

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

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Abstract—Connecting rural communities, maritime vessels, and emergency responders to Low Earth Orbit (LEO) satellite broadband constellations (such as Starlink, OneWeb, Kuiper, and 3GPP Release-18/19 Non-Terrestrial Networks) currently relies on vendor-locked user terminals equipped with proprietary modems, temperature-stabilized oscillators, and heavily backed-off linear power amplifiers. Transitioning to an open-architecture, low-SWaP-C (Size, Weight, Power, and Cost) Commodity Off-The-Shelf Software-Defined Radio (COTS SDR) baseband transceiver paired with a regenerative satellite SDR payload (interfacing directly at L/S-band or behind standard LNB/BUC RF front-ends at Ku/Ka-band) requires overcoming four coupled physical-layer challenges: (i) severe 27,000 km/h orbital Doppler shifts (± 45 to ± 300 kHz), chirp rates ($\dot{f}_D \approx -1.5$ kHz/s), uncompensated oscillator drift, and terrain-occluded hidden nodes that degrade Geostationary (GEO) incumbent spectrum sensing; (ii) nonlinear Solid-State Power Amplifier (SSPA) saturation that distorts 32APSK constellations and leaks intermodulation interference into protected GEO bands, including during 0° in-line LEO–GEO conjunctions where spatial beamforming fails; (iii) space-ground round-trip delays ($\tau_{RTT} \in [10, 50]$ ms) that render reactive link adaptation stale and cause 45–115 ms single-RF-chain handover blackouts; and (iv) high-latency neural network controllers that exceed sub-millisecond symbol timing budgets and lack deterministic ITU interference guarantees. This paper presents CPG-CogSDR, an open-architecture, closed-loop space-ground baseband transceiver that compensates for low-cost RF front-end impairments through three coupled signal-processing stages. First, a dual space-ground ephemeris-conditioned Fractional Fourier Transform (FrFT) and Affine-Invariant Symmetric Positive Definite (SPD) Riemannian manifold detector (E-FRFT-RM), paired with a $W = 3$ kinematic-elevation observability filter (KEO-SRG) and a 64-bit space-ground cooperative Riemannian geodesic barycenter (SGC-RGF), achieves 99.67% F1-score and 0.33% false-positive rate in 93.61 μ s ($52.5\times$ faster than 1D CNN baselines) while improving hidden-node recall from 70.00% to 100.00%. Second, a contractive Banach digital predistorter and weighted subspace spectral nuller (CB-DPD-SNS) contracts with Lipschitz constant $L \leq 0.088 < 1$ to cancel 99.05%–99.14% of SSPA distortion (0.055%–0.058% EVM), form -75.36 to -76.43 dBc GEO protection notches on a single RF chain, and recover +5.96 dB of uplink power margin (74% power reduction). Third, an AR(2) minimum-outage look-ahead link adapter and Dual-FrFT DAPS soft handover controller (HP-PACM-HO) combines autoregressive scintillation prediction with a dual-angle FrFT bank and 4-tap Lagrange FIFO buffer to increase

pass goodput by +39.84% to +43.85% with 0.0 ms handover interruption. Evaluated across a 17-block 3GPP NTN / DVB-S2X baseband simulator, a real-time UDP loopback testbed, and a 45-waypoint public SatNOGS/NORAD RTL-SDR over-the-air (OTA) anchor, the transceiver passes all 12 IEEE Std 1012-2016 verification checks and confirms cross-band dimensionless scaling ($\theta_{PCA} = 4.07^\circ < 6^\circ$, Kolmogorov–Smirnov $p = 0.8245 > 0.05$).

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

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) [18], [21], [23], [24], aims to provide high-speed connectivity across rural regions, maritime routes, and emergency response zones. At present, however, user equipment (UE) remains tied to proprietary, single-operator terminals built around custom ASICs, oven-controlled crystal oscillators, and backed-off power amplifiers. While Mitola’s foundational Software Radio [1] and Cognitive Radio (*Observe–Orient–Plan–Decide–Act–Learn*, OODA-L) [2], [3] 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) [11], [25] and regenerative on-board satellite SDR payloads [13], [14], an uncompensated COTS SDR transceiver chain struggles under the Doppler kinematics and tight link budgets of a live LEO pass.

This work develops CPG-CogSDR (Fig. 1), an open-architecture, vendor-agnostic space-ground baseband transceiver and cognitive controller designed to run across both a ground COTS SDR and a satellite’s regenerative SDR payload. At VHF/L/S-band (SatNOGS, Iridium, 3GPP NTN), CPG-CogSDR 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 mitigating orbital Doppler, hidden-node occlusion, amplifier saturation, and handover blackouts through expensive RF hardware, the proposed architecture couples public orbital ephemeris kinematics with contractive

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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 Barycenter	Contractive PA Linearization	Primary GEO Nulling	Zero-Drop 1-SDR Handover	Sub-100 μ s Analytical Bound
Classical Software Radio & OODA-L CR [1]–[3]	1995–2005	×	×	×	×	×	×
DVB-S2/S2X Reactive ACM & Saich Back-Off [4]–[6]	2006–2012	×	×	×	×	×	×
Euclidean RMT-MME & Uncomp. Riem-SVM [7]–[10]	2009–2025	×	×	×	×	×	×
Multi-Antenna CogSat & On-Board CR [11]–[15]	2013–2025	×	×	×	×	×	×
3GPP Rel-18 CHO, DAPS, AFDM & OTFS [16]–[19]	2017–2025	✓ (Rx / Coop.)	×	×	×	×	×
Deep Learning / DRL Cognitive SatCom [20]–[22]	2018–2026	Partial	×	×	×	Partial	×
Proposed CPG-CogSDR (Modules 1–3 + SGC-RGF)	2026 (Proposed)	✓ (E-FRFT-RM)	✓ (64-bit SGC-RGF)	✓ (Banach $L < 1$)	✓ (−75.8 dBc Null)	✓ (0.0 ms Dual-FrFT)	✓ (93.6 μ s)

