n\|^2/(2\rho) (< 3 \times 10^{-7}$ rad in Section V). Therefore,

$$\mathbf{h}(t) \simeq \gamma(t)\mathbf{a}(t), \quad [\mathbf{a}(t)]_n = e^{j\kappa\mathbf{q}^T(t)\mathbf{x}_n(t)}, \quad (6)$$

where $\gamma(t) = \sqrt{\beta(t)}e^{-j\kappa\rho(t)}$ is common to all FAs and therefore does not affect array combining: its amplitude $\sqrt{\beta(t)}$ is left untouched, so that the link budget still improves toward culmination, and its phase is absorbed by standard carrier recovery together with the Doppler term of (3); no equalization to a worst-case gain is involved. The design objective is thus to keep only the normalized spatial channel $\mathbf{a}(t)$ invariant over the visibility interval $\mathcal{T} = [t_a, t_b]$, defined by the elevation exceeding a prescribed mask, so that the full array gain N is obtained at every instant on top of the time-varying path gain.

III. ORBITAL CHANNEL STATIONARIZATION

A. Channel-Invariance Condition

Let $\mathbf{a}_{\text{ref}} = [e^{j\phi_1}, \dots, e^{j\phi_N}]^T$ be the desired time-invariant spatial channel.

Proposition 1 (Orbital channel-invariance condition). *The LoS spatial channel satisfies $\mathbf{a}(t) = \mathbf{a}_{\text{ref}}$ for all $t \in \mathcal{T}$ if and only if every FA satisfies*

$$\mathbf{q}^T(t)\mathbf{x}_n(t) = c_n + \ell_n(t)\lambda, \quad c_n = \phi_n/\kappa, \quad \ell_n(t) \in \mathbb{Z}. \quad (7)$$

Proof. From (6), $[\mathbf{a}(t)]_n = e^{j\phi_n}$ holds if and only if $\kappa\mathbf{q}^T(t)\mathbf{x}_n(t) - \phi_n \in 2\pi\mathbb{Z}$, which is (7) after division by κ . $\square$

Condition (7) defines, at each time instant, an iso-phase line of admissible FA positions that evolves deterministically with

$\mathbf{q}(t)$: each FA only needs to move from one orbital iso-phase line to the next, without any optimization. Since $\mathbf{q}(t) \neq \mathbf{0}$ for $\theta_{\text{el}}(t) < 90^\circ$, we define the unit vector orthogonal to the projected LoS,

$$\mathbf{v}_\perp(t) = \frac{1}{\|\mathbf{q}(t)\|} [-q_2(t), q_1(t)]^\top, \quad \mathbf{q}^\top(t)\mathbf{v}_\perp(t) = 0, \quad (8)$$

which spans the direction of every iso-phase line.

B. Closed-Form Counter-Motion

For a continuous tracking branch, $\ell_n(t) = \ell_n$ is constant and we define $b_n = c_n + \ell_n \lambda$. Given the previous position $\mathbf{x}_{n,k-1}$ and the predicted projection $\mathbf{q}_k = \mathbf{q}(t_k)$, the minimum-displacement stationarizing position solves

$$\min_{\mathbf{x}} \|\mathbf{x} - \mathbf{x}_{n,k-1}\|^2 \quad \text{s.t.} \quad \mathbf{q}_k^\top \mathbf{x} = b_n. \quad (9)$$

Introducing the multiplier ν , the Lagrangian is $\mathcal{L} = \|\mathbf{x} - \mathbf{x}_{n,k-1}\|^2 + \nu(\mathbf{q}_k^\top \mathbf{x} - b_n)$, and stationarity $\nabla_{\mathbf{x}} \mathcal{L} = 2(\mathbf{x} - \mathbf{x}_{n,k-1}) + \nu \mathbf{q}_k = \mathbf{0}$ gives $\mathbf{x} = \mathbf{x}_{n,k-1} - (\nu/2)\mathbf{q}_k$, i.e., the displacement is parallel to $\mathbf{q}_k$. Substituting into the constraint yields $\nu/2 = (b_n - \mathbf{q}_k^\top \mathbf{x}_{n,k-1})/\|\mathbf{q}_k\|^2$, and hence the orthogonal projection onto the iso-phase line,

$$\mathbf{x}_{n,k}^* = \mathbf{x}_{n,k-1} + \frac{b_n - \mathbf{q}_k^\top \mathbf{x}_{n,k-1}}{\|\mathbf{q}_k\|^2} \mathbf{q}_k. \quad (10)$$

Since the objective of (9) is strictly convex and the constraint is affine, (10) is the unique minimizer, with displacement $|b_n - \mathbf{q}_k^\top \mathbf{x}_{n,k-1}|/\|\mathbf{q}_k\|$.

