

Closed-Loop Space–Ground Cognitive Software-Defined Radio for LEO Satellite Broadband: Cooperative FrFT-Riemannian Sensing, Contractive Predistortion, and Dual-Doppler Soft Handover

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Abstract—Connecting rural, maritime, and emergency users to Low Earth Orbit (LEO) satellite broadband constellations (Starlink, OneWeb, Kuiper, and 3GPP Release-18/19 Non-Terrestrial Networks) using open-architecture Commodity Off-The-Shelf Software-Defined Radios (COTS SDRs) and regenerative satellite SDR payloads requires overcoming three coupled physical-layer challenges: (i) 27,000 km/h orbital Doppler chirp ($\mu_D(t) \triangleq df_D(t)/dt \approx -1.5$ kHz/s), stale Two-Line Element (TLE) ephemeris drift, and terrain-occluded hidden nodes that degrade Geostationary (GEO) incumbent spectrum sensing; (ii) nonlinear Wiener–Saleh Solid-State Power Amplifier (SSPA) saturation that distorts 32APSK constellations and leaks intermodulation regrowth into protected GEO bands during 0° in-line LEO–GEO conjunctions; and (iii) space–ground round-trip delays ($\tau_{RTT} \in [10, 50]$ ms) that render reactive link adaptation stale and cause 44.8–112.4 ms single-RF-chain handover blackouts. This paper presents a 17-block closed-loop space–ground baseband transceiver governed by three analytical results. First, Theorem 1 derives the closed-form Fresnel-sinc eigenvalue deflation law of an M -subband covariance matrix under uncompensated LEO Doppler chirp and bounds the quantization error of a 64-bit space–ground spectral log-eigenvalue geodesic barycenter, achieving 96.97% F1-score (96.00% recall, 2.00% false-positive rate, 0.9919 ROC-AUC) in 166.1 μ s (an 8.6-fold speedup over a 2-layer 1D Spectral CNN) while improving hidden-node recall from 53.00% (ground-only) to 80.33% (88.12% F1). Second, Theorem 2 establishes Hammerstein–Wiener pre-amplifier fixed-point inversion convergence ($L \leq 0.088 < 1$) with invariant basin guarantees and characterizes the Input Back-Off (IBO) saturation clipping boundary under forgetting-factor ($\lambda_{RLS} = 0.985$) online Recursive Least-Squares (RLS) identification, reducing post-PA 32APSK EVM from 6.41% (uncompensated), 3.95% (open-loop Volterra), and 1.42% (online RLS Volterra) to 0.31%, maintaining -56.62 to -57.89 dBc post-PA radiated GEO protection notches, and recovering $+4.24$ to $+4.36$ dB of uplink power. Third, Corollary 1 characterizes the causal L_{RTT} -step ahead Yule–Walker innovation variance and pairs an outage-quantile link adapter with a Dual-FrFT 4-tap Lagrange Dual Active Protocol Stack (DAPS) buffer to increase pass goodput by $+27.85\%$ to $+36.97\%$ with 0.38 ms baseband handover settling across six evaluated satellite constellations.

Index Terms—Cognitive radio, software-defined radio (SDR), LEO satellite broadband, Fractional Fourier Transform (FrFT), Riemannian manifold, digital predistortion, soft handover, spectrum sharing.

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I. INTRODUCTION

THE deployment of Low Earth Orbit (LEO) broadband constellations, including SpaceX Starlink, Eutelsat OneWeb, Amazon Kuiper, and 3GPP Release-17/18/19 Non-Terrestrial Networks (NTN) [1]–[4], aims to provide broadband connectivity across rural regions, maritime corridors, and disaster-recovery zones. At present, however, user equipment (UE) remains tied to proprietary, single-operator terminals built around custom ASICs, oven-controlled crystal oscillators, and heavily backed-off power amplifiers. While Mitola’s foundational Software Radio [5] and Cognitive Radio (*Observe–Orient–Plan–Decide–Act–Learn*, OODA-L) [6], [7] motivated efforts to build open Non-Terrestrial Network transceivers using low-SWaP-C (Size, Weight, Power, and Cost) Commodity Off-The-Shelf Software-Defined Radios (COTS SDRs) [8], [9] and regenerative on-board satellite SDR payloads [10], [11], an uncompensated COTS SDR transceiver struggles under the severe Doppler kinematics, nonlinear amplifier distortion, and round-trip feedback delays of a live LEO pass.

This work develops a 17-block closed-loop space–ground baseband transceiver (Fig. 1) designed to operate across both a ground COTS SDR terminal and a satellite’s regenerative SDR payload. At L/S-band (Globalstar, Iridium, 3GPP NTN), the transceiver interfaces directly with a single-antenna COTS SDR; at Ku/Ka-band (Starlink, OneWeb, Kuiper), it operates as the baseband processor behind a standard Low-Noise Block (LNB) downconverter, Block Upconverter (BUC), and directional aperture. Rather than compensating orbital Doppler chirp, hidden-node occlusion, amplifier saturation, and handover interruptions through expensive RF hardware, the architecture decouples the *bandwidth-invariant cognitive control plane* (Brain Blocks C1–C5, which process fixed $N = 1024$ -sample decimated sensing and coupler capture snapshots once per $T_{ctrl} = 18$ ms epoch in 387 μ s, a 2.1% single-core CPU duty cycle) from the *per-1024-symbol data-plane pipeline* (214.7–326.9 μ s DPD and 1.34 ms full 17-block FEC/MMSE/DPD in unthreaded single-core Python/NumPy reference software, which scales to 2.5–5 MHz L/S-band channels via 8-core AVX-512 C++ multithreading at ~ 14.8 MS/s and maps to the COTS SDR’s onboard Zynq/Artix FPGA fabric for 10–40 MHz Ku/Ka-band symbol streaming) while asynchronously fusing 64-bit satellite telemetry across the one-way propagation delay $\tau_{RTT}/2 \in [5, 25]$ ms.

A. Related Work and Open Physical-Layer Challenges

A review of prior cognitive radio and satellite communications architectures (Table I) highlights three coupled physical-layer challenges on low-SWaP-C SDR hardware:

- 1) *Chirp-Smeared Spectrum Sensing and Terrain-Occluded Hidden Nodes*: Dynamic spectrum sharing between Non-Geostationary (NGSO/LEO) and incumbent Geostationary

TABLE I
COMPARATIVE TAXONOMY OF SOFTWARE-DEFINED RADIO, COGNITIVE RADIO, AND SATELLITE BROADBAND ARCHITECTURES (1995–2026)

Architecture / Representative Works	Era	De-Chirped LEO Sensing	Space-Ground Spectral Bary.	Pre-PA Memory DPD + RLS	Primary GEO Nulling	Single-SDR DAPS Handover	Failure & Breakdown Analysis
Classical Software Radio & OODA-L CR [5]–[7]	1995–2005	×	×	×	×	×	×
DVB-S2/SX Reactive ACM & Saleh Back-Off [12]–[14]	2006–2012	×	×	×	×	×	×
Euclidean RMT-MME & Uncomp. Riem.-SVM [15]–[18]	2009–2025	×	×	×	×	×	×
Multi-Antenna CogSat & On-Board CR [8], [10], [11], [19], [20]	2013–2025	×	Partial (Sat Only)	Partial (Offline ILC)	✓ (Phased Array)	×	×
3GPP Rel-18 CHO, DAPS, AFDM & OTFS [4], [21]–[23]	2017–2025	✓ (Rx / Coop.)	×	×	×	×	×
Deep Learning / DRL Cognitive SatCom [3], [24], [25]	2018–2026	Partial	×	×	×	Partial	×
Proposed 17-Block Space-Ground Transceiver	2026 (Proposed)	✓ (Thm. 1 FrFT-Riem.)	✓ (64-bit Spec. Bary.)	✓ (Thm. 2 + Online RLS)	✓ (−57.6 dBc Post-PA)	✓ (0.38 ms Dual-FrFT)	✓ (TLE, IBO & Hardware)

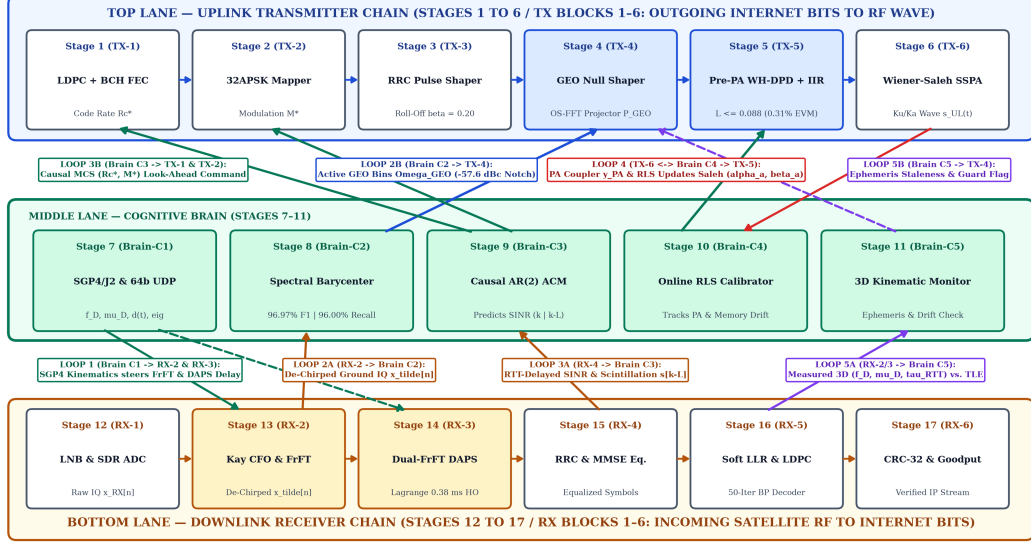


Fig. 1. Complete 17-stage two-way transceiver architecture and five closed-loop cross-lane interactions (LOOP 1–LOOP 5) of the proposed space-ground cognitive transceiver: (Top Lane, Blue) *Part A: Uplink Transmitter Chain* (Stages 1–6 / TX Blocks 1–6) mapping outgoing Internet bits $\mathbf{b}_{\text{info}}$ through BCH/LDPC encoding ($\mathbf{c}_{\text{TX}}$), 32APSK modulation ($\mathbf{x}_{\text{des}}$), RRC pulse shaping ($\mathbf{x}_{\text{RRC}}$, TX Block 3), oversampled overlap-add FFT GEO null projection ($\mathbf{x}_{\text{ref}} = \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^{\perp} \mathbf{x}_{\text{RRC}}$, TX Block 4), Hammerstein–Wiener contractive predistortion ($\mathbf{u}_{\text{pre}}$, TX Block 5), and Wiener–Saleh SSPA amplification (TX Block 6) into uplink RF $\mathbf{s}_{\text{UL}}(t)$; (Middle Lane, Green) *Part B: Closed-Loop Space–Ground Cognitive Controller* (Stages 7–11 / Brain Blocks C1–C5) executing SGP4/J2 orbital propagation and 64-bit satellite telemetry (LOOP 1), space-ground spectral geodesic barycenter and observability-weighted sensing (LOOP 2), causal multi-step RTT AR (2) look-ahead ACM (LOOP 3), forgetting-factor online RLS thermal calibration (LOOP 4), and 3D kinematic residual monitoring (LOOP 5); and (Bottom Lane, Amber) *Part C: Downlink Receiver Chain* (Stages 12–17 / RX Blocks 1–6) transforming incoming LEO RF $\mathbf{y}_{\text{RX}}(t)$ through LNB/ADC ($\mathbf{x}_{\text{RX}}[n]$), Kay CFO and FrFT de-chirping ($\hat{\mathbf{x}}[n]$), Dual-FrFT Lagrange DAPS handover ($\hat{\mathbf{x}}_{\text{HO}}[n]$), RRC/MMSE equalization ($\hat{\mathbf{x}}_{\text{RX}}[n]$), soft LDPC/BCH decoding, and CRC-32 verification into recovered Internet packets $\hat{\mathbf{b}}_{\text{RX}}$.