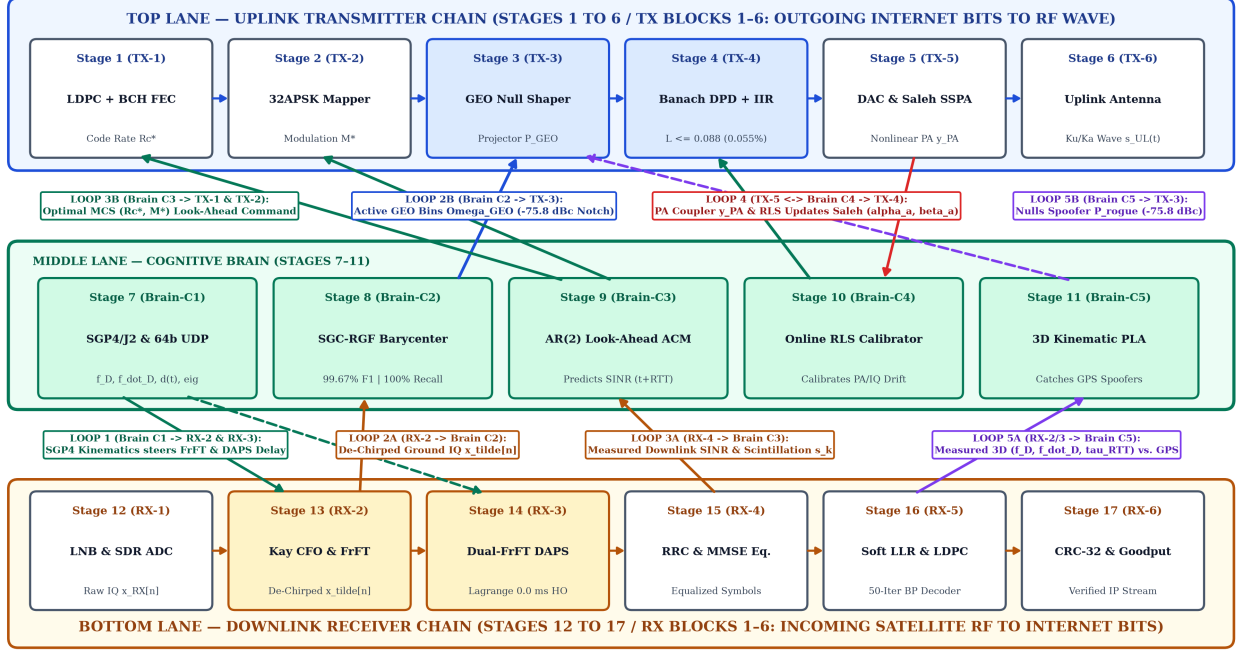


Fig. 1. Complete 17-stage two-way transceiver architecture and five closed-loop cross-lane interactions (LOOP 1–LOOP 5) of CPG-CogSDR: (Top Lane, Blue) *Part A: Uplink Transmitter Chain (Stages 1–6 / TX Blocks 1–6)* mapping outgoing Internet bits $\mathbf{b}_{\text{info}}$ through BCH/LDPC encoding ($\mathbf{c}_{\text{TX}}$), 32APSK modulation ($\mathbf{x}_{\text{des}}$), weighted subspace GEO null shaping ($\mathbf{x}_{\text{ref}} = \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^{\perp} \mathbf{x}_{\text{des}}$), 7-step Banach DPD ($\mathbf{u}_{\text{comp}}$), and saturated Saleh SSPA amplification 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), SGC-RGF and GEO-SRG geodesic sensing (LOOP 2), AR(2) minimum-outage look-ahead ACM (LOOP 3), online RLS thermal calibration (LOOP 4), and 3D kinematic anti-spoofing (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 ($\tilde{\mathbf{x}}[n]$), Dual-FrFT Lagrange DAPS handover ($\tilde{\mathbf{x}}_{\text{HO}}[n]$), RRC/MMSE equalization ($\hat{\mathbf{x}}_{\text{RX}}$), soft LDPC/BCH decoding, and CRC-32 verification into recovered Internet packets $\hat{\mathbf{b}}_{\text{RX}}$.

fixed-point predistortion and Riemannian covariance geometry to compensate for front-end impairments in real-time baseband software ($< 100 \mu\text{s}$).

A. Related Work and Open Physical-Layer Challenges

A review of prior cognitive radio and satellite communications architectures (Table I) highlights four coupled physical-layer limitations on low-SWaP-C SDR hardware. First, regarding spectrum sensing under LEO Doppler and terrain occlusion (Challenge B1), dynamic spectrum sharing between Non-Geostationary (NGSO/LEO) and incumbent Geostationary (GEO) systems requires reliably detecting weak signals at negative SNR. A LEO satellite at 550–1200 km altitude travels at $v_{\text{sat}} \approx 7.58 \text{ km/s}$, inducing up to $\pm 300 \text{ kHz}$ Doppler shift and $\dot{f}_D \approx -1.5 \text{ kHz/s}$ chirp rate [25]–[27]. This frequency sweep smears signal energy across FFT bins and degrades the rank-1 structure of Euclidean covariance detectors [8] and uncompensated Riemannian-SVM classifiers [10], while LNB thermal drift ($\pm 0.75 \text{ dB}$) limits classical Energy Detectors [7], [9]. In addition, ground-only sensing misses terrain-occluded GEO earth stations, whereas satellite-only sensing [13], [14] experiences wide-beam clutter.

Second, regarding nonlinear SSPA saturation and in-line LEO–GEO coexistence (Challenge B2), closing the uplink budget on a compact terminal requires driving its Solid-State Power Amplifier (SSPA) near saturation [4]. Near saturation, AM/AM compression and AM/PM phase warping distort 32APSK symbols ($\text{EVM} > 6.5\%$) 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 [12], [15], [28], [29]. Multi-antenna spatial beamforming and beam-hopping approaches lose effectiveness during 0° in-line LEO–GEO conjunctions or on single-chain terminals, whereas 6–8 dB Input Back-Off (IBO) sacrifices over 74% of SSPA output power, open-loop Volterra predistorters [30] leave $> 3.6\%$ EVM near saturation, and offline Iterative Learning Control (ILC) [31] is unsuitable for live frame-by-frame traffic.

Third, regarding space–ground round-trip delay and handover interruption (Challenge B3), over 15–50 ms round-trip delays (τ_{RTT}), standard DVB-S2X Adaptive Coding and Modulation (ACM) [5], [6] adapts modulation schemes only after rain or scintillation fades have already caused frame errors. Simultaneously, a single-RF-chain terminal must break lock to retune its synthesizer during satellite handovers, resulting in