The continuous-time counterpart follows by differentiating $\mathbf{q}^\top(t)\mathbf{x}_n(t) = b_n$, which gives the velocity constraint

$$\dot{\mathbf{q}}^\top(t)\mathbf{x}_n(t) + \mathbf{q}^\top(t)\dot{\mathbf{x}}_n(t) = 0. \quad (11)$$

The minimum-norm velocity solves $\min_{\dot{\mathbf{x}}} \|\dot{\mathbf{x}}\|^2$ subject to (11), which has the structure of (9) with $\mathbf{x}_{n,k-1} \rightarrow \mathbf{0}$ and $b_n \rightarrow -\dot{\mathbf{q}}^\top(t)\mathbf{x}_n(t)$; by the same argument,

$$\dot{\mathbf{x}}_n^*(t) = -\frac{\dot{\mathbf{q}}^\top(t)\mathbf{x}_n(t)}{\|\mathbf{q}(t)\|^2} \mathbf{q}(t), \quad v_{n,\text{req}}(t) = \frac{|\dot{\mathbf{q}}^\top(t)\mathbf{x}_n(t)|}{\|\mathbf{q}(t)\|}. \quad (12)$$

Every velocity satisfying (11) can be written as $\dot{\mathbf{x}}_n = \dot{\mathbf{x}}_n^* + \alpha \mathbf{v}_\perp$ with $\alpha \in \mathbb{R}$ arbitrary: motion along the iso-phase line is free and leaves the channel unchanged, a null-space freedom exploited next.

Remark 1 (Aperture feasibility). *The iso-phase line in (7) lies at distance $|b_n|/\|\mathbf{q}(t)\|$ from the aperture center. Since $\|\mathbf{q}(t)\| = \cos \theta_{\text{el}}(t) \rightarrow 0$ as the satellite approaches zenith, any branch with $b_n \neq 0$ leaves a finite aperture at sufficiently high elevation; e.g., $|b_n| = \lambda/4$ already requires $\|\mathbf{x}_n\| \geq 1.5\lambda$ at 80° elevation. Hence $b_n = 0$ for all n , i.e., $\phi_n = 0$ and $\ell_n = 0$, is the only choice that is feasible within a fixed aperture over a complete pass, and it is adopted in the sequel.*

C. Phase-Neutral Configuration

With $\phi_n = 0$, $\forall n$, the reference channel is $\mathbf{a}_{\text{ref}} = \mathbf{1}_N$ and (7) reduces to $\mathbf{q}^\top(t)\mathbf{x}_n(t) = 0$, i.e., $\mathbf{x}_n(t) \in \text{span}\{\mathbf{v}_\perp(t)\}$. Every stationarizing trajectory is therefore of the form $\mathbf{x}_n(t) = s_n(t)\mathbf{v}_\perp(t)$ with $s_n : \mathcal{T} \rightarrow \mathbb{R}$. Writing $\mathbf{q}(t) =$

$\|\mathbf{q}(t)\|[\cos \psi(t), \sin \psi(t)]^\top$ with $\psi(t) = \text{atan2}(q_2(t), q_1(t))$ gives $\mathbf{v}_\perp(t) = [-\sin \psi(t), \cos \psi(t)]^\top$. The following result characterizes the optimal choice of the coordinates $s_n(t)$.