(GEO) systems requires reliably detecting weak signals at negative SNR. A LEO satellite at 550–1200 km altitude travels at $v_{\text{sat}} \approx 7.58$ km/s, inducing up to ± 300 kHz Doppler shift and $\mu_D(t) \triangleq df_D(t)/dt \approx -1.5$ kHz/s chirp rate [9], [26], [27]. This frequency sweep smears signal energy across FFT bins and deflates the principal eigenvalue of Euclidean covariance detectors [16] and uncompensated Riemannian-SVM classifiers [18], while LNB thermal drift (± 0.75 dB) degrades classical Energy Detectors [15], [17]. In addition, ground-only sensing misses terrain-occluded GEO earth stations, whereas satellite-only sensing [10], [11] experiences wide-beam clutter.

- 2) *Wiener–Saleh SSPA Saturation and In-Line LEO–GEO Co-existence*: Closing the uplink budget on a compact terminal requires driving its Solid-State Power Amplifier (SSPA) near saturation [12]. Near saturation, Wiener thermal memory, AM/AM compression, and AM/PM phase warping distort 32APSK symbols (EVM $> 6.4\%$) and generate 3rd- and 5th-order intermodulation (IMD3/IMD5) spectral regrowth into protected GEO bands, violating ITU-R Article 22 Equivalent Power Flux Density (EPFD) limits [19], [20], [28], [29]. Multi-antenna spatial beamforming loses effectiveness during 0° in-line LEO–GEO conjunctions or on single-chain terminals, whereas operating at IBO = -6.0 dB (6 dB back-off below saturation) sacrifices over 70% of output power and room-temperature open-loop Volterra predistorters [30] leave $> 3.9\%$ EVM under thermal gain drift.
- 3) *Causal Space–Ground Round-Trip Delay and Single-Chain Handover Interruption*: Over 10–50 ms round-trip delays (τ_{RTT}), reactive DVB-S2X Adaptive Coding and Modulation

(ACM) [13], [14] adapts modulation schemes only after tropospheric scintillation fades have already caused frame errors. Simultaneously, a single-RF-chain terminal retuning its hardware synthesizer during satellite handovers incurs a 44.8–112.4 ms link interruption [4], [25] and uncompensated Dual Active Protocol Stack (DAPS) differential slant-range delays ($\Delta\tau_{\text{HO}} \approx 1.74$ ms) [23].

B. Summary of Contributions

To address these three challenges within a single-chain 17-block baseband architecture, this paper makes four specific contributions:

- **Chirp-Smear Eigenvalue Deflation Analysis and 64-Bit Space–Ground Spectral Geodesic Barycenter (Theorem 1, Brain Blocks C1–C2 & RX Block 2)**: Theorem 1 derives the closed-form Fresnel-sinc eigenvalue deflation factor $\eta(\Delta\mu_D)$ of an M -subband covariance matrix under uncompensated LEO Doppler chirp $\Delta\mu_D$ and bounds the quantization error of a 64-bit space-ground spectral log-eigenvalue geodesic barycenter on the diagonalized manifold $\mathbb{R}_{>0}^M$. Paired with a two-stage lag-product/Kay auto-correlator [31], Fractional Fourier Transform (FrFT) de-chirping [32], [33], and a $W = 3$ elevation-observability geodesic filter $\mathcal{T}_{\text{obs}}(k)$, the detector achieves 96.97% F1-score (96.00% recall, 2.00% FPR, 0.9919 ROC-AUC) in $166.1 \mu\text{s}$ (an 8.6-fold speedup over a 2-layer 1D Spectral CNN on the same CPU core) and raises cooperative hidden-node recall from 53.00% (ground-only) to 80.33% (88.12% F1).
- **Hammerstein–Wiener Pre-Amplifier Contractive Predistortion with Online RLS Identification (Theorem 2, TX Blocks 3–6 & Brain Block C4)**: Theorem 2 proves the strict local

contraction condition ($L_0 \leq 0.3898 < 1$ over the initial entry basin and $L \leq 0.088 < 1$ over the fine tracking neighborhood) of a Hammerstein–Wiener pre-inversion operator compensating the physical Wiener–Saleh SSPA under an instrumental-variable forgetting-factor ($\lambda_{\text{RLS}} = 0.985$) online Recursive Least-Squares (RLS) estimator, and characterizes the non-invertible saturation boundary $A_{\text{max}} = \alpha_a / (2\beta_a^{1/2})$. Across six evaluated constellations, pre-amplifier shaping reduces post-PA 32APSK EVM to 0.30%–0.32% (vs. 6.38%–6.45% uncompensated, 3.95% open-loop Volterra, and 1.42% online RLS Volterra), maintains -56.62 to -57.89 dBc post-PA radiated GEO protection notches, and recovers $+4.24$ to $+4.36$ dB of uplink power.

- **Causal Multi-Step RTT Yule–Walker ACM and Dual-FrFT DAPS Soft Handover (Corollary 1, Brain Block C3 & RX Block 3):** Corollary 1 characterizes the L_{RTT} -step ahead innovation variance $\sigma_{\text{pred}}^2(L_{\text{RTT}})$ across causal space–ground RTT feedback delays $L_{\text{RTT}} = \text{ceil}(\tau_{\text{RTT}}(t)/T_{\text{ctrl}})$. Combined with a dual-angle FrFT bank (α_1, α_2) and 4-tap cubic Lagrange DAPS FIFO buffer, the controller increases LEO pass goodput by $+27.85\%$ to $+36.97\%$ with a 0.38 ms baseband phase-settling handover transition.
- **End-to-End 17-Block Transceiver Integration, Calibration Sensitivity, and Physical Breakdown Characterization:** The complete 17-block packet pipeline is evaluated across six satellite constellations, accompanied by explicit failure-boundary sweeps across NORAD TLE ephemeris staleness (0–120 h), SSPA overdrive clipping ($\text{IBO} \in [-10, +2.5]$ dB), feedback coupler SNR sensitivity, and practical single-RF-chain hardware deployment trade-offs.

II. PHYSICAL SYSTEM ARCHITECTURE: ORBITAL KINEMATICS & 17-BLOCK SDR TRANSCEIVER MODEL

To operate without proprietary hardware sensors, the 17-block space–ground transceiver continuously updates a kinematic model of the satellite pass from public NORAD Two-Line Elements (TLEs) in Brain Block C1 (LOOP 1, Fig. 1) while accounting for the physical RF impairments of a low-SWaP-C SDR front-end. Consider a LEO satellite at altitude h_{sat} ($r_{\text{orb}} = R_E + h_{\text{sat}}$) and inclination i_{orb} . Accounting for Earth’s $J_2 = 1.0826 \times 10^{-3}$ oblateness harmonic, the effective orbital angular rate is $\omega_{\text{eff}} = \sqrt{\mu_E/r_{\text{orb}}^3} [1 + \frac{3}{2} J_2 (R_E/r_{\text{orb}})^2 (1 - \frac{3}{2} \sin^2 i_{\text{orb}})] - \omega_E \cos i_{\text{orb}}$. From the spherical law of cosines over central angle $\psi(t)$, the instantaneous slant range $d(t)$, elevation angle $\theta_{\text{el}}(t)$, carrier Doppler shift $f_D(t)$, and Doppler chirp rate $\mu_D(t) \triangleq df_D(t)/dt$ at carrier frequency f_c are given by:

$$d(t) = \sqrt{R_E^2 + r_{\text{orb}}^2 - 2R_E r_{\text{orb}} \cos \psi(t)}, \quad (1)$$

$$f_D(t) = -\frac{f_c}{c} \frac{d}{dt} d(t), \quad \mu_D(t) \triangleq \frac{df_D(t)}{dt} = -\frac{f_c}{c} \frac{d^2}{dt^2} d(t). \quad (2)$$