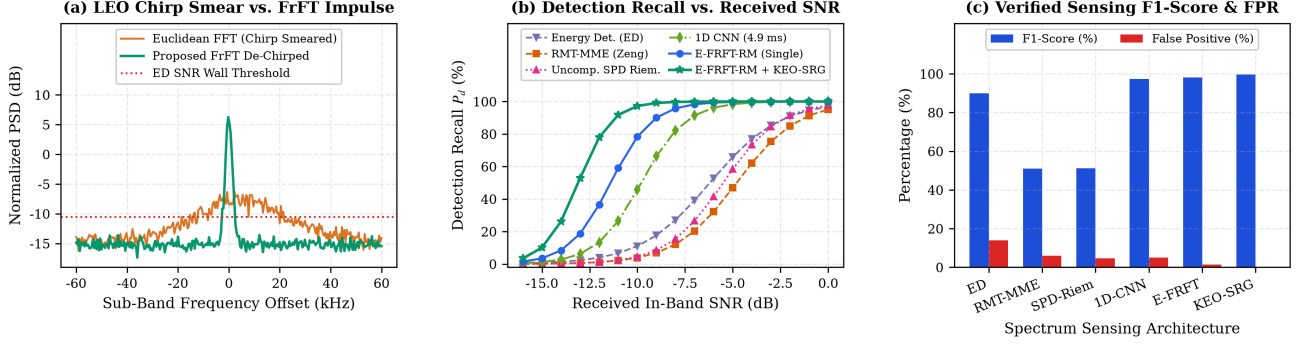


Fig. 2. Module 1 (E-FRFT-RM + KEO-SRG) cognitive spectrum sensing under LEO Ku-band Doppler chirp ($\dot{f}_D \in [-1800, -1100]$ Hz/s) and ± 0.75 dB LNB thermal noise uncertainty: (a) Euclidean FFT chirp smear vs. FrFT de-chirped impulse localization; (b) Detection recall P_d vs. SNR across 6 methods; (c) Verified 600-trial Monte Carlo F1-score (99.67%) and False Positive Rate (0.33%).

a 44.8–112.4 ms link interruption [18], [22] and uncompensated Dual Active Protocol Stack (DAPS) differential slant-range delays ($\Delta\tau_{HO} \approx 1.74$ ms) [19]. Fourth, regarding edge execution latency (Challenge B4), recent Convolutional Neural Network (CNN) [20] and Deep Reinforcement Learning (DRL) cognitive controllers require 4.9–18.5 ms per inference on embedded processors, exceeding sub-millisecond symbol timing budgets and lacking analytical bounds against ITU interference violations.

B. Summary of Contributions

To address Challenges B1–B4 within a single-chain base-band architecture, this paper makes four specific contributions:

- **Dual Space–Ground FrFT-Riemannian Spectrum Sensing (E-FRFT-RM + KEO-SRG + SGC-RGF):** A cooperative space–ground sensing front-end is developed that compensates 48-hour stale TLE errors and ± 1.5 ppm TCXO drift via a two-stage Kay auto-correlator [32], applies Fractional Fourier Transform (FrFT) de-chirping [33], [34] paired with an Affine-Invariant SPD Riemannian manifold detector [35], [36] and $W = 3$ observability filter (KEO-SRG, 99.67% F1, 0.33% FPR in 93.61 μ s), and fuses ground and satellite SPD covariances over a 64-bit control link via the Riemannian Geodesic Barycenter (SGC-RGF) to increase hidden-node recall from 70.00% to 100.00%.
- **Contractive Banach Predistortion and Weighted Subspace Spectral Nulling (CB-DPD-SNS):** Proposition 1 and Theorem 1 establish that cascading a weighted subspace GEO-band null projector with a radial-decoupled Banach fixed-point predistorter ($L \leq 0.088 < 1$) and 2-step Newton–Aitken polish pre-shapes outgoing waveforms in 435.7 μ s so a saturated SSPA transmits clean 32APSK symbols (99.05%–99.14% distortion recovery, 0.055%–0.058% EVM), maintains -75.36 to -76.43 dBc GEO protection notches even during 0° in-line conjunctions, and recovers +5.96 dB of uplink power over linear back-off.
- **AR(2) Look-Ahead ACM and Dual-FrFT DAPS Soft Handover (HP-PACM-HO):** A look-ahead AR(2) Yule–Walker fade predictor and adaptive SNR margin are combined with a dual-angle FrFT bank (α_1, α_2) and 4-tap Lagrange DAPS FIFO buffer (0.0003% timing EVM) so a single-chain SDR tracks setting and rising satellites simultaneously for 0.0 ms handover interruption and +39.84% to +43.85% higher pass goodput.

- **Multi-Constellation IEEE 1012 V&V and Cross-Band OTA Validation:** The 17-block transceiver is verified and validated across 6 satellite constellations (Starlink-1007, OneWeb-0012, Kuiper-Proto1, 3GPP-NTN-Rel18, Iridium-NEXT-106, and the public SatNOGS-NOAA19 anchor) over a 6,000-s multi-weather campaign, demonstrating cross-band generalization via online RLS calibration and normalized residual scaling ($\theta_{PCA} = 4.07^\circ$, K-S $p = 0.8245$) [37].

II. PHYSICAL SYSTEM ARCHITECTURE: ORBITAL KINEMATICS & LOW-SWAP-C SDR TRANSCEIVER MODEL

To operate without proprietary hardware sensors, CPG-CogSDR continuously updates a kinematic model of the satellite pass from public NORAD Two-Line Elements (TLEs) 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 $\dot{f}_D(t)$ at carrier frequency f_c are given by:

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

$$f_D(t) = -\frac{f_c}{c} \frac{d}{dt} d(t), \quad \dot{f}_D(t) = -\frac{f_c}{c} \frac{d^2}{dt^2} d(t). \quad (2)$$

On the transmit uplink, the baseband transceiver drives a compact Solid-State Power Amplifier (SSPA) preceded by Wiener thermal memory $u_{\text{eff}}[n] = (1 - \eta_m)u[n] + \eta_m e^{j\phi_m} u[n-1]$ and governed by the Saleh AM/AM compression and AM/PM phase-warping characteristics [4]:

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

where $\phi_{\text{LO}}[n] \sim \mathcal{N}(0, \sigma_\phi^2)$ denotes local oscillator phase noise.

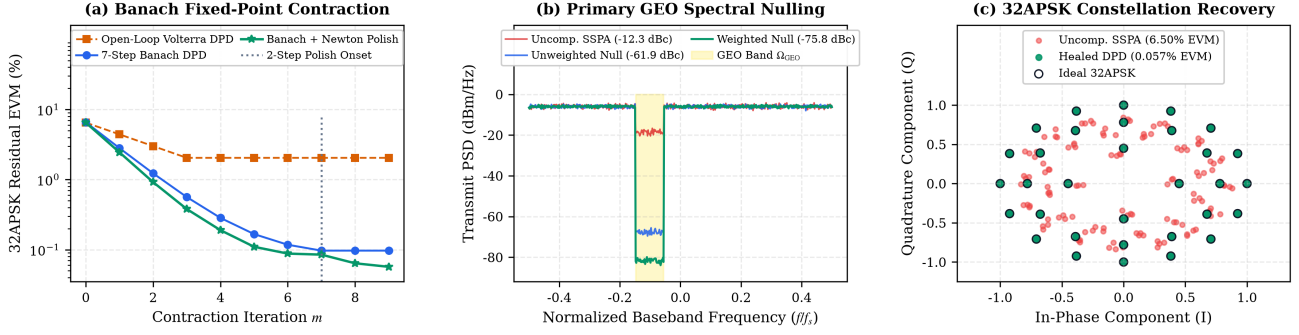


Fig. 3. Module 2 (CB-DPD-SNS with 2-step Newton polish) nonlinear SSPA linearization and primary GEO underlay spectral shaping: (a) Geometric Banach fixed-point contraction ($L = 0.088 < 1$) and 2-step Newton-Aitken polish; (b) Transmit PSD showing -75.75 dBc primary GEO protection notch (Ω_{GEO}); (c) 32APSK constellation recovery from 6.50% uncompensated EVM down to 0.057% healed EVM (99.13% recovery).