Proposition 2 (Optimality of the phase-neutral configuration). *Let the FAs be confined to a circular aperture of radius R with pairwise spacing $\|\mathbf{x}_n - \mathbf{x}_m\| \geq d_{\min}$, $n \neq m$. Among all stationarizing trajectories $\mathbf{x}_n(t) = s_n(t)\mathbf{v}_\perp(t)$: (i) feasibility requires $R \geq R_{\min} \triangleq (N-1)d_{\min}/2$, with equality if and only if the coordinates are equispaced by $d_{\min}$ and centered, i.e., up to relabeling,*

$$\mathbf{x}_n^*(t) = s_n \mathbf{v}_\perp(t), \quad s_n = \left(n - \frac{N+1}{2}\right) d_{\min}; \quad (13)$$

(ii) for every n and t , $\|\dot{\mathbf{x}}_n(t)\| \geq |s_n(t)|\dot{\psi}(t)$, with equality if and only if $\dot{s}_n(t) = 0$. Hence (13) minimizes both the aperture radius and the instantaneous speed of every FA.

Proof. (i) At any t , the N coordinates $s_n(t)$ lie on a line with pairwise distance at least $d_{\min}$, so that $\max_n |s_n(t)| \geq (N-1)d_{\min}/2$, with equality if and only if they are equispaced by $d_{\min}$ and symmetric about the origin. (ii) Differentiating $\mathbf{v}_\perp$ gives $\dot{\mathbf{v}}_\perp = -\dot{\psi}[\cos \psi, \sin \psi]^\top = -\dot{\psi} \mathbf{q}/\|\mathbf{q}\|$, which is orthogonal to $\mathbf{v}_\perp$. Therefore $\dot{\mathbf{x}}_n = \dot{s}_n \mathbf{v}_\perp - s_n \dot{\psi} \mathbf{q}/\|\mathbf{q}\|$ and, by orthogonality, $\|\dot{\mathbf{x}}_n\|^2 = \dot{s}_n^2 + s_n^2 \dot{\psi}^2 \geq s_n^2 \dot{\psi}^2$. $\square$

Configuration (13) places all FAs on the instantaneous iso-phase line of the incoming wavefront; the satellite motion rotates this line and the FA geometry counter-rotates accordingly (Fig. 1), so that $\mathbf{a}(t) = \mathbf{1}_N$ for all $t \in \mathcal{T}$. Its velocity $\dot{\mathbf{x}}_n^* = -s_n \dot{\psi} \mathbf{q}/\|\mathbf{q}\|$ is parallel to $\mathbf{q}(t)$, consistent with (12), and the adjacent spacing $|s_n - s_m|$ equals $d_{\min}$ at all times. Like a gimbal or an analog phased array, the configuration serves one satellite at a time; multi-satellite operation, as with a fully digital array, requires one aperture per satellite or digital combining on top of the FA motion. Differentiating $\mathbf{q} = \|\mathbf{q}\|[\cos \psi, \sin \psi]^\top$ gives $\dot{\mathbf{q}} = (d\|\mathbf{q}\|/dt)[\cos \psi, \sin \psi]^\top + \|\mathbf{q}\|\dot{\psi} \mathbf{v}_\perp$, so that $q_1 \dot{q}_2 - q_2 \dot{q}_1 = \|\mathbf{q}\|^2 \dot{\psi}$. Hence, the angular rate of the projected LoS and the maximum actuation speed required by the array are

$$\dot{\psi}(t) = \frac{q_1(t)\dot{q}_2(t) - q_2(t)\dot{q}_1(t)}{\|\mathbf{q}(t)\|^2}, \quad v_{\text{req,max}} = R_{\min} \max_{t \in \mathcal{T}} |\dot{\psi}(t)|. \quad (14)$$

The angular rate can be bounded directly in terms of the orbit. From (5), $\dot{\mathbf{q}} = \dot{\mathbf{B}}_g^\top \mathbf{u} + \mathbf{B}_g^\top \dot{\mathbf{u}}$, where $\dot{\mathbf{u}} = (\mathbf{I} - \mathbf{u}\mathbf{u}^\top)(\mathbf{v}_s - \mathbf{v}_g)/\rho$ is the derivative of the unit LoS vector and $\dot{\mathbf{B}}_g = [\boldsymbol{\omega}_E \times \mathbf{e}_1, \boldsymbol{\omega}_E \times \mathbf{e}_2]$, so that $\|\mathbf{B}_g^\top \dot{\mathbf{u}}\| \leq \|\mathbf{v}_s - \mathbf{v}_g\|/\rho$ and $\|\dot{\mathbf{B}}_g^\top \mathbf{u}\| = \|\mathbf{B}_g^\top (\boldsymbol{\omega}_E \times \mathbf{u})\| \leq \omega_E$. Since $|\dot{\psi}| = |\mathbf{v}_\perp^\top \dot{\mathbf{q}}|/\|\mathbf{q}\| \leq \|\dot{\mathbf{q}}\|/\|\mathbf{q}\|$ and $\|\mathbf{q}\| = \cos \theta_{\text{el}}$, (14) yields