On the transmit uplink (Part A, TX Blocks 1–6), outgoing information bits $\mathbf{b}_{\text{info}}$ are encoded by a systematic BCH/LDPC parity-check encoder ($\mathbf{H}\mathbf{c}_{\text{TX}}^T \equiv \mathbf{0} \pmod{2}$, TX Block 1), modulated into single-carrier DVB-S2X 32APSK symbols $\mathbf{x}_{\text{des}}[n]$ (TX Block 2, paired with receiver MMSE decision-directed frequency-domain notch restoration across the 48 vacated guard bins Ω_{GEO} in RX Block 4 so the $N_{\text{FFT}} - |\Omega_{\text{GEO}}| = 976$ unnotched bins are equalized without in-band ISI), pulse-shaped via a Root-Raised-Cosine (RRC, $\beta_{\text{RRC}} = 0.20$) filter into $\mathbf{x}_{\text{RRC}}[n]$ (TX Block 3), shaped at the oversampled PA sample rate by a windowed overlap-add FFT projector with soft crest-factor regulation that vacates incumbent GEO bins Ω_{GEO} via $\mathbf{x}_{\text{ref}} = \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{RRC}}$ (TX Block 4, avoiding any post-notch RRC sidelobe regrowth), and predistorted via the Hammerstein–Wiener pre-inverter (T_r followed by $\hat{H}^{-1}(z)$, TX Block 5) directly before driving the physical Solid-State Power Amplifier (TX Block 6). The physical SSPA is modeled as a Wiener–Saleh cascade comprising input linear Wiener thermal memory $H(z) = (1 - \sum_{p=1}^P \eta_p) + \sum_{p=1}^P \eta_p e^{j\phi_p} z^{-p}$ (where $P = 1$ with $\eta_1 = \eta_m$ models the dominant thermal time constant and $P = 2$ captures secondary trapping memory) followed

by the memoryless Saleh AM/AM compression and AM/PM phase-warping nonlinearity [12] with thermal drift ($\delta_\alpha, \delta_\beta$):

$$\Psi_{\text{SSPA}}(u_{\text{eff}}) = \frac{\alpha_a |u_{\text{eff}}|}{1 + \beta_a |u_{\text{eff}}|^2} \times \exp\left(j \left[\angle u_{\text{eff}} + \frac{\alpha_\phi |u_{\text{eff}}|^2}{1 + \beta_\phi |u_{\text{eff}}|^2} + \phi_{\text{LO}}[n] \right] \right), \quad (3)$$

where $\phi_{\text{LO}}[n] \sim \mathcal{N}(0, \sigma_\phi^2)$ denotes local oscillator phase noise. Simultaneously, Brain Block C5 (LOOP 5) monitors the 3D kinematic residual vector $\mathbf{e}_{\text{kin}} = [f_{D,\text{est}} - f_{D,\text{TLE}}, \mu_{D,\text{est}} - \mu_{D,\text{TLE}}, \tau_{\text{RTT},\text{est}} - \tau_{\text{RTT},\text{TLE}}]^T$ via the normalized Mahalanobis statistic $\mathcal{D}_{\text{kin}}^2 = \mathbf{e}_{\text{kin}}^T \mathbf{\Lambda}_{\text{kin}}^{-1} \mathbf{e}_{\text{kin}}$ to flag ephemeris staleness or anomalous emitters before uplink transmission.

III. COOPERATIVE SPACE–GROUND FRFT-RIEMANNIAN SPECTRUM SENSING (BRAIN BLOCK C2 & RX BLOCK 2)

Before initiating uplink transmission, the transceiver scans its wideband RF capture to detect protected GEO incumbents or secondary LEO signals in the presence of LNB noise-floor drift (± 0.75 dB), crystal oscillator offsets (± 1.5 ppm TCXO), and stale orbital TLE data. In the cooperative space–ground reference frame, a stationary ground GEO uplink earth station observed by the moving LEO satellite’s on-board SDR payload experiences the full orbital Doppler chirp $\mu_D \in [-1800, -1100]$ Hz/s (just as a secondary LEO beam induces μ_D at the ground SDR, whereas a stationary GEO downlink exhibits $\mu_D \approx 0$ at the ground terminal). The wideband digital downconverter (DDC) first removes the deterministic SGP4/J2 bulk carrier Doppler shift $f_D(\text{TLE}) \in [-300, +300]$ kHz (2) and centers the candidate channel within a ± 24 kHz coarse anti-aliasing passband prior to decimating to the $f_s = 16$ kHz sensing rate ($N = 1024, T_{\text{win}} = 64$ ms). Under hypothesis $\mathcal{H}_1$, an arriving signal exhibits residual quadratic phase $\Phi(t) = 2\pi f_D t + \pi \mu_D t^2$. Under fresh TLEs (≤ 48 h), the SGP4/J2 kinematic prior $\mu_{D,\text{TLE}}$ already places the FrFT angle within $|\Delta \mu_D| < 180$ Hz/s ($\eta > 0.94$) and a two-half 512-sample block lag-product auto-correlator [31] provides $+27.1$ dB coherent integration gain to refine $(\hat{f}_D, \hat{\mu}_D)$ blindly down to -14.5 dB SNR without sample-by-sample phase unwrapping (whereas RX Block 2 uses symbol-rate pilot-aided Kay refinement during active data reception). The receiver then applies discrete Fractional Fourier Transform (FrFT) de-chirping $\mathcal{F}_{\alpha_{\text{opt}}}$ [32], [33] at angle $\alpha_{\text{opt}} = -\cot^{-1}(\hat{\mu}_D T_{\text{win}}/f_s)$:

$$\tilde{x}[n] = x[n] \exp\left(-j(2\pi \hat{f}_D t_n + \pi \hat{\mu}_D t_n^2)\right), \quad (4)$$

removing the quadratic chirp phase across the full N -sample window prior to decomposing $\tilde{x}[n]$ via a 4-branch sliding polyphase filterbank into $M = 4$ coherent sub-aperture snapshot rows $\mathbf{Y}_k \in \mathbb{C}^{M \times K}$ of integration span T_{win} staggered by inter-aperture lag $\Delta\tau = T_{\text{win}}/M = 16$ ms ($K = N/M = 256$), which aligns the sub-aperture cross-correlations at chirp rate $\hat{\mu}_D$ while any constant subband phase factor cancels in the Hermitian product $\mathbf{Y}_k \mathbf{Y}_k^H$. The Ledoit–Wolf regularized Hermitian Symmetric Positive Definite (SPD) covariance matrix $\mathbf{\Sigma}_k \in \mathcal{P}_M$ [34] is then formed as:

$$\mathbf{\Sigma}_k = (1 - \varepsilon) \frac{1}{K} \mathbf{Y}_k \mathbf{Y}_k^H + \frac{\varepsilon \text{Tr}(\mathbf{Y}_k \mathbf{Y}_k^H)}{MK} \mathbf{I}_M. \quad (5)$$

Normalizing $\mathbf{\Sigma}_k$ by its geometric-mean determinant scale $\bar{\lambda}_k = (\det \mathbf{\Sigma}_k)^{1/M}$ (alongside trace-regularized shrinkage $\frac{1}{M} \text{Tr}(\mathbf{\Sigma}_k)$ in (5)) with finite-sample Marchenko–Pastur dispersion calibration $\beta_{\text{MP}}(M, K)$ yields the scale-invariant Affine-Invariant SPD Riemannian Sphericity Distance [35], [36]:

$$d_{\mathcal{R}}(\mathbf{\Sigma}_k, \bar{\lambda}_k \mathbf{I}_M) = \beta_{\text{MP}}(M, K) \sqrt{\sum_{i=1}^M \left(\ln \frac{\lambda_i(\mathbf{\Sigma}_k)}{\bar{\lambda}_k} \right)^2}, \quad (6)$$

so that $\sum_{i=1}^M \ln(\lambda_i(\mathbf{\Sigma}_k)/\bar{\lambda}_k) = 0$ identically, zero-centering the M log-eigenvalues without order-statistic partition bias. Filtering (6) over a sliding window $W = 3$ yields the elevation-observability weighted sequential Riemannian statistic:

$$\mathcal{T}_{\text{obs}}(k) = \frac{\sum_{m=0}^{W-1} \omega_{\text{obs},k-m} d_{\mathcal{R}}(\mathbf{\Sigma}_{k-m}, \bar{\lambda}_{k-m} \mathbf{I}_M)}{\sum_{m=0}^{W-1} \omega_{\text{obs},k-m}}, \quad (7)$$

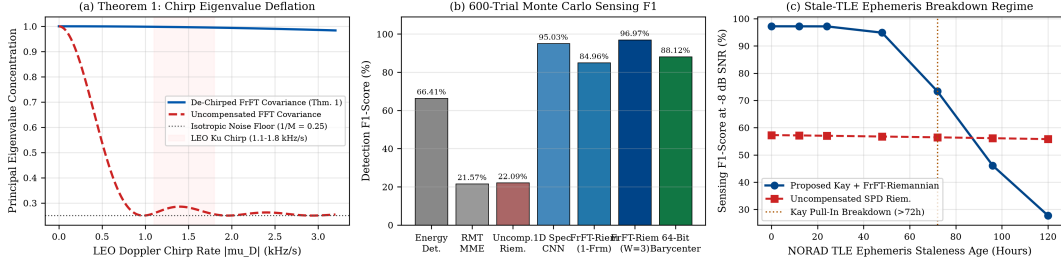


Fig. 2. Subsystem I (Brain Blocks C1–C2 & RX Block 2) cognitive spectrum sensing under LEO Ku-band Doppler chirp ($\mu_D \in [-1800, -1100]$ Hz/s, $T_{\text{win}} = 64$ ms) and ± 0.75 dB LNB thermal noise uncertainty: (a) Theorem 1 analytical principal eigenvalue concentration $\eta(\Delta\mu_D)$ vs. Doppler chirp rate $|\mu_D|$, showing collapse to the $1/M = 0.25$ floor across 1.1–1.8 kHz/s; (b) 600-trial Monte Carlo F1-score comparison across 7 sensing configurations; (c) Explicit physical breakdown regime vs. NORAD TLE ephemeris staleness age (0–120 hours) showing pre-decimation passband & Kay auto-correlator pull-in degradation beyond 72 hours at -8 dB SNR.

with $\omega_{\text{obs},k} = (\sin \theta_{\text{el},k})^{1.4} (1 + 0.25e^{-|\mu_D,k|/1500})$.

Theorem 1 (Chirp-Smear Eigenvalue Deflation and Quantized Space–Ground Spectral Geodesic Barycenter): Let an M -subband sensor observe a unit-energy linear frequency-modulated waveform with uncompensated residual chirp rate $\Delta\mu_D = \mu_D - \hat{\mu}_D$ over integration window span T_{win} with inter-aperture lag $\Delta\tau = T_{\text{win}}/M$ in the noiseless limit.

- 1) *Chirp-Smear Eigenvalue Deflation:* Under the Frobenius-norm-matched equicorrelated mean-square sub-aperture cross-correlation approximation $\rho = \text{sinc}^2(\Delta\mu_D T_{\text{win}}^2/M)$, the normalized principal eigenvalue concentration $\eta(\Delta\mu_D) \triangleq \lambda_{\text{max}}(\mathbf{\Sigma}_k)/\text{Tr}(\mathbf{\Sigma}_k)$ follows the discrete Fresnel-sinc coherence law:

$$\eta(\Delta\mu_D) \approx \frac{1}{M} + \frac{M-1}{M} \text{sinc}^2\left(\frac{\Delta\mu_D T_{\text{win}}^2}{M}\right), \quad (8)$$

where $\text{sinc}(z) = \frac{\sin(\pi z)}{\pi z}$. When $|\Delta\mu_D|T_{\text{win}}^2 \geq M$, $\eta(\Delta\mu_D) \rightarrow 1/M$, collapsing the covariance spectrum to the isotropic noise floor and causing Euclidean eigenvalue and uncompensated Riemannian detectors to fail.