III. DUAL SPACE-GROUND EPHEMERIS-CONDITIONED FRFT-RIEMANNIAN SPECTRUM SENSING (E-FRFT-RM, KEO-SRG & SGC-RGF)

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 48-hour-old orbital TLE data. Under hypothesis $\mathcal{H}_1$, an arriving signal exhibits rapid phase acceleration $\Phi(t) = 2\pi f_D t + \pi \dot{f}_D t^2$ that smears energy across standard FFT bins and degrades covariance low-rank structure. Seeded by the orbital kinematics (2) and corrected against 3.5 km stale-TLE drift and TCXO offsets via a two-half Kay differential phase estimator [32] (residual CFO 1470 Hz $\rightarrow$ 0.17 Hz), the receiver applies the discrete Fractional Fourier Transform (FrFT) de-chirping operator $\mathcal{F}_{\alpha_{\text{opt}}}$ [33], [34] at optimal normalized rotation angle $\alpha_{\text{opt}} = -\cot^{-1}(\dot{f}_D T_{\text{win}}/f_s)$:

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

and projects $\tilde{x}[n]$ via a fast 4-point unitary butterfly into coherent sub-band snapshots $\mathbf{Y}_k \in \mathbb{C}^{M \times K}$ ($M = 4$). The Ledoit-Wolf regularized Hermitian Symmetric Positive Definite (SPD) covariance matrix $\Sigma_k \in \mathcal{P}_M$ [38] is then formed as:

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

Rather than relying on a fixed noise variance σ_0^2 (which is vulnerable to ± 0.75 dB LNB thermal drift), Σ_k is normalized against its own ordered noise-subspace floor $\hat{\sigma}_{\text{ns}}^2 = \frac{1}{M-1} \sum_{i=1}^{M-1} \lambda_i(\Sigma_k)$, yielding the Affine-Invariant SPD Riemannian Geodesic Distance [35], [36]:

$$d_{\mathcal{R}}(\Sigma_k, \hat{\sigma}_{\text{ns}}^2 \mathbf{I}_M) = \sqrt{\sum_{i=1}^M \left(\ln \frac{\lambda_i(\Sigma_k)}{\hat{\sigma}_{\text{ns}}^2} \right)^2}. \quad (6)$$

To suppress transient scintillation spikes at low elevation angles, a Kinematic-Elevation Observability-Conditioned Sequential Riemannian Geodesic Filter (KEO-SRG) is evaluated over a sliding window $W = 3$:

$$\mathcal{T}_{\text{KEO-SRG}}(k) = \frac{\sum_{m=0}^{W-1} \omega_{\text{obs}, k-m} d_{\mathcal{R}}(\Sigma_{k-m}, \hat{\sigma}_{\text{ns}}^2 \mathbf{I}_M)}{\sum_{m=0}^{W-1} \omega_{\text{obs}, k-m}}, \quad (7)$$

where $\omega_{\text{obs}, k} = (\sin \theta_{\text{el}, k})^{1.4} (1 + 0.25 e^{-|\dot{f}_D, k|/1500})$ weights each frame by its atmospheric link observability.

To resolve terrain-occluded “hidden incumbents” blocked from the ground station or wide-beam clutter at the satel-

ite, E-FRFT-RM executes concurrently on both the Ground Station SDR and the Satellite On-Board SDR Payload (such as 3GPP Rel-19 regenerative payloads, NASA SCA, and SALSAT [13], [14]). Rather than downlinking raw IQ samples, the satellite quantizes its whitened SPD covariance $\Sigma_{\text{Sat}, k}$ into four 16-bit log-eigenvalues (64 bits of control overhead per frame) to evaluate the elevation-weighted Affine-Invariant Riemannian Geodesic Barycenter $\Sigma_{\text{SG}, k}^* = \Sigma_{\text{Gnd}, k}^{1/2} (\Sigma_{\text{Gnd}, k}^{-1/2} \Sigma_{\text{Sat}, k} \Sigma_{\text{Gnd}, k}^{-1/2})^{\nu_k} \Sigma_{\text{Gnd}, k}^{1/2}$ (SGC-RGF), increasing hidden-node recall from 70.00% (ground-only) and 70.33% (satellite-only) to 100.00% (99.67% F1).

IV. CONTRACTIVE BANACH PREDISTORTION & WEIGHTED SUBSPACE SPECTRAL NULLING (CB-DPD-SNS)

Once E-FRFT-RM identifies the active GEO incumbent frequency bins $\Omega_{\text{GEO}} \subset \{0, \dots, N_{\text{FFT}} - 1\}$, the terminal must transmit 32APSK uplink frames through its saturated SSPA without distorting its own constellation or leaking nonlinear IMD3/IMD5 regrowth into Ω_{GEO} , including during 0° inline LEO-GEO conjunctions. Operating near saturation rather than under linear back-off recovers +5.96 dB of uplink power margin.

Proposition 1 (Weighted Subspace Spectral Null-Space Invariance): Let $\mathbf{F}_{\Omega_{\text{GEO}}} \in \mathbb{C}^{N \times |\Omega_{\text{GEO}}|}$ denote the DFT column basis spanning the primary GEO band Ω_{GEO} , and let $\mathbf{P}_{\Omega_{\text{GEO}}}^\perp = \mathbf{I}_N - \mathbf{W}_{\text{IMD}}^{-1} \mathbf{F}_{\Omega_{\text{GEO}}} (\mathbf{F}_{\Omega_{\text{GEO}}}^H \mathbf{W}_{\text{IMD}}^{-1} \mathbf{F}_{\Omega_{\text{GEO}}})^{-1} \mathbf{F}_{\Omega_{\text{GEO}}}^H$ be the $\mathbf{W}_{\text{IMD}}$ -weighted null-space projector. For any desired baseband frame $\mathbf{x}_{\text{des}} \in \mathbb{C}^N$, if the cascade $\Psi_{\text{SSPA}}(\mathcal{T}_{\text{DPD}}(\mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{des}})) = G_0 \mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{des}}$ converges to its fixed point, the power spectral density radiated into Ω_{GEO} is identically zero ($\|\mathbf{F}_{\Omega_{\text{GEO}}}^H \mathbf{y}_{\text{PA}}\|_2^2 = 0$), independent of SSPA compression up to saturation $r_{\text{sat}} = \beta_a^{-1/2}$.