$$v_{\text{req,max}} \leq R_{\min} \frac{v_{\text{rel,max}}/\rho_{\min} + \omega_E}{\cos \theta_{\text{el,max}}}, \quad (15)$$

where $v_{\text{rel,max}}$, $\rho_{\min}$, and $\theta_{\text{el,max}}$ are the maximum relative speed, minimum range, and maximum elevation of the pass, with $v_{\text{rel,max}} \leq \sqrt{\mu/a} + \omega_E R_E$ for a circular orbit and Earth radius R_E . Equation (15) makes explicit that the FA speed is governed by the angular rate v_{rel}/ρ of the satellite as seen from the terminal (about 0.013 rad/s at 600 km), scaled by the aperture radius, and not by the several-km/s

translational velocity of the satellite; this is what makes spatial channel stationarization feasible through slow local motion. Note that (13) preserves the spacing exactly, whereas repeated application of (10) to a rotating line shrinks $\|\mathbf{x}_n\|$ by $\cos(\Delta\psi)$ per step.

Remark 2 (Exactness beyond the far-field model). *Expanding (4) as $d_n = \rho\sqrt{1 - 2\mathbf{q}^\top \mathbf{x}_n/\rho + \|\mathbf{x}_n\|^2/\rho^2} = \rho - \mathbf{q}^\top \mathbf{x}_n + [\|\mathbf{x}_n\|^2 - (\mathbf{q}^\top \mathbf{x}_n)^2]/(2\rho) + O(R^3/\rho^2)$ identifies the term neglected in (5) as the Fresnel correction. Under (13), $\mathbf{q}^\top \mathbf{x}_n^* = 0$, so the exact spatial phase equals $-\kappa s_n^2/(2\rho(t))$ up to $O(\kappa R^3/\rho^2)$. It is bounded by $\kappa R_{\min}^2/(2\rho_{\min})$, i.e., 2.4×10^{-7} rad in Section V, and is itself ephemeris-known.*

Remark 3 (Interpretation and zenith behavior). *Configuration (13) is a collinear array of fixed spacing rotating in the aperture plane by $\psi(t)$: it realizes, by per-element FA motion, the rotation a turntable would provide, but without a rotary joint, on discrete ports if needed (Section IV), and with a fixed, phase-shifter-free combiner; since the array remains a broadside uniform linear array, element patterns and mutual coupling are also time invariant. The rate $\dot{\psi}(t)$ in (14) is unbounded for passes through zenith, where $\|\mathbf{q}(t)\| \rightarrow 0$; there, however, the channel becomes insensitive to the FA positions, since a positional lag $\Delta\mathbf{x}_n$ produces a phase error of at most $\kappa\|\mathbf{q}(t)\|\|\Delta\mathbf{x}_n\|$. A rate-limited tracker,*

$$\mathbf{x}_{n,k} = \mathbf{x}_{n,k-1} + \min\left\{1, \frac{v_{\max} T_s}{\|\mathbf{x}_{n,k}^* - \mathbf{x}_{n,k-1}\|}\right\} (\mathbf{x}_{n,k}^* - \mathbf{x}_{n,k-1}), \quad (16)$$

with T_s the update interval and $v_{\max}$ the actuation limit, therefore incurs only a small loss around culmination (Section V).