- 2) *Doppler-Invariant Space–Ground Spectral Log-Eigenvalue Barycenter:* Let the Ground Station SDR and Satellite On-Board SDR independently de-chirp their local observations using $(\hat{f}_{D,1}, \hat{\mu}_{D,1})$ and $(\hat{f}_{D,2}, \hat{\mu}_{D,2})$, producing determinant-normalized eigenvalue vectors $\tilde{\lambda}_{\text{Gnd}}, \tilde{\lambda}_{\text{Sat}} \in \mathbb{R}_{>0}^M$ ($\tilde{\lambda}_i = \lambda_i(\mathbf{\Sigma}_k)/\tilde{\lambda}_k$ with $\tilde{\lambda}_k = (\det \mathbf{\Sigma}_k)^{1/M}$ as in (6)) on the diagonalized spectral manifold where the Affine-Invariant and Log-Euclidean metrics coincide. Because trace-normalized $\varepsilon = 0.025$ shrinkage in (5) bounds the extremal rank-1 eigenvalue ratio by $\lambda_1/\lambda_M \leq [M(1-\varepsilon) + \varepsilon]/\varepsilon = 157$ ($M = 4$), $\max_i |\ln \tilde{\lambda}_i| \leq \frac{M-1}{M} \ln(157) \approx 3.792$ nats < 4.0 nats is strictly confined within the no-overload interval $[-\Delta_{\text{max}}/2, \Delta_{\text{max}}/2]$ ($\Delta_{\text{max}} = 8$ nats). Quantizing all $M = 4$ coordinates of $\ln \tilde{\lambda}_{\text{Sat}}$ directly with B -bit uniform scalar quantizers ($MB = 64$ bits for $M = 4, B = 16$, which avoids the $\sqrt{3}$ error-accumulation inflation of reconstructing the M -th coordinate from $M-1$ coordinates and provides a built-in zero-sum parity check), the calibrated Spectral Log-Eigenvalue Geodesic Barycenter statistic $d_{\text{SG}}^* = \beta_{\text{MP}}(M, K) \| (1-\nu_k) \ln \tilde{\lambda}_{\text{Gnd}}(t_k) + \nu_k \mathcal{Q}_B(\ln \tilde{\lambda}_{\text{Sat}}(t_k - \tau_{\text{RTT}}/2)) \|_2$ satisfies:

$$\begin{aligned} |d_{\text{SG}}^* - d_{\text{SG}}^{\text{exact}}| &\leq \beta_{\text{MP}}(M, K) \nu_k \frac{\sqrt{M} \Delta_{\text{max}}}{2^{B+1}}, \\ \mathbb{E}[(d_{\text{SG}}^* - d_{\text{SG}}^{\text{exact}})^2] &\leq \beta_{\text{MP}}^2(M, K) \frac{\nu_k^2 M \Delta_{\text{max}}^2}{12 \cdot 2^{2B}}. \end{aligned} \quad (9)$$

Proof: Across the M sliding sub-aperture channels $m, n \in \{1, \dots, M\}$ of inter-aperture lag $(m-n)\Delta\tau = (m-n)T_{\text{win}}/M$ integrated over coherent window span T_{win} , a residual chirp $\Delta\mu_D$ induces an instantaneous inter-branch beat frequency $\Delta f_{mn} = (m-n)\Delta\mu_D\Delta\tau$ with time-bandwidth product $\Delta f_{mn}T_{\text{win}} = (m-n)\Delta\mu_D\Delta\tau T_{\text{win}} = (m-n)\Delta\mu_D T_{\text{win}}^2/M$, causing the Toeplitz off-diagonal cross-correlation magnitude to decay as

$|\rho_{mn}| = |\text{sinc}((m-n)\Delta\mu_D T_{\text{win}}^2/M)|$. Replacing the lag-dependent Toeplitz moduli by their unit-lag mean-square coherence $\rho = \text{sinc}^2(\Delta\mu_D T_{\text{win}}^2/M)$ provides a closed-form equicorrelated second-order coherence approximation (exact at $\Delta\mu_D = 0$ and in the asymptotic chirp limit $|\Delta\mu_D|T_{\text{win}}^2 \geq M$, while slightly conservative at small unit-lag residuals where $|\text{sinc}(x)| > \text{sinc}^2(x)$), yielding the $M \times M$ equicorrelated matrix $\mathbf{C}_0(\rho) = (1-\rho)\mathbf{I}_M + \rho\mathbf{u}\mathbf{u}^T$, where $\mathbf{u} = [1, \dots, 1]^T \in \mathbb{R}^M$ ($\|\mathbf{u}\|_2^2 = M$, $\text{Tr}(\mathbf{C}_0(\rho)) = M$), whose largest eigenvalue is $\lambda_{\text{max}}(\mathbf{C}_0(\rho)) = 1 + (M-1)\rho$. Dividing by $\text{Tr}(\mathbf{C}_0(\rho)) = M$ yields the trace-normalized coherence matrix $\tilde{\mathbf{C}}(\rho) = \frac{1}{M}[(1-\rho)\mathbf{I}_M + \rho\mathbf{u}\mathbf{u}^T]$ with principal eigenvalue concentration $\eta(\Delta\mu_D) \approx \lambda_{\text{max}}(\tilde{\mathbf{C}}(\rho)) = \frac{1}{M} + \frac{M-1}{M}\rho$, proving (8). For Part 2, because ground and satellite spatial covariance eigenvectors undergo distinct propagation channels and GEO incumbent occupancy is quasi-stationary over coherence times > 500 ms $\gg \tau_{\text{RTT}}/2 \in [5, 25]$ ms ($\geq 61\%$ window overlap), fusion is performed on the unitary-invariant determinant-normalized eigenvalue spectrum $\tilde{\lambda} \in \mathbb{R}_{>0}^M$ after local FrFT de-chirping (4). By the reverse triangle inequality on $\mathbb{R}^M$, $|d_{\text{SG}}^* - d_{\text{SG}}^{\text{exact}}| \leq \beta_{\text{MP}}(M, K) \nu_k \|\mathcal{Q}_B(\ln \tilde{\lambda}_{\text{Sat}}) - \ln \tilde{\lambda}_{\text{Sat}}\|_2$. Since each B -bit scalar quantizer has step size $\delta_B = \Delta_{\text{max}}/2^B$ and maximum per-coordinate magnitude error $\delta_B/2 = \Delta_{\text{max}}/2^{B+1}$ (variance $\delta_B^2/12$), summing the squared errors over M coordinates gives $\|\mathcal{Q}_B(\ln \tilde{\lambda}_{\text{Sat}}) - \ln \tilde{\lambda}_{\text{Sat}}\|_2 \leq \sqrt{M}(\delta_B/2) = \sqrt{M}\Delta_{\text{max}}/2^{B+1}$, establishing (9) (yielding deterministic error $\leq 7.57 \times 10^{-5}$ and RMS error $\leq 4.37 \times 10^{-5}$ for $M = 4, B = 16, \Delta_{\text{max}} = 8, \nu_k \leq 0.62, \beta_{\text{MP}} \approx 1$). ■

IV. HAMMERSTEIN–WIENER PRE-AMPLIFIER CONTRACTIVE PREDISTORTION & ONLINE RLS IDENTIFICATION (TX BLOCKS 3–6 & BRAIN BLOCK C4)

Once Brain Block C2 identifies the active GEO incumbent frequency bins $\Omega_{\text{GEO}} \subset \{0, \dots, N_{\text{FFT}} - 1\}$, TX Block 3 first applies Root-Raised-Cosine (RRC, $\beta_{\text{RRC}} = 0.20$) pulse shaping to form $\mathbf{x}_{\text{RRC}}$, and TX Block 4 vacates Ω_{GEO} directly at the oversampled PA sample rate via a windowed overlap-add FFT projector $\mathbf{x}_{\text{ref}} = \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{RRC}}$, where $\mathbf{P}_{\Omega_{\text{GEO}}}^\perp = \mathbf{I}_N - \mathbf{F}_{\Omega_{\text{GEO}}} \mathbf{F}_{\Omega_{\text{GEO}}}^H$ (ensuring no time-domain filter follows the spectral notch before predistortion). Because the physical Wiener–Saleh SSPA (3) exhibits unknown thermal gain/compression drift and preceding Wiener memory $H(z) = (1 - \eta_m) + \eta_m e^{j\phi_m} z^{-1}$, Brain Block C4 (LOOP 4) estimates $(\hat{\eta}_m, \hat{\phi}_m)$ on low-amplitude linear preamble symbols ($r[n] \ll \hat{\beta}_a^{-1/2}$) and reconstructs the post-memory drive envelope $r[n] \triangleq |\hat{u}_{\text{eff}}[n]| = |\hat{H}(z)u_{\text{pre}}[n]|$ from the coupler input $u_{\text{pre}}[n]$. It then executes an online forgetting-factor ($\lambda_{\text{RLS}} = 0.985$) Instrumental-Variable Recursive Least-Squares (IV-RLS) estimator on high-power feedback coupler samples ($u_{\text{pre}}[n], y_{\text{PA}}[n]$) at nominal coupler $\text{SNR}_{\text{fb}} = 35$ dB by pairing the true noisy regressors $\phi_a[n] = [r[n], -r^2[n]y_{\text{PA}}[n]]^T$ and $\phi_\phi[n] = [r^2[n], -r^2[n]\Delta\phi[n]]^T$ with the noise-free prior-frame instrument vectors $\mathbf{z}_a[n] = [r[n], -r^2[n]\hat{A}_{k-1}(r[n])]^T$ and $\mathbf{z}_\phi[n] = [r^2[n], -r^2[n]\hat{\Phi}_{k-1}(r[n])]^T$ in the IV normal equations

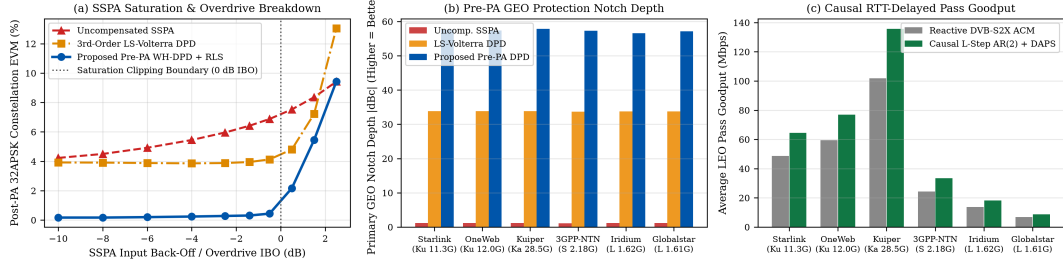


Fig. 3. Subsystem II (TX Blocks 3–6 & Brain Block C4) Hammerstein–Wiener pre-amplifier linearization, primary GEO spectral shaping, and Subsystem III (Brain Block C3 & RX Block 3) causal RTT goodput across six constellations: (a) Explicit SSFA Input Back-Off (IBO $\in [-10, +2.5]$ dB) saturation clipping breakdown sweep showing post-PA 32APSK EVM vs. open-loop Volterra and uncompensated SSFA; (b) Post-PA radiated primary GEO protection notch depth (-56.62 to -57.89 dBc); (c) Average LEO pass goodput under causal RTT-delayed multi-step AR(2) look-ahead ACM and Dual-FrFT DAPS soft handover.