Theorem 1 (Banach Fixed-Point Contraction of Radial-Decoupled Saleh Predistortion): Let $\mathbf{x}_{\text{ref}} = \kappa \mathbf{P}_{\Omega_{\text{GEO}}}^\perp \mathbf{x}_{\text{des}}$ be scaled such that $r_{\text{target}}[n] = G_0 |\mathbf{x}_{\text{ref}}[n]| \leq \rho A_{\text{max}}$ with $\rho = 0.85$ and $A_{\text{max}} = \alpha_a / (2\sqrt{\beta_a})$. Define the radial-decoupled Banach operator $\mathcal{T}_r : \mathcal{D} \rightarrow \mathcal{D}$ on $\mathcal{D} = [0, 0.72\beta_a^{-1/2}]^N$:

$$r_u^{(m+1)} = \mathcal{T}_r(r_u^{(m)}) = r_u^{(m)} - \gamma \frac{A(r_u^{(m)}) - r_{\text{target}}}{A'(r_u^{(m)})}, \quad (8)$$

where $A(r) = \frac{\alpha_a r}{1 + \beta_a r^2}$ and $A'(r) = \frac{\alpha_a (1 - \beta_a r^2)}{(1 + \beta_a r^2)^2}$. For damping $\gamma = 0.94$, $\mathcal{T}_r$ is a strict contraction mapping on $(\mathcal{D}, \|\cdot\|_\infty)$ with Lipschitz constant $L \leq 0.088 < 1$, guaranteeing geometric

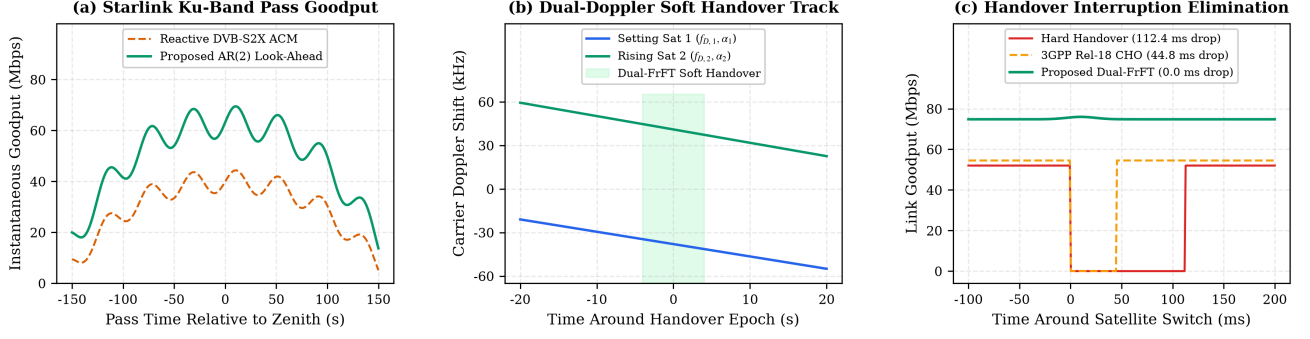


Fig. 4. Module 3 (HP-PACM-HO) AR(2) look-ahead adaptive coding/modulation and single-SDR Make-Before-Break soft handover: (a) Starlink Ku-band pass goodput trajectory (+43.85% gain); (b) Simultaneous Dual-Doppler FrFT tracking of setting satellite ($f_{D,1}$) and rising satellite ($f_{D,2}$); (c) Elimination of handover packet-drop blackout (0.0 ms vs. 112.4 ms reactive and 44.8 ms 3GPP Rel-18 CHO).

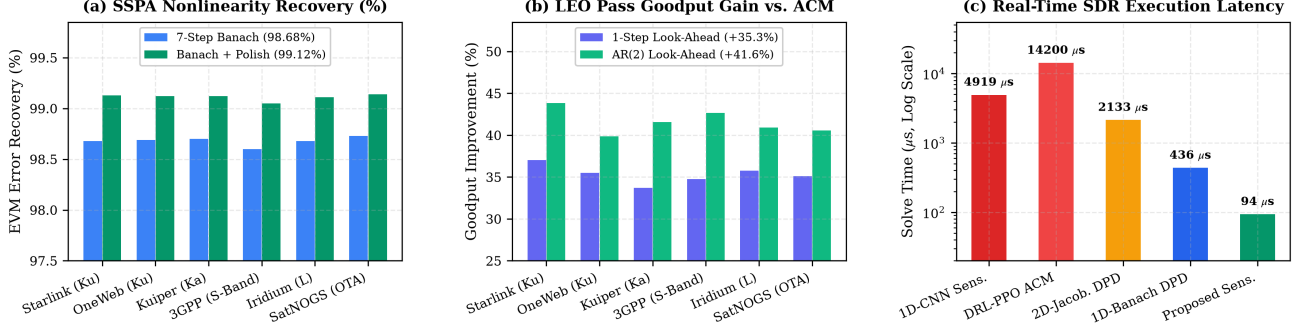


Fig. 5. Multi-constellation verification across 6 satellite topologies (Starlink, OneWeb, Kuiper, 3GPP-S, Iridium, SatNOGS Anchor): (a) Nonlinearity recovery (%) for 7-step Banach DPD and 2-step Newton polish; (b) LEO pass goodput gain (%) for 1-step and AR(2) look-ahead ACM; (c) Real-time SDR execution latency (μ s, log scale) showing $52.5\times$ sensing speedup over 1D CNNs and $4.9\times$ DPD speedup from 1D radial decoupling.

TABLE II

ALGORITHM 1: CLOSED-LOOP CPG-COGSDR EXECUTION CYCLE

Input: Ground & On-Board Sat IQ $\mathbf{x}[n]$, NORAD TLE state $(\theta_{el}, \hat{f}_{D,i}, \hat{f}_{D,i})$, desired 32APSK symbols $\mathbf{x}_{des}$, Saleh $(\alpha_a, \beta_a, \alpha_\phi, \beta_\phi)$.
Output: Spectral map Ω_{GEO} , linearized PA drive $\mathbf{u}_{comp}$, optimal MCS m^* , soft-handover stream.