IV. PRACTICAL IMPLEMENTATION

1) *Discrete FA ports:* A practical FAS may offer a finite set of ports $\mathcal{P} = \{\mathbf{p}_1, \dots, \mathbf{p}_Q\}$. At time t_k , the port of FA n is selected sequentially over $n = 1, \dots, N$ as

$$\mathbf{p}_{n,k}^* = \arg \min_{\mathbf{p} \in \mathcal{P}_{n,k}} (\kappa \mathbf{q}_k^\top \mathbf{p} - \phi_n)^2 + \eta \|\mathbf{p} - \mathbf{x}_{n,k}^*\|^2, \quad (17)$$

where $\mathcal{P}_{n,k}$ contains the ports that lie in the aperture, are at least $d_{\min}$ away from the ports already assigned to FAs $1, \dots, n-1$, and are reachable from $\mathbf{p}_{n,k-1}^*$ within $v_{\max} T_s$. The first term minimizes the residual channel-phase error, while the second, weighted by $\eta \geq 0$, keeps the selected port close to the nominal position (13) and thus prevents drift along the iso-phase line. Since $\mathbf{q}_k$ follows from the ephemeris, the complete port schedule can be precomputed for the pass.

2) *Finite actuation speed:* Exact stationarization is feasible whenever $v_{\text{req},\max} \leq v_{\max}$ in (14); otherwise the rate-limited tracker (16) applies.

3) *Pointing and positioning errors:* Let $\mathbf{q}(t) = \hat{\mathbf{q}}(t) + \Delta\mathbf{q}(t)$ with $\|\Delta\mathbf{q}(t)\| \leq \epsilon_q$ denote the true and predicted projections, where ϵ_q is the pointing error induced by ephemeris inaccuracy, equal to the angular error in radians to first order, and $\tilde{\mathbf{x}}_n(t) = \mathbf{x}_n^*(t) + \Delta\mathbf{x}_n(t)$ with $\|\Delta\mathbf{x}_n(t)\| \leq \epsilon_x$ the implemented position, where $\kappa \hat{\mathbf{q}}^\top(t) \mathbf{x}_n^*(t) = \phi_n + 2\pi\ell_n$. The residual phase error is $\delta_n(t) = \kappa[\Delta\mathbf{q}^\top \mathbf{x}_n^* + \hat{\mathbf{q}}^\top \Delta\mathbf{x}_n + \Delta\mathbf{q}^\top \Delta\mathbf{x}_n]$ and, since $\|\mathbf{x}_n^*(t)\| \leq R$ and $\|\hat{\mathbf{q}}(t)\| \leq 1$, the Cauchy-Schwarz inequality gives $|\delta_n(t)| \leq \Delta_{\max} \triangleq \kappa[R\epsilon_q + (1 + \epsilon_q)\epsilon_x]$.

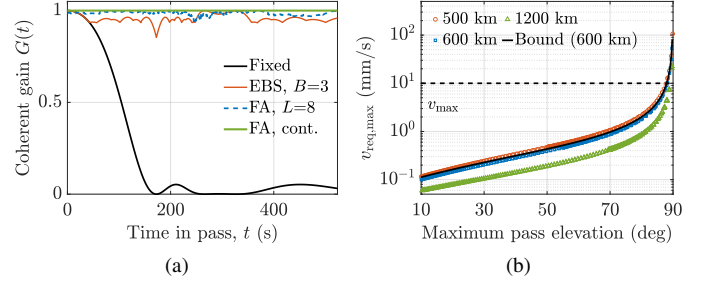


Fig. 2. (a) Normalized coherent gain over a 600-km pass with 60° maximum elevation for the fixed array, EBS with $B = 3$ bits, the proposed continuous counter-motion, and its discrete-port version with $L = 8$ ports per wavelength ($f_c = 20$ GHz, $N = 8$). (b) Maximum required FA speed (14) versus maximum pass elevation for 500, 600, and 1200 km orbits, the closed-form bound (15) for 600 km (solid line), and the actuation limit $v_{\max} = 10$ mm/s (dashed line).

Defining the normalized stationarization error as $\varepsilon_h(t) = \frac{1}{N} \|\tilde{\mathbf{a}}(t) - \mathbf{a}_{\text{ref}}\|^2$ and using $|e^{jz} - 1|^2 = 4 \sin^2(z/2) \leq z^2$, we obtain

$$\varepsilon_h(t) = \frac{1}{N} \sum_{n=1}^N |e^{j\delta_n(t)} - 1|^2 \leq \Delta_{\max}^2, \quad (18)$$

which is informative for $\Delta_{\max} < 2$ (trivially $\varepsilon_h \leq 4$). For the parameters of Section V ($\kappa = 419$ rad/m, $R = R_{\min} = 26.25$ mm, $\kappa R \simeq 11$), a pointing error $\epsilon_q = 10^{-2}$ (0.6° , far coarser than typical ephemeris accuracy) contributes 0.11 rad, whereas $|\delta_n| \leq 0.1$ rad requires $\epsilon_x \leq 0.24$ mm: sub-millimeter positioning at 20 GHz is the binding requirement.