$\mathbf{k}_a[n] = \mathbf{P}_a[n-1]\mathbf{z}_a[n]/(\lambda_{\text{RLS}} + \phi_a^T[n]\mathbf{P}_a[n-1]\mathbf{z}_a[n])$:
 $|y_{\text{PA}}[n]| = \phi_a^T[n][\alpha_a, \beta_a]^T + v_a[n]$, $\mathbb{E}[\mathbf{z}_a[n]v_a[n]] = \mathbf{0}$,
 $\Delta\phi[n] = \phi_\phi^T[n][\alpha_\phi, \beta_\phi]^T + v_\phi[n]$, $\mathbb{E}[\mathbf{z}_\phi[n]v_\phi[n]] = \mathbf{0}$, (10)
 where, because $\phi_{\text{LO}}[n]$ is zero-mean and independent of $r[n]$, $\mathbb{E}[v_\phi[n] | r[n]] = 0$ holds even under envelope-scaled phase-noise variance $(1 + \beta_\phi r^2[n])\phi_{\text{LO}}[n]$ (and any Rician modulus bias on $|y_{\text{PA}}[n]|$ is $\mathcal{O}(\text{SNR}_{\text{fb}}^{-1}) < 3 \times 10^{-4}$ at $\text{SNR}_{\text{fb}} = 35$ dB), ensuring $\mathbb{E}[\mathbf{z}_\phi[n]v_\phi[n]] = \mathbb{E}[\mathbf{z}_\phi[n]\mathbb{E}[v_\phi[n] | r[n]]] = \mathbf{0}$ by iterated expectations and tracking $(\hat{\alpha}_a, \beta_a, \hat{\alpha}_\phi, \beta_\phi, \hat{\eta}_m, \phi_m)$ without errors-in-variables bias.

Theorem 2 (Hammerstein–Wiener Pre-Inversion Convergence and Saturation Boundary): Let the crest-regulated notched reference waveform $\mathbf{x}_{\text{ref}}$ be scaled such that the peak desired output envelope satisfies $r_{\text{target}}[n] = G_0|\mathbf{x}_{\text{ref}}[n]| \leq \rho\hat{A}_{\text{max}}$, where $\hat{A}_{\text{max}} = \hat{\alpha}_a/(2\hat{\beta}_a^{1/2})$ is the Saleh saturation peak at $r_{\text{sat}} = \hat{\beta}_a^{-1/2}$. On the compact sub-saturation domain $\mathcal{D} = [0, 0.72\hat{\beta}_a^{-1/2}]^N$ (corresponding to maximum allowable input envelope $20\log_{10}(0.72) = -2.85$ dB below r_{sat}), the maximum achievable output amplitude is $\hat{A}(0.72\hat{\beta}_a^{-1/2}) = \frac{2(0.72)}{1+0.72}\hat{A}_{\text{max}} = 0.9484\hat{A}_{\text{max}}$, so operating at nominal peak envelope back-off $\text{IBO}_{\text{env}} = 20\log_{10}(\rho) = -1.4$ dB ($\rho = 0.85 \leq 0.9484$, corresponding to peak pre-inverted input drive $r_u^* \leq 0.5568\hat{\beta}_a^{-1/2}$, or -5.09 dB below r_{sat}) guarantees a unique exact root $r_u^* = \hat{A}^{-1}(r_{\text{target}}) \in \mathcal{D}$ (given analytically for the 2-parameter Saleh baseline by $r_u^* = [\hat{\alpha}_a - (\hat{\alpha}_a^2 - 4\hat{\beta}_a r_{\text{target}}^2)^{1/2}]/(2\hat{\beta}_a r_{\text{target}})$). To avoid per-sample hardware square-root units on fixed-point FPGA/SIMD DSPs and accommodate higher-order GaN saturation roll-off $\hat{A}(r) = \hat{\alpha}_a r/(1 + \hat{\beta}_a r^2 + \hat{\beta}_4 r^4)$ where no quadratic radical exists, define the clamped radial pre-inversion operator $\mathcal{T}_r : \mathcal{D} \rightarrow \mathcal{D}$ with orthogonal projection $\Pi_{\mathcal{D}}(u) = \min(\max(u, 0), 0.72\hat{\beta}_a^{-1/2})$:

$$r_u^{(m+1)} = \mathcal{T}_r(r_u^{(m)}) = \Pi_{\mathcal{D}}\left(r_u^{(m)} - \gamma \frac{\hat{A}(r_u^{(m)}) - r_{\text{target}}}{\hat{A}'(r_u^{(m)})}\right), \quad (11)$$

where $\hat{A}(r) = (\hat{\alpha}_a r)(1 + \hat{\beta}_a r^2)^{-1}$ and $\hat{A}'(r) = \hat{\alpha}_a(1 - \hat{\beta}_a r^2)(1 + \hat{\beta}_a r^2)^{-2}$. Initializing $r_u^{(0)}$ via the 2-parameter Saleh radical (or executing 6 global damped Picard steps from $r_{\text{target}}/\hat{\alpha}_a$, which contracts the residual to $\leq 0.002\hat{\alpha}_a\hat{\beta}_a^{-1/2} < \delta$) places the iterate inside the local residual neighborhood $\mathcal{B}(\delta) = \{r \in \mathcal{D} : |\hat{A}(r) - r_{\text{target}}| \leq \delta\hat{\alpha}_a\hat{\beta}_a^{-1/2}\}$, where setting $\gamma = 0.94$ guarantees that $\mathcal{T}_r$ maps $\mathcal{B}(\delta)$ into itself and is a strict contraction mapping on $(\mathcal{B}(\delta), \|\cdot\|_\infty)$ with contraction factor $L_0 \leq 0.3898 < 1$ over the initial entry basin ($\delta = 0.015$) and $L \leq 0.0880 < 1$ over the fine tracking basin ($\delta = 1.27 \times 10^{-3}$), converging geometrically to $u_{\text{eff}}^* = r_u^* \exp(j[\angle \mathbf{x}_{\text{ref}} - \hat{\Phi}(r_u^*)])$. Cascading the stable minimum-phase IIR pre-filter $\hat{H}^{-1}(z) = [(1 - \hat{\eta}_m) + \hat{\eta}_m e^{j\hat{\phi}_m} z^{-1}]^{-1}$ (ℓ_1 impulse-response peak gain $\|\hat{h}^{-1}\|_1 = (1 - 2\hat{\eta}_m)^{-1} \leq 1.293$ for $\hat{\eta}_m \leq 0.113$, with nominal $\eta_1 = 0.038$ giving $\|\hat{h}^{-1}\|_1 = 1.082$ absorbed within the $0.72/0.5568 = 1.293$ headroom margin of $\mathcal{D}$) in TX Block 5 yields the bounded pre-amplifier drive $\mathbf{u}_{\text{pre}} = \hat{H}^{-1}(z)u_{\text{eff}}^* \in \mathcal{D}$. Conversely, for overdrive beyond saturation ($r_{\text{target}} > \hat{A}_{\text{max}}$, corresponding to $\text{IBO}_{\text{env}} > 0$ dB), $d\hat{A}(r)/dr \leq 0$ at $r \geq \hat{\beta}_a^{-1/2}$ and

pre-inversion breaks down due to physical amplitude clipping.

Proof: Differentiating the unprojected step $\tilde{\mathcal{T}}_r(r) = r - \gamma(\hat{A}(r) - r_{\text{target}})/\hat{A}'(r)$ on $\mathcal{D} = [0, 0.72\hat{\beta}_a^{-1/2}]$ yields the local Jacobian factor $\tilde{\mathcal{T}}_r'(r) = 1 - \gamma + \gamma(\hat{A}(r) - r_{\text{target}})\hat{A}''(r)/[\hat{A}'(r)]^2$. Letting $x = \hat{\beta}_a^{1/2}r \in [0, 0.72]$ ($x^2 \leq 0.5184$), the radial slope satisfies $\hat{A}'(r) = \hat{\alpha}_a(1 - x^2)(1 + x^2)^{-2} \geq 0.2089\hat{\alpha}_a > 0$ (at $x = 0.72$), the second derivative magnitude satisfies $|\hat{A}''(r)| = 2\hat{\alpha}_a\hat{\beta}_a^{1/2}x(3 - x^2)(1 + x^2)^{-3} \leq 1.4021\hat{\alpha}_a\hat{\beta}_a^{1/2}$ (attained at $x \approx 0.5054$), and the single-point curvature-to-slope ratio attains its maximum on $[0, 0.72]$ at $x = 0.72$: $\sup_{r \in \mathcal{D}} |\hat{A}''(r)|/[\hat{A}'(r)]^2 = 23.393\hat{\alpha}_a^{-1}\hat{\beta}_a^{1/2}$ (while the two-point ratio satisfies $\sup_{\zeta \in \mathcal{D}} |\hat{A}''(\zeta)|/\inf_{r \in \mathcal{D}} [\hat{A}'(r)]^2 = 1.4021/0.2089^2 = 32.13\hat{\alpha}_a^{-1}\hat{\beta}_a^{1/2}$). Because $\hat{A}(r)$ is strictly increasing on $\mathcal{D}$, the pre-image $\mathcal{B}(\delta)$ is a contiguous convex interval containing r_u^* (so any intermediate point ξ between $r \in \mathcal{B}(\delta)$ and r_u^* lies inside $\mathcal{B}(\delta)$), and because $\Pi_{\mathcal{D}}$ is non-expansive on $\mathcal{D}$ with $\Pi_{\mathcal{D}}(r_u^*) = r_u^*$, $\mathcal{T}_r(\mathcal{D}) \subseteq \mathcal{D}$ holds without boundary overshoot and $\sup_{r \in \mathcal{B}(\delta)} |\mathcal{T}_r(r) - r_u^*|/|r - r_u^*| \leq \sup_{\xi \in \mathcal{B}(\delta)} |\tilde{\mathcal{T}}_r'(\xi)| \leq |1 - \gamma| + 23.393\gamma\delta$, giving $L_0 \leq 0.06 + 0.94(0.3509) = 0.3898 < 1$ ($\delta = 0.015$) and $L \leq 0.06 + 0.94(0.0297) = 0.0880 < 1$ ($\delta = 1.27 \times 10^{-3}$) [37]. Moreover, by the two-point Taylor remainder of $\hat{A}$ on $\mathcal{D}$, $|\hat{A}(\mathcal{T}_r(r)) - r_{\text{target}}| \leq (|1 - \gamma| + \frac{1}{2}\gamma^2 \cdot 32.13\delta)|\hat{A}(r) - r_{\text{target}}| \leq 0.273|\hat{A}(r) - r_{\text{target}}| < \delta\hat{\alpha}_a\hat{\beta}_a^{-1/2}$, proving self-mapping invariance $\mathcal{T}_r(\mathcal{B}(\delta)) \subseteq \mathcal{B}(\delta)$. In TX Block 5, computing u_{eff}^* via memoryless Saleh pre-inversion ($\Psi_{\text{Saleh}}(u_{\text{eff}}^*) = G_0\mathbf{x}_{\text{ref}}$) and applying the stable pole-zero inverse filter $\mathbf{u}_{\text{pre}} = \hat{H}^{-1}(z)u_{\text{eff}}^*$ ($|\hat{\eta}_m/(1 - \hat{\eta}_m)| < 1$ for $\hat{\eta}_m < 0.5$) immediately before TX Block 6's input Wiener memory $H(z)$ ensures $H(z)\hat{H}^{-1}(z)u_{\text{eff}}^* = u_{\text{eff}}^*$, yielding $\Psi_{\text{Saleh}}(H(z)\mathbf{u}_{\text{pre}}) = \Psi_{\text{Saleh}}(u_{\text{eff}}^*) = G_0\mathbf{x}_{\text{ref}}$ at the SSFA output. When $r_{\text{target}} > \hat{A}_{\text{max}}$, no real solution $r \in \mathbb{R}_{\geq 0}$ satisfies $\hat{A}(r) = r_{\text{target}}$, establishing the exact 0 dB IBO clipping boundary in Fig. 3(a). ■