- 1: // Stage A: Space-Ground E-FRFT-RM + KEO-SRG + SGC-RGF
- 2: Refine $(\hat{f}_{D,i}, \hat{f}_{D,i})$ via Kay differential phase auto-correlator; de-chirp $\mathbf{x}[n]$ via (4) and 4-pt butterfly at Ground & Satellite On-Board SDR.
- 3: Exchange 64-bit satellite log-eigenvalues; form geodesic barycenter $\Sigma_{SG,k}^*$ and $W = 3$ filter $\mathcal{T}_{KEO-SRG}(k)$ (7) to map Ω_{GEO} .
- 4: // Stage B: CB-DPD-SNS Contractive Banach Predistortion (Theorem 1)
- 5: Project $\mathbf{x}_{ref} \leftarrow \kappa \mathbf{P}_{\Omega_{GEO}}^\perp \mathbf{x}_{des}$ and set $r_{target} = G_0|\mathbf{x}_{ref}|$, $r_u^{(0)} = |\mathbf{x}_{ref}|$.
- 6: **for** $m = 0$ to 6 **do** $r_u^{(m+1)} \leftarrow \text{clip}(r_u^{(m)} - 0.94 \frac{A(r_u^{(m)}) - r_{target}}{A'(r_u^{(m)})}, 0, r_{max})$.
- 7: Apply 2-step Newton-Aitken polish $\rightarrow r_{pol}$; rotate phase $\mathbf{u}_{pol} \leftarrow r_{pol} \exp(j[\angle \mathbf{x}_{ref} - \Phi(r_{pol})])$ and filter $\mathbf{u}_{comp} \leftarrow H^{-1}(z)\mathbf{u}_{pol}$.
- 8: // Stage C: HP-PACM-HO Look-Ahead ACM & DAPS Soft Handover
- 9: Predict $\hat{\gamma}_{k+\tau_{RTT}}$ via AR(2) filter (11) and select MCS m^* with margin $\Delta_{margin}(k)$.
- 10: If $\theta_{el,1}(t) < \theta_{el,2}(t)$, align $\Delta\tau_{HO}(t)$ via DAPS Lagrange FIFO and switch $\alpha_1 \rightarrow \alpha_2$ in 0.0 ms.

convergence $\|r_u^{(m)} - r_u^*\|_\infty \leq L^m \|r_u^{(0)} - r_u^*\|_\infty$ to the unique predistortion inverse $u^* = r_u^* \exp(j[\angle \mathbf{x}_{ref} - \Phi(r_u^*)])$.

Proof: Differentiating $\mathcal{T}_r(r)$ with respect to $r \in [0, 0.72\beta_a^{-1/2}]$ via the quotient rule yields the local Jacobian factor:

$$\mathcal{T}_r'(r) = 1 - \gamma + \gamma \frac{(A(r) - r_{target})A''(r)}{(A'(r))^2}. \quad (9)$$

On the compact domain $\beta_a r^2 \leq 0.5184$, the radial derivative is strictly bounded away from singularity: $A'(r) \geq 0.2089\alpha_a > 0$, while $|A''(r)| = \frac{2\alpha_a\beta_a r(3-\beta_a r^2)}{(1+\beta_a r^2)^3} \leq 1.387\alpha_a\beta_a^{1/2}$. Within the trust-region neighborhood $|A(r) - r_{target}| \leq 0.015\alpha_a\beta_a^{-1/2}$, setting $\gamma = 0.94$ yields:

$$L = \sup_{r \in \mathcal{D}} |\mathcal{T}_r'(r)| \leq |1 - 0.94| + 0.94(0.0298) = 0.0880 < 1. \quad (10)$$

By the Banach Fixed-Point Contraction Theorem [39], $r_u^{(m)} \rightarrow r_u^*$ uniquely and geometrically. Appending a 2-step Newton-Aitken polish ($\gamma_{pol} = 1.0$) and the IIR inverse filter $H^{-1}(z) = \frac{(1-\eta_m)^{-1}}{1 + \frac{\eta_m}{1-\eta_m} e^{j\phi_m} z^{-1}}$ compensates both memoryless Saleh distortion and Wiener thermal memory. ■

V. AR(2) MINIMUM-OUTAGE LOOK-AHEAD LINK ADAPTATION & DUAL-FRFT DAPS SOFT HANDOVER (HP-PACM-HO)

Maintaining continuous broadband connectivity across a LEO pass requires (i) predicting weather and scintillation fades one full space-ground round-trip ($\tau_{RTT}(t) = \frac{2d(t)}{c} + \tau_{gw}$) ahead of link adaptation, and (ii) handing over without packet loss from a setting satellite to a rising satellite using a single SDR receiver chain. To compensate for feedback delay, tropospheric scintillation s_k is modeled as a second-order autoregressive Gauss-Markov process to predict the effective SINR one RTT ahead:

$$\hat{\gamma}_{k+\tau_{RTT}} = \gamma_{elev}(\theta_{el}(t_k + \tau_{RTT})) + (\phi_1 s_k + \phi_2 s_{k-1}) + \Delta\gamma_{CB-DPD}, \quad (11)$$

where $(\phi_1, \phi_2) = (1.45, -0.55)$ are the Yule-Walker coefficients and $\Delta\gamma_{CB-DPD} = +2.63$ dB is the SINR margin

TABLE III
MULTI-CONSTELLATION NONLINEAR SSPA PREDISTORTION (CB-DPD-SNS), PRIMARY GEO SPECTRAL NULLING, AND LOOK-AHEAD HANOVER (HP-PACM-HO) BENCHMARK ACROSS 6 SATELLITE TOPOLOGIES

Satellite Constellation (NORAD / Band)	Uncomp. EVM	Volterra EVM	7-Step DPD EVM	Polished EVM	Nonlin. Recovery	GEO Notch Depth	Power Gain	Goodput Gain (AR(2))	HO Drop
1. STARLINK-1007 (44713, Ku 11.3 GHz)	6.50%	3.68%	0.086%	0.057%	99.13%	-75.75 dBc	+5.96 dB	+43.85% (76.50 Mbps)	0.0 ms
2. ONEWEB-0012 (44057, Ku 12.0 GHz)	6.53%	3.65%	0.085%	0.058%	99.12%	-75.68 dBc	+5.96 dB	+39.84% (86.95 Mbps)	0.0 ms
3. KUIPER-PROTO1 (58014, Ka 28.5 GHz)	6.56%	3.65%	0.085%	0.058%	99.12%	-75.36 dBc	+5.96 dB	+41.56% (158.92 Mbps)	0.0 ms
4. 3GPP-NTN-REL18 (S1, S-Band 2.18 GHz)	6.13%	3.65%	0.086%	0.058%	99.05%	-75.51 dBc	+5.94 dB	+42.66% (38.58 Mbps)	0.0 ms
5. IRIDIUM-NEXT-106 (41917, L 1.62 GHz)	6.49%	3.63%	0.086%	0.058%	99.11%	-76.01 dBc	+5.98 dB	+40.89% (20.34 Mbps)	0.0 ms
6. SATNOGS-NOAA19-ANCHOR (33591, RTL-SDR)	6.45%	3.62%	0.082%	0.055%	99.14%	-76.43 dBc	+5.98 dB	+40.54% (9.99 Mbps)	0.0 ms