V. NUMERICAL RESULTS

We consider circular orbits at 600 km altitude (500 and 1200 km in Fig. 2(b)) with inclination 53° , a ground terminal at 49.6°N , 6.2°E with a horizontal aperture, Earth rotation as in (2), and a 10° elevation mask. The carrier frequency is $f_c = 20$ GHz ($\lambda \simeq 15$ mm), and the terminal has $N = 8$ FAs with $d_{\min} = \lambda/2$, so that $R_{\min} = 7\lambda/4 \simeq 26.25$ mm by Proposition 2, within a circular aperture of radius $R = 2\lambda$. Further, $T_s = T_u = 1$ s, $v_{\max} = 10$ mm/s, and $\eta = 10^3$ rad²/m². Pass geometries are generated by sweeping Ω over $[0^\circ, 360^\circ)$ and retaining the first complete pass of each orbit; all results use the exact distance (4).

The metric is the normalized coherent gain $G(t) = |\mathbf{w}^\top \mathbf{a}(t)|^2/N^2$ of a combiner $\mathbf{w}$. Four schemes are compared: (i) a *fixed array*, i.e., configuration (13) frozen at acquisition $t = t_a$ and never updated; (ii) *ephemeris-driven electronic beam steering* (EBS) on the same fixed array, with $\mathbf{w}_n(t_k) = \exp\{jQ_B(\kappa \mathbf{q}_k^\top \mathbf{x}_n)\}$ refreshed every T_u , where $Q_B(\cdot)$ is a B -bit phase quantizer, which uses the same ephemeris information and no moving parts but requires N phase shifters ($T_u = T_s = 1$ s keeps the inter-update phase drift at the outer element, $\kappa R_{\min} \|\mathbf{q}\| \|\psi\| T_u \lesssim 0.25$ rad, below the 3-bit step $2\pi/8$); (iii) the proposed *continuous* counter-motion (13) with the rate limiter (16); and (iv) its *discrete-port* implementation (17) on a square port grid of pitch λ/L . Schemes (i), (iii), and (iv) use the fixed combiner $\mathbf{w} = \mathbf{1}_N$.

Fig. 2(a) shows $G(t)$ over a representative 600-km pass with 60.0° maximum elevation, lasting 524 s, during which the

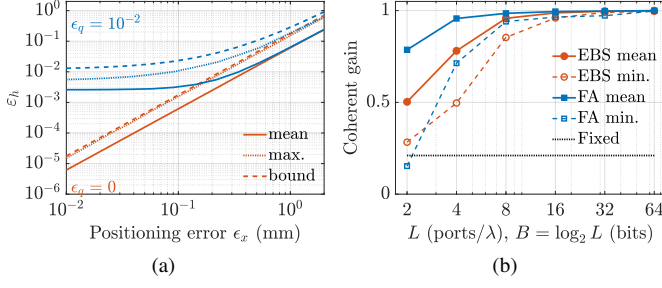


Fig. 3. (a) Stationarization error ϵ_h versus FA positioning error ϵ_x for $\epsilon_q \in \{0, 10^{-2}\}$: Monte Carlo mean (solid) and maximum (dotted) against the analytical bound (18) (dashed). (b) Time-averaged (solid) and minimum (dashed) coherent gain over the pass of Fig. 2(a) versus hardware resolution: EBS with B -bit phase shifters and the proposed discrete-port FA scheme with $L = 2^B$ ports per wavelength; the dotted line is the mean gain of the fixed array.