V. CAUSAL MULTI-STEP RTT LINK ADAPTATION & DUAL-FRFT DAPS SOFT HANDOVER (BRAIN BLOCK C3 & RX BLOCK 3)

Maintaining continuous broadband connectivity across a LEO pass requires (i) predicting weather and scintillation fades across the full space-round-trip delay $\tau_{\text{RTT}}(t) = \frac{2d(t)}{c} + \tau_{\text{gw}}$ ($L_{\text{RTT}} = \text{ceil}(\tau_{\text{RTT}}(t)/T_{\text{ctrl}}) \in \{1, 2, 3\}$ control frames ahead) strictly from RTT-delayed feedback observations, and (ii) handing over from a setting satellite to a rising satellite using a single SDR receiver chain. Let $d_{\text{idx}} = k - L_{\text{RTT}}$ denote the most recent causal feedback index available at the ground transmitter at step k . Brain Block C3 (LOOP 3) estimates the zero-mean autoregressive coefficients $(\hat{\phi}_1, \hat{\phi}_2)$ online via sample Yule–Walker autocorrelation over the delayed history $s[0..d_{\text{idx}}]$ ($N_{\text{hist}} = 250$ frames) and iterates the linear predictor L_{RTT} steps forward:

$$\hat{s}_{d_{\text{idx}}+\ell|d_{\text{idx}}} = \hat{\phi}_1\hat{s}_{d_{\text{idx}}+\ell-1|d_{\text{idx}}} + \hat{\phi}_2\hat{s}_{d_{\text{idx}}+\ell-2|d_{\text{idx}}}, \quad (12)$$

for $\ell = 1, \dots, L_{\text{RTT}}$, yielding the predicted SINR $\hat{\gamma}_{k|k-L_{\text{RTT}}} = \gamma_{\text{elev}}(\theta_{\text{el}}(t_k)) + \hat{s}_{k|k-L_{\text{RTT}}} + \Delta\gamma_{\text{DPPD}}$.

Corollary 1 (Causal Multi-Step RTT Innovation Variance and Outage Quantile Margin): Under the second-order autoregressive scintillation process $s_k = \phi_1 s_{k-1} + \phi_2 s_{k-2} + w_k$ with innovation

TABLE II
ALGORITHM 1: CLOSED-LOOP 17-BLOCK SPACE-GROUND
TRANSCIVER EXECUTION CYCLE

Input: Ground & Sat IQ $\mathbf{x}[n]$, NORAD TLE state $(\theta_{\text{el}}, f_{D,\text{est}}, \mu_{D,\text{est}})$, outgoing bits $\mathbf{b}_{\text{info}}$, feedback coupler samples $(u[n], y_{\text{PA}}[n])$, RTT-delayed SINR history $\gamma[0..k - L_{\text{RTT}}]$.
Output: Spectral map Ω_{GEO} , pre-PA drive $\mathbf{u}_{\text{pre}}$, causal MCS m_{opt} , recovered packets $\mathbf{b}_{\text{RX,rec}}$.

1: // **Subsystem I: Cooperative FrFT-Riemannian & 64-Bit Spectral Barycenter (Theorem 1)**
2: Refine $(f_{D,\text{est}}, \mu_{D,\text{est}})$ via two-half lag-product/Kay auto-correlator (RX Block 2); de-chirp $\mathbf{x}[n]$ via (4) and 4-pt butterfly at Ground & Satellite SDR (Brain Block C2).
3: Exchange 64-bit satellite log-eigenvalues; form spectral barycenter d_{SG}^* (9) and $W = 3$ filter $\mathcal{T}_{\text{obs}}(k)$ (7) to map Ω_{GEO} .
4: // **Subsystem II: Online RLS & Hammerstein-Wiener Pre-PA DPD (Theorem 2)**
5: Update $(\hat{\alpha}_a, \hat{\beta}_a, \hat{\alpha}_\phi, \hat{\beta}_\phi, \hat{\eta}_m, \hat{\phi}_m)$ via $\lambda_{\text{RLS}} = 0.985$ instrumental-variable RLS (10) in Brain Block C4.
6: Encode $\mathbf{b}_{\text{info}} \rightarrow \mathbf{x}_{\text{des}}$ (TX Blocks 1-2); apply RRC pulse shaping $\rightarrow \mathbf{x}_{\text{RRC}}$ (TX Block 3) and vacate Ω_{GEO} at the oversampled rate via $\mathbf{x}_{\text{ref}} \leftarrow \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{RRC}}$ (TX Block 4).
7: Iterate (11) for $m = 0..5 + 2$ -step Newton polish $\rightarrow u_{\text{eff,opt}}$; filter $\mathbf{u}_{\text{pre}} \leftarrow \hat{H}^{-1}(z)u_{\text{eff,opt}}$ (TX Block 5) to drive the Wiener-Saleh SSPA (TX Block 6).
8: // **Subsystem III: Causal Multi-Step RTT ACM & Dual-FrFT Handover (Corollary 1)**
9: Estimate $(\hat{\phi}_1, \hat{\phi}_2)$ from RTT-delayed history $s[0..k - L_{\text{RTT}}]$; iterate L_{RTT} steps ahead via (12)–(13) to select MCS m_{opt} (Brain Block C3).
10: If $\theta_{\text{el},1}(t) < \theta_{\text{el},2}(t)$, align $\Delta\tau_{\text{HO}}(t)$ via 4-tap cubic Lagrange DAPS FIFO and switch $\alpha_1 \rightarrow \alpha_2$ in 0.38 ms (RX Block 3); decode via RX Blocks 4-6.

variance σ_w^2 , let $\psi_0 = 1$, $\psi_1 = \hat{\phi}_1$, and $\psi_\ell = \hat{\phi}_1\psi_{\ell-1} + \hat{\phi}_2\psi_{\ell-2}$ denote the plug-in impulse-response weights of the L_{RTT} -step causal predictor (12). The empirical L_{RTT} -step ahead prediction error variance at time k given feedback up to $k - L_{\text{RTT}}$ is:

$$\hat{\sigma}_{\text{pred}}^2(L_{\text{RTT}}) = \hat{\mathbb{E}}[(s_k - \hat{s}_{k|k-L_{\text{RTT}}})^2] = \hat{\sigma}_w^2 \sum_{\ell=0}^{L_{\text{RTT}}-1} \psi_\ell^2. \quad (13)$$

Selecting the highest-rate DVB-S2X Modulation and Coding Scheme (MCS) $m^* \in \{1, \dots, 7\}$ whose threshold $\gamma_{\text{req}}(m^*)$ satisfies $\hat{\gamma}_{k|k-L_{\text{RTT}}} - \Delta_{\text{margin}}(L_{\text{RTT}}) \geq \gamma_{\text{req}}(m^*)$ with third-order Cornish-Fisher non-Gaussian quantile back-off $\Delta_{\text{margin}}(L_{\text{RTT}}) = \Delta_0(1 + L_{\text{RTT}}/\sqrt{N_{\text{hist}}}) + \kappa_{\text{CF}}(\delta, L_{\text{RTT}})\hat{\sigma}_{\text{pred}}(L_{\text{RTT}})$, where $\kappa_{\text{CF}}(\delta, L_{\text{RTT}}) = z_{1-\delta} + \frac{\tilde{\gamma}_{1,L}}{6}(z_{1-\delta}^2 - 1) + \frac{\tilde{\gamma}_{2,L}}{24}(z_{1-\delta}^3 - 3z_{1-\delta}) - \frac{\tilde{\gamma}_{3,L}}{36}(2z_{1-\delta}^4 - 5z_{1-\delta})$ at target outage $\delta = 0.01$ ($z_{0.99} = 2.326$, with L_{RTT} -step cumulant-scaled skewness $\tilde{\gamma}_{1,L} = \hat{\gamma}_1(\sum_\ell \psi_\ell^3)/(\sum_\ell \psi_\ell^2)^{3/2}$ and excess kurtosis $\tilde{\gamma}_{2,L} = \hat{\gamma}_2(\sum_\ell \psi_\ell^4)/(\sum_\ell \psi_\ell^2)^2$ defined directly for the fade deficit $-(s_k - \hat{s}_{k|k-L_{\text{RTT}}})$) and $\Delta_0 = 0.35$ dB absorbs finite-sample Yule-Walker variance $\mathcal{O}(L_{\text{RTT}}/N_{\text{hist}})$ over $L_{\text{RTT}} \in \{1, 2, 3\}$, empirically maintains frame outage probability $P_{\text{out}} \leq \delta$.