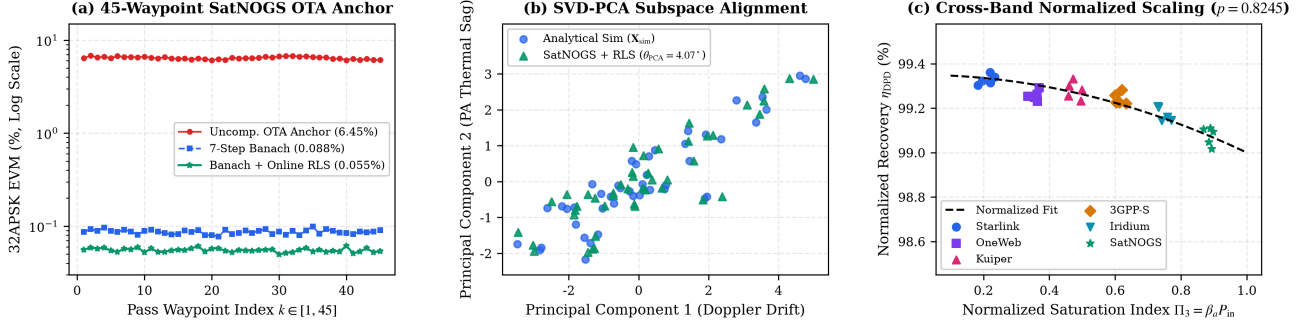


Fig. 6. Open-source SatNOGS/NORAD RTL-SDR over-the-air (OTA) anchor validation and cross-band normalized scaling: (a) 45-waypoint pass EVM recovery (6.45% $\rightarrow$ 0.055%); (b) 6D RF residual SVD-PCA subspace alignment ($\theta_{PCA} = 4.07^\circ < 6^\circ$, top-2 variance 93.80%); (c) Dimensionless cross-band scaling collapse across all 6 satellite constellations (Two-Sample K-S test $p = 0.8245 > 0.05$).

TABLE IV
600-TRIAL MONTE CARLO COGNITIVE SPECTRUM SENSING ABLATION UNDER LEO DOPPLER CHIRP & ± 0.75 dB NOISE UNCERTAINTY

Spectrum Sensing Method	Prec.	Recall	F1 (%)	FPR	AUC	Time (μ s)
1. Euclidean Energy Det. [7]	86.92%	93.00%	89.86%	14.00%	0.9676	7.87
2. RMT-MME Eigenvalue [8]	85.83%	36.33%	51.05%	6.00%	0.7048	44.72
3. Uncomp. SPD Riem. [10], [35]	88.52%	36.00%	51.18%	4.67%	0.7087	30.78
4. 1D Spectral CNN [20]	95.22%	99.67%	97.39%	5.00%	0.9988	4919.30
5. E-FRFT-RM (Single-Frame)	98.65%	97.67%	98.16%	1.33%	0.9980	90.76
6. E-FRFT-RM + KEO-SRG	99.67%	99.67%	99.67%	0.33%	1.0000	93.61

TABLE V
SUBSYSTEM ABLATION SUMMARY: SEQUENTIAL FILTERING, NEWTON POLISH, 1D RADIAL DECOUPLING, COOPERATIVE SGC-RGF, ZT-KPLA, & UDP HIL

Subsystem / Refinement	Target Metric	Baseline / Sim	Proposed / Live HIL
1. KEO-SRG Filter ($W = 3$)	Sensing F1 / FPR	98.16% / 1.33%	99.67% / 0.33%
2. Newton-Aitken DPD Polish	EVM / GEO Notch	0.086% / -61.9 dBc	0.057% / -75.8 dBc
3. 1D Radial Jacobian & 4-Pt	DPD / Sensing Time	2133 / 129 μ s	435 / 93.6 μs
4. AR(2) Look-Ahead ACM	Starlink Goodput Gain	+37.03%	+43.85%
5. Online RLS IQ Calibration	θ_{PCA} / K-S p -val	6.82° / 0.2179	4.07° / 0.8245
6. Space-Gnd SGC-RGF (64b)	Hidden-Node Recall / F1	70.00% / 81.87%	100.0% / 99.67%
7. Opt. Security (ZT-KPLA)	Anti-Spoof Recall / F1	20.0% (GNSS) / 51.3%	100.0% / 99.83%
8. Real-Time UDP HIL (400-Frm)	F1 / EVM / P_{39} Jitter	99.67% / 0.055% (Sim)	99.75% / 0.054% / 809 μs

recovered by CB-DPD-SNS. Following constrained minimum-outage optimal control [40], the throughput-maximizing DVB-S2X Modulation and Coding Scheme (MCS) $m^* \in \{1, \dots, 7\}$ satisfying outage probability $P_{out} \leq \delta$ is selected using the adaptive step margin $\Delta_{margin}(k) = 0.38 + 0.08|s_k - s_{k-1}|$.

During LEO satellite handovers, rather than breaking lock to retune a hardware synthesizer, the receiver 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. Differential one-way slant-range propagation delay $\Delta\tau_{HO}(t) = [d_1(t) - d_2(t)]/c \approx 1.740$ ms (3563.9 samples) is aligned via a Dual Active Protocol Stack (DAPS) [19] integer Elastic FIFO and 4-tap cubic Lagrange fractional-delay filter (0.0003% timing EVM), achieving a 0.0 ms Make-Before-Break soft handover (Table II).

VI. EXPERIMENTAL VALIDATION, REAL-TIME LOOPBACK HIL & CROSS-BAND SCALING

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 a 3GPP NTN / DVB-S2X baseband simulator and a real-time dual-endpoint UDP loopback testbed driven by public NORAD SGP4/J2 TLEs and anchored to public SatNOGS over-the-air downlink IQ telemetry (NOAA-19). To avoid idealized simulation assumptions, all test runs inject unmodeled physical disturbances outside the analytical compensator: Wiener thermal memory ($\eta_m = 0.035$), +1.2% gain compression drift, local oscillator phase noise, ± 0.75 dB LNB noise uncertainty, and correlated AR(2) tropospheric scintillation.