projected LoS direction $\psi(t)$ sweeps 162° . The fixed array loses coherence rapidly: its gain falls below 0.5 after 105 s and below 0.1 after 146 s, remains below 0.1 for 72% of the pass, and averages 0.21. EBS with $B = 3$ bits recovers most of the loss (mean 0.958, minimum 0.854) but exhibits quantization ripple and 1-s staleness. The proposed continuous counter-motion yields $G(t) = 1$ to numerical precision over the entire pass with $w = \mathbf{1}_N$; the largest deviation between the exact-distance phase and the far-field law (5) is 2×10^{-7} rad, and the rate limiter is never active. The discrete-port implementation with $L = 8$ (pitch 1.9 mm) attains a mean gain of 0.985 and a minimum of 0.940 with the same fixed combiner, thus outperforming EBS of equal resolution ($2^B = L$), because the spatial phase step $2\pi\|q\|/L$ is scaled by $\|q\| \leq 1$ and the two-dimensional port grid offers more phase-equivalent choices than a scalar quantizer.

Fig. 2(b) reports $v_{\text{req,max}}$ for every pass geometry versus its maximum elevation. At 600 km, the required speed is 0.21, 0.56, and 1.8 mm/s for passes culminating at 30° , 60° , and 80° , respectively, and it scales inversely with altitude (0.67 and 0.27 mm/s at 500 and 1200 km for 60°). The closed-form bound (15), evaluated with $\rho_{\min}$ given by the maximum elevation, follows the simulated maxima closely and overestimates them by only 11–13% for every pass geometry. The speed grows without bound only for near-zenith passes, in agreement with (14), and exceeds $v_{\max} = 10$ mm/s only for maximum elevations above 88.2° (600 km). For a pass culminating at 89.1° , where $v_{\text{req,max}} = 20$ mm/s, the rate limiter (16) is active for only 5 s around culmination and the minimum gain is 0.996, confirming Remark 3. Hence, sub-mm/s to few-mm/s actuation suffices for virtually all passes.

Fig. 3(a) evaluates the robustness of the stationarized channel along the pass of Fig. 2(a) by perturbing the predicted projection and the implemented FA positions with errors of norm ϵ_q and ϵ_x and uniformly random direction (200 trials per time sample). With perfect ephemeris ($\epsilon_q = 0$), $\epsilon_x = 0.1$ mm produces a mean $\epsilon_h = 6.4 \times 10^{-4}$ (maximum 1.6×10^{-3}) against a bound of 1.8×10^{-3} , while $\epsilon_x = 1$ mm yields a mean of 0.064 (a loss of about 0.3 dB) and a maximum of 0.16 against a bound of 0.18: (18) is within a factor of 1.2 of the worst case and scales as ϵ_x^2 . A coarse projection error

$\epsilon_q = 10^{-2}$ adds a floor of 3.2×10^{-3} that dominates for $\epsilon_x \lesssim 0.2$ mm, where the bound remains within a factor of 2.3 of the observed maximum. The mean error reaches 0.1 only for $\epsilon_x \simeq 1.3$ mm, and the bound guarantees $\epsilon_h \leq 0.1$ for $\epsilon_x \leq 0.74$ mm.

Fig. 3(b) compares EBS and the discrete-port FA scheme versus hardware resolution. At the coarsest resolution ($B = 1$, $L = 2$), the FA scheme attains a mean gain of 0.79 against 0.50 for EBS; at $B = 2$ ($L = 4$) the values are 0.96 and 0.78; and at $B = 4$ ($L = 16$, pitch 0.94 mm) both exceed 0.98, with the FA scheme at 0.995. For $L \geq 32$ both are within 0.4% of the ideal gain, and the minimum gains of the two schemes are comparable for $L \geq 16$. Hence, a port pitch of about $\lambda/16$ suffices to replace 4-bit phase shifters by a fixed in-phase combiner, whereas the fixed array averages 0.21 regardless of resolution.

VI. CONCLUSION

This letter introduced ephemeris-driven orbital channel stationarization for FA-assisted LEO communications, yielding closed-form counter-motion laws that keep the normalized LoS spatial channel time invariant. Practical effects including discrete ports, finite actuation speed, and ephemeris/positioning errors were also characterized. At 20 GHz, sub-mm/s to few-mm/s FA motion enables phase-shifter-free combining, while a port pitch of $\lambda/16$ achieves performance comparable to 4-bit electronic beam steering. Multipath channels and multi-satellite operation are left for future work.

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