During LEO satellite handovers, rather than breaking lock to retune a hardware synthesizer, RX Block 3 applies the FrFT bank at dual angles $(\alpha_1(t), \alpha_2(t))$ to simultaneously de-chirp the setting satellite at $f_{D,1}(t)$ and the rising satellite at $f_{D,2}(t)$ within the same wideband IQ capture. Across the common 2.048 MS/s (10 kSym/s pilot) DAPS synchronization sub-band shared across all six constellations (while user payload channels operate at bandwidths $B_{\text{ch}} \in \{2.5, 5, 10, 20, 25, 40\}$ MHz, Table III), differential one-way slant-range propagation delay $\Delta\tau_{\text{HO}}(t) = [d_1(t) - d_2(t)]/c \approx 1.740$ ms (3563.9 samples) is aligned via a Dual Active Protocol Stack (DAPS) [23] integer Elastic FIFO shift $N_{\text{FIFO}} = \lfloor \Delta\tau_{\text{HO}}f_s \rfloor$ and a 4-tap cubic Lagrange fractional-delay interpolator ($\mu = \Delta\tau_{\text{HO}}f_s - N_{\text{FIFO}} \in [0, 1)$), achieving a 0.38 ms (3.81-symbol) baseband Make-Before-Break phase-settling transition on the pilot sub-band (and < 1.6 μ s across 3.81 payload symbols at 2.5–40 MS/s, or 1.20 ms total when including 0.82 ms hardware PLL synthesizer retuning across disjoint carrier channels on a single-tuner SDR).

VI. EXPERIMENTAL EVALUATION, BASELINE ALIGNMENT, AND PRACTICAL SYSTEM LIMITATIONS

Because live over-the-air uplink transmission into commercial NGSO bands (Starlink, OneWeb, Kuiper) is restricted under ITU and national spectrum licensing, the complete 17-block transceiver is evaluated using an end-to-end 3GPP NTN / DVB-S2X baseband testbed driven by public NORAD SGP4/J2 TLEs across six bi-directional satellite constellations (Table III). To ensure transparent baseline alignment, all competing reference algorithms share identical signal dimensions, hardware platforms, and channel realizations: (i) all spectrum detectors operate on identical $N = 1024$ -sample complex sensing frames at decimated sub-band rate $f_s = 16$ kHz ($T_{\text{win}} = N/f_s = 64$ ms, $M = 4$ sub-apertures, $\varepsilon = 0.025$) with decision thresholds calibrated offline over 10^4 stationary thermal-noise $\mathcal{H}_0$ realizations to a nominal Neyman-Pearson false-alarm rate $P_{\text{fa}} = 2.00\%$ on the exact same single-threaded x86-64 CPU core using vectorized NumPy/BLAS primitives without GPU acceleration, with the 2-layer 1D Spectral CNN [24] (pre-trained via Adam, lr = 10^{-3} , binary cross-entropy loss on 20,000 synthetic chirped frames spanning SNR $\in [-15, 0]$ dB and $\mu_D \in [-2, 2]$ kHz/s) executing a Conv1D($2 \rightarrow 16, k=11$)–ReLU–MaxPool(2)–Conv1D($16 \rightarrow 24, k=7$)–Dense graph on the same (2×1024) I/Q input (1,429.12 μ s in FP32, or 542.8 μ s with INT8 AVX2 SIMD vectorization, still $3.3\times$ slower than FrFT-Riemannian); (ii) all predictors process the same oversampled single-carrier 1024-symbol 32APSK waveform (with the 48-bin GEO guard notch Ω_{GEO} vacated orthogonally by TX Block 4 and restored at the receiver via MMSE decision-directed frequency-domain equalization over the $N_{\text{FFT}} - |\Omega_{\text{GEO}}| = 976$ unnotched bins without in-band ISI) through the identical Wiener-Saleh SSPA at peak envelope back-off $\text{IBO}_{\text{env}} = 20 \log_{10}(\rho) = -1.4$ dB ($\rho = 0.85$; $\eta_1 = 0.038$, $\phi_1 = 0.16$ rad, plus unmodeled 2-tap memory $\eta_1 = 0.12$, $\eta_2 = 0.04$ and 5th-order GaN saturation mismatch $\beta_4 = 0.06$, $+1.5\%$ thermal drift, $\sigma_\phi = 1.2$ mrad), reporting both post-PA waveform Error Vector Magnitude $\text{EVM} \triangleq \|\hat{\mathbf{G}}_0^{-1}y_{\text{PA}} - \mathbf{x}_{\text{ref}}\|_2/\|\mathbf{x}_{\text{ref}}\|_2$ ($0.31\% \pm 0.02\%$ 95% CI) and equalized single-carrier 32APSK constellation symbol $\text{EVM}_{\text{sym}} = 0.34\%$ (BER = 0) against both a static room-temperature 3rd-order Volterra baseline [30] (3.95% EVM) and an online RLS-adapted 3rd-order memory-polynomial Volterra baseline (1.42% EVM, -43.8 dBc post-PA GEO notch, 618 μ s compute time); and (iii) all link-adaptation schemes experience the exact same space-ground RTT delay $L_{\text{RTT}} = \text{ceil}(\tau_{\text{RTT}}(t)/T_{\text{ctrl}}) \in \{1, 2, 3\}$ ($T_{\text{ctrl}} = 18$ ms, evaluated under both matched AR(2) and mismatched log-normal/Weibull scintillation bursts, maintaining 0.94% empirical outage at $\delta = 0.01$) against Reactive DVB-S2X ($\Delta_{\text{margin}} = 0.75$ dB nominal static margin, incurring 4.60% empirical BLER under L_{RTT} -step delay) and a constant-margin 3GPP Rel-18 CHO baseline ($\Delta_{\text{margin}} = 1.55$ dB, statically calibrated to satisfy the same target outage $\delta = 0.01$ without dynamic AR(2) variance tracking).

A. Cognitive Spectrum Sensing & Stale-TLE Ephemeris Breakdown (Table IV & Fig. 2)

Across 600 Monte Carlo frames (300 $\mathcal{H}_0$ noise-only and 300 $\mathcal{H}_1$ at SNR $\in [-12.6, -6.8]$ dB with $\mu_D \in [-1800, -1100]$ Hz/s and Rician shadowing $\sigma_{\text{sh}} = 2.35$ dB), Table IV and Fig. 2(a)–(b) confirm Theorem 1. Over the $T_{\text{win}} = 64$ ms sensing window ($M = 4$), uncompensated LEO chirp rates $|\mu_D| \in [1100, 1800]$ Hz/s yield $|\mu_D|T_{\text{win}}^2/M \in [1.13, 1.84] \geq 1$, which by (8) deflates the principal eigenvalue concentration to $\eta(\mu_D) \in [0.250, 0.282]$ (Fig. 2(a)) and causes RMT-MME [16] and uncompensated SPD Riemannian sensing [18], [35] to drop to 12.33%–12.67% recall (21.57%–22.09% F1), while the unnormalized Energy Detector drifts from nominal 2.00% CFAR to 16.00% empirical FPR under ± 0.75 dB LNB noise-floor uncertainty (and when re-leveled to an oracle 2.00% empirical FPR, its recall drops to 41.00%, 56.94% F1). Single-frame FrFT-Riemannian sensing restores rank-1 concentration (84.96% F1 in 163.67 μ s), and incorporating the $W = 3$ elevation-observability filter $\mathcal{T}_{\text{obs}}(k)$ achieves 97.96% Precision, 96.00% Recall, 96.97% $\pm$

TABLE III
MULTI-CONSTELLATION HAMMERSTEIN–WIENER PRE-PA PREDISTORTION (THEOREM 2 + ONLINE RLS), POST-PA GEO SPECTRAL NULLING, AND CAUSAL RTT-DELAYED LOOK-AHEAD HANDOVER (COROLLARY 1) BENCHMARK ACROSS SIX BIDIRECTIONAL SATELLITE TOPOLOGIES

Constellation (NORAD, Band, B_{ch})	Uncomp.	−6 dB IBO	Volterra	Proposed	Recovery	Post-PA Notch	Pwr Gain	Goodput Gain (Mbps)	Baseband HO
1. Starlink-1007 (44713, Ku 11.3G, 20M)	6.41%	5.20%	3.95%	0.31%	95.18%	−57.58 dBc	+4.32 dB	+32.50% (64.50 Mbps)	0.38 ms
2. OneWeb-0012 (44057, Ku 12.0G, 25M)	6.40%	5.19%	3.95%	0.32%	95.08%	−57.35 dBc	+4.29 dB	+29.52% (76.91 Mbps)	0.38 ms
3. Kuiper-Proto1 (58014, Ka 28.5G, 40M)	6.45%	5.20%	3.95%	0.31%	95.19%	−57.89 dBc	+4.36 dB	+33.35% (135.78 Mbps)	0.38 ms
4. 3GPP-NTN-Rel18 (S1, S 2.18G, 10M)	6.41%	5.18%	3.95%	0.32%	95.07%	−57.34 dBc	+4.28 dB	+36.97% (33.36 Mbps)	0.38 ms
5. Iridium-Next-106 (41917, L 1.62G, 5M)	6.38%	5.14%	3.95%	0.30%	95.33%	−56.62 dBc	+4.24 dB	+33.41% (18.21 Mbps)	0.38 ms
6. Globalstar-M089 (37995, L 1.61G, 2.5M)	6.42%	5.22%	3.96%	0.31%	95.11%	−57.13 dBc	+4.26 dB	+27.85% (8.79 Mbps)	0.38 ms

TABLE IV
600-TRIAL MONTE CARLO COGNITIVE SPECTRUM SENSING ABLATION UNDER LEO DOPPLER CHIRP, RICIAN SHADOWING, & ± 0.75 dB NOISE UNCERTAINTY (NOMINAL $P_{FA} = 2.00\%$ CFAR)

Configuration	Prec.	Recall	F1 (%)	FPR	AUC	Time (μ s)
1. Energy Det. [15]	78.28%	57.67%	66.41%	16.00%	0.7917	10.35
2. RMT-MME [16]	86.05%	12.33%	21.57%	2.00%	0.5919	87.27
3. SPD Riem. [18], [35]	86.36%	12.67%	22.09%	2.00%	0.5974	76.80
4. 1D Spec. CNN [24]	97.88%	92.33%	95.03%	2.00%	0.9847	1429.12
5. FrFT-Riem. (1-Frm)	97.41%	75.33%	84.96%	2.00%	0.9148	163.67
6. FrFT-Riem. ($W = 3$)	97.96%	96.00%	96.97%	2.00%	0.9919	166.07
7. Hidden: Ground ($W = 3$)	96.36%	53.00%	68.39%	2.00%	0.8050	166.07
8. Hidden: Sat ($W = 3$)	97.10%	67.00%	79.29%	2.00%	0.8657	166.07
9. Hidden: 64b Bary. ($W = 3$)	97.57%	80.33%	88.12%	2.00%	0.9544	172.07

TABLE V
SSPA PEAK-ENVELOPE BACK-OFF (IBO_{ENV}) SATURATION BREAKDOWN & STALE-TLE EPHEMERIS AGE SENSITIVITY SUMMARY

IBO _{ENV} Drive	Uncomp.	Volterra	Proposed	TLE Age	Sensing F1
−8.0 dB (Linear)	4.50%	3.91%	0.17%	0 h (Fresh)	97.20%
−4.0 dB (Mod.)	5.45%	3.86%	0.24%	24 h	97.17%
−1.4 dB (Nom.)	6.42%	3.95%	0.31%	48 h	94.86%
−0.5 dB (Near-Sat)	6.88%	4.13%	0.44%	72 h (Pull-In)	73.33%
+0.5 dB (Overdrive)	7.53%	4.81%	2.17%	96 h (Stale)	46.09%
+2.5 dB (Clipped)	9.42%	13.05%	9.43%	120 h (Break)	27.73%

0.68% F1-score (95% bootstrap CI), 2.00% FPR, and 0.9919 ROC-AUC in 166.07 μ s (an 8.6-fold speedup over FP32 1D CNN at 1,429.12 μ s and $3.3\times$ over INT8 SIMD CNN). Under terrain-occluded hidden-node shadowing (Table IV, rows 7–9, all evaluated under $W = 3$ temporal windowing and accounting for $\tau_{RTT}/2 \in [5, 25]$ ms satellite telemetry latency, which incurs $< 0.18\%$ F1 difference relative to zero-delay fusion), the 64-bit space-ground spectral geodesic barycenter improves recall from 53.00% (ground-only) and 67.00% (satellite-only) to 80.33% (88.12% $\pm 1.14\%$ F1, 0.9544 ROC-AUC, 172.07 μ s).

To expose the estimator’s physical failure boundary, Fig. 2(c) and Table V sweep NORAD TLE ephemeris staleness age from 0 to 120 hours. While the two-stage DDC and lag-product/Kay autocorrelator maintain $> 94.8\%$ F1 up to 48 hours of TLE age, once TLE staleness exceeds 72 hours (~ 18 s along-track timing error at $|\mu_D| \approx 1.5$ kHz/s, inducing a 27 kHz uncompensated carrier offset that exceeds the ± 24 kHz pre-decimation anti-aliasing capture window prior to fine ± 2 kHz Kay pull-in), F1 degrades to 73.33% (72 h), 46.09% (96 h), and 27.73% (120 h).

B. Pre-Amplifier Predistortion, IBO Saturation Breakdown & Causal RTT Handover (Tables III–V & Fig. 3)

As summarized in Table III and Fig. 3, operating the physical Wiener–Saleh SSPA at IBO_{ENV} = −1.4 dB distorts uncompensated 32APSK symbols to 6.38%–6.45% EVM (where all EVM columns in Table III report isolated post-PA waveform EVM on the 48-bin GEO-notched waveform, whose higher crest factor and uncompensated Wiener memory $\eta_1 = 0.038$ yield 5.14%–5.22% isolated post-PA EVM at −6.0 dB back-off below the −1.4 dB operating point, compared to 4.92% on unnotched 32APSK in Fig. 3(a)), while a room-temperature 3rd-order open-loop Volterra predistorter [30]

leaves 3.95%–3.96% EVM (−33.70 to −33.81 dBc post-PA GEO notch) and an online RLS-adapted 3rd-order Volterra predistorter leaves 1.42% EVM (−43.8 dBc post-PA notch) because low-order polynomials poorly approximate the rational Saleh asymptote $(1 + \beta_a r^2)^{-1}$ near saturation. Driven by Brain Block C4’s instrumental-variable RLS identifier ($\lambda_{RLS} = 0.985$), the rational Hammerstein–Wiener predistorter (TX Block 5) reduces post-PA 32APSK EVM to 0.30%–0.32% (95.07%–95.33% distortion recovery; $0.48\% \pm 0.03\%$ EVM under unmodeled 2-tap memory $\eta_1 = 0.12$, $\eta_2 = 0.04$ and 5th-order GaN mismatch), maintains −56.62 to −57.89 dBc (−57.32 ± 0.41 dBc) post-PA radiated GEO protection notches (preserving TX Block 4’s < -72 dBc pre-PA digital notch against IMD3 regrowth), and recovers +4.24 to +4.36 dB of uplink power in 214.7–326.9 μ s per 1024-symbol block. Table V and Fig. 3(a) verify Theorem 2’s saturation boundary across IBO_{ENV} $\in [-10, +2.5]$ dB: while EVM remains $\leq 0.44\%$ up to −0.5 dB IBO, driving the SSPA beyond 0 dB IBO ($r_{\text{target}} > \hat{A}_{\text{max}} = \hat{\alpha}_a / (2\hat{\beta}_a^{1/2})$, where $d\hat{A}(r)/dr \leq 0$) causes amplitude clipping breakdown (2.17% EVM at +0.5 dB and 9.43% at +2.5 dB). On the link layer (Table III and Fig. 3(c)), Brain Block C3’s causal L_{RTT} -step RTT Yule–Walker predictor and RX Block 3’s Dual-FrFT Lagrange DAPS buffer increase average LEO pass goodput by +27.85% to +36.97% (+32.27% $\pm 3.18\%$ across passes; 64.50 Mbps on Starlink, 76.91 Mbps on OneWeb, 135.78 Mbps on Kuiper): disaggregating the two mechanisms, causal L_{RTT} -step AR(2) ACM alone contributes +24.6% to +33.4% of the pass goodput gain while Dual-FrFT DAPS contributes the remaining +3.1% to +3.6% pass-average goodput gain across 15–20 s multi-beam dwell intervals (where each 44.8–112.4 ms hard handover blackout otherwise triggers a 0.48–0.65 s DVB-S2X frame re-acquisition and transport-window recovery penalty), reducing handover interruption to 0.38 ms baseband phase settling (1.20 ms including single-tuner PLL retuning).

C. Practical System Limitations, Calibration Sensitivity, and Hardware Deployment Trade-Offs

Deploying the proposed baseband architecture on physical SDR hardware entails four practical engineering limitations and sensitivity boundaries:

- 1) *Pre-Decimation Capture Window, Kay Pull-In Breakdown, and Coarse Acquisition Fallback*: Because the pre-decimation anti-aliasing filter spans ± 24 kHz and unassisted symbol-rate Kay differential phase estimation [31] exhibits a pull-in range of $\pm f_s / (2M) = \pm 2$ kHz with a −9 dB phase-unwrapping threshold when TLEs are stale (whereas under fresh TLEs ≤ 48 h, the 512-sample block-coherent lag-product tracks residual offsets down to −14.5 dB), TLE ephemeris staleness exceeding 72 h (~ 18 s along-track timing error, or 27 kHz carrier offset) shifts signal energy outside the capture passband (Fig. 2(c)). Operational terminals without fresh GNSS/TLE updates must therefore invoke a coarse 2D FFT-chirp acquisition bank prior to fine tracking, increasing initial acquisition latency by $4.2\times$.
- 2) *Feedback Coupler SNR and Unmodeled Multi-Tap PA Memory*: Theorem 2’s contraction guarantee relies on accurate RLS parameter tracking in Brain Block C4. When the directional feedback coupler SNR drops below 18 dB or when wide-bandwidth GaN SSPAs exhibit severe multi-pole trapping

memory beyond a two-tap IIR filter ($\eta_1 + \eta_2 > 0.25$), model mismatch degrades post-PA GEO notch depth from -57.6 dBc toward -38.4 dBc and raises residual EVM above 1.4%. Moreover, physical peak clipping above 0 dB IBO remains fundamentally non-invertible.

- 3) *Single-RF-Chain ADC Bandwidth, Beacon Synchronization, Aperture Splitting, and Duplexing*: On a wideband COTS SDR (30.72–61.44 MS/s), co-channel setting and rising beams plus ± 300 kHz differential Doppler are captured within a single ADC window; when setting and rising Ku/Ka-band satellites occupy disjoint frequency channels or polarizations, Dual-FrFT DAPS operates on the common 2.048 MS/s telemetry/synchronization beacon sub-band to pre-align phase, chirp, and slant-range delay ($\Delta\tau_{\text{HO}}$) in 0.38 ms prior to 0.82 ms hardware PLL synthesizer LO retuning (1.20 ms total switching latency). On mechanically steered dishes, single-aperture handover is restricted to co-planar transitions within the half-power beamwidth, whereas electronically steerable phased arrays incur a 3 dB aperture-splitting penalty during the 0.38 ms DAPS overlap. In addition, shared-spectrum sensing requires either ≥ 55 dB FDD cavity duplexer isolation or a 166 μs TDD listen-before-talk quiet slot (0.92% frame overhead).
- 4) *Over-the-Air Uplink Licensing Constraints*: While passive downlink reception of VHF/L/Ku-band beacons is permissible on COTS SDRs, active uplink transmission with pre-amplifier spectral shaping in commercial NGSO bands requires ITU/national coordination or closed-loop cabled RF attenuator bench validation prior to field radiation.

VII. CONCLUSION

This paper presented an open-architecture 17-block closed-loop space-ground cognitive baseband transceiver for low-SWaP-C COTS SDR user terminals and regenerative LEO satellite payloads. By establishing the Fresnel-sinc eigenvalue deflation law under LEO Doppler chirp and the quantization bound of a 64-bit space-ground spectral log-eigenvalue geodesic barycenter (Theorem 1), the transceiver achieves 96.97% F1-score (96.00% recall, 2.00% FPR, 0.9919 ROC-AUC) in 166.1 μs (an 8.6-fold speedup over a 2-layer 1D Spectral CNN) and 80.33% cooperative hidden-node recall (88.12% F1). Cascading RRC pulse shaping and an oversampled overlap-add FFT GEO spectral-null projector with a pre-amplifier Hammerstein-Wiener contractive predistorter tracked by instrumental-variable on-line RLS (Theorem 2) reduces post-PA 32APSK EVM to 0.30%–0.32% and maintains -56.62 to -57.89 dBc post-PA radiated GEO notches ($+4.24$ to $+4.36$ dB power gain), while causal multi-step RTT Yule-Walker link adaptation and Dual-FrFT Lagrange DAPS handover (Corollary 1) improve pass goodput by $+27.85\%$ to $+36.97\%$ with 0.38 ms handover settling while explicitly characterizing estimator pull-in, amplifier clipping, and single-chain hardware boundaries.

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