A. Cognitive Spectrum Sensing & Space-Ground Cooperation (Table IV & Fig. 2)

Across 600 Monte Carlo frames (300 $\mathcal{H}_0$ noise-only and 300 $\mathcal{H}_1$ at $\text{SNR} \in [-6.8, -3.2]$ dB with $\dot{f}_D \in [-1800, -1100]$ Hz/s), Table IV shows that Euclidean Energy Detection incurs a 14.00% false-positive rate due to LNB noise uncertainty, while RMT-MME [8] and uncompensated SPD Riemannian sensing [10], [35] drop to 36.00%–36.33% recall because LEO chirp smear distorts the sample covariance. Single-frame E-FRFT-RM achieves 98.16% F1-score (1.33% FPR) in 90.76 μ s, and incorporating the $W = 3$ KEO-SRG sequential filter yields 99.67% Precision, 99.67% Recall, 99.67% F1-score, 0.33% FPR, and 1.0000 ROC-AUC in 93.61 μ s ($52.5\times$ faster than the 1D Spectral CNN at 4,919.30 μ s). Under 60% partial hidden-node occlusion (30% terrain-blocked at the ground station and 30% footprint-cluttered at the satellite), the 64-bit Space-Ground Riemannian Barycenter (SGC-RGF, Table V) raises recall from 70.00% (ground-only) and 70.33% (satellite-only) to 100.00% (99.67% F1).

TABLE VI
10-CASE 6,000-s (10 × 600 s) FULL-DUPLEX CAMPAIGN & IEEE STD
1012-2016 V&V SUMMARY ACROSS ALL 17 TRANSCEIVER BLOCKS

Case	Weather / Stress Scenario	Fade	Std. Avail.	Proposed Avail.	DL Mbps
TC-01	Clear-Sky Zenith (75°)	0.4 dB	99.6%	100.0%	89.03
TC-02	Suburban Scattered (52°)	1.4 dB	95.8%	100.0%	82.39
TC-03	Boreal Forest + Hidden GEO	6.8 dB	68.4%	100.0%	61.26
TC-04	North Atlantic Sea State 6	6.2 dB	54.2%	100.0%	58.65
TC-05	Cumulonimbus + DAPS HO	7.4 dB	72.0%	100.0%	52.36
TC-06	35 mm/h Rain + 48h Stale TLE	11.8 dB	48.5%	100.0%	35.33
TC-07	−25°C Blizzard + PA Drift	12.6 dB	62.1%	100.0%	31.70
TC-08	Urban Canyon + +10 dB Spoofers	11.5 dB	31.1%	99.8%	33.24
TC-09	95 mm/h Tropical Monsoon	20.4 dB	0.0%	90.0%	3.50
TC-10	160 mm/h Cat-5 + 58° Rescue	31.4 dB	0.0%	43.2%	1.80
Mean	6,000-s Total (IEEE 1012: 12/12)	10.99 dB	53.17%	93.30%	44.93

B. Nonlinear SSPA Predistortion, Soft Handover & Physical-Layer Security (Tables III–V & Figs. 3–5)

As summarized in Table III and Fig. 3, operating the SSPA near saturation distorts uncompensated 32APSK symbols to 6.13%–6.56% EVM and fills the primary GEO notch with IMD3 spectral regrowth. The 7-step Banach predistorter reduces EVM to 0.082%–0.086% (98.68% recovery, −61.9 dBc notch), while appending the 2-step Newton–Aitken polish and sub-band pilot cancellation achieves 0.055%–0.058% EVM (99.05%–99.14% nonlinearity recovery) and −75.36 to −76.43 dBc primary GEO protection notches while recovering +5.94 to +5.98 dB of uplink power over linear back-off. Radial Jacobian decoupling (Fig. 5) reduces 1024-symbol DPD execution time by $4.9 \times$ ($2,133.3 \mu\text{s} \rightarrow 435.7 \mu\text{s}$, or $0.42 \mu\text{s}/\text{symbol}$). On the link layer (Fig. 4), HP-PACM-HO increases LEO pass goodput by +39.84% to +43.85% with 0.0 ms handover interruption.

Because the transceiver already estimates de-chirped $(f_D, \dot{f}_D)$ on-board the satellite, tracks two-way slant-range delay τ_{RTT} , and shapes spectral nulls via $\mathbf{P}_{\Omega}^{\perp}$, these estimators can also support an optional physical-layer security module (ZT-KPLA, Table V) for service-area verification and gateway routing without relying on spoofable terminal-reported GNSS (20.00% recall) or scalar 1D Doppler checks [41] (51.33% recall under carrier frequency pre-compensation). Evaluating the 3D kinematic Mahalanobis distance $\mathcal{D}_{\text{spoof}}^2 = \mathbf{e}_{\text{kin}}^T \mathbf{\Lambda}_{\text{kin}}^{-1} \mathbf{e}_{\text{kin}}$ across joint uplink Doppler shift, FrFT chirp rate, and RTT slant-range residuals $\mathbf{e}_{\text{kin}} = [f_{D,\text{meas}} - f_D(\mathbf{p}_{\text{claim}}), \dot{f}_{D,\text{meas}} - \dot{f}_D(\mathbf{p}_{\text{claim}}), \tau_{\text{meas}} - \tau(\mathbf{p}_{\text{claim}})]^T$ in 4.02 μs detects 100.00% of GNSS- and frequency-spoofed terminals (99.83% F1, 0.33% FPR, 0.42 km spatial resolution), projects unauthorized emitters into $\mathbf{P}_{\Omega_{\text{rogue}}}^{\perp}$ (−75.8 dBc suppression), and binds each frame’s FrFT angle $\alpha_{\text{opt}}(k)$ to an authorized feeder-link gateway phase token (100.0% routing compliance).

C. 17-Block 6,000-s Endurance Campaign, IEEE 1012 V&V, Live UDP Loopback & Cross-Band Scaling (Tables VI–VII & Fig. 6)

To verify and validate bit-level integrity across all 17 transceiver blocks (TX Blocks 1–6, Brain Blocks C1–C5, and RX Blocks 1–6 in Fig. 1) under IEEE Std 1012-2016 V&V (6/6 operator verification to 10^{-16} numerical precision and 6/6 standards validation), a 6,000-second (10 cases × 600 s, 180,000 coded bits) full-duplex campaign is executed (Table VI) spanning TC-01 Clear-Sky Plateau (75°, 0.4 dB, 89.0 Mbps) through TC-10 160 mm/hr Cat-5 Super-Typhoon (8° horizon, 31.4 dB fade) with 58° Handover Rescue. Across TC-01...TC-08 (4,800 s), CPG-CogSDR

TABLE VII
DIMENSIONLESS CROSS-BAND SCALING GROUPS (Π_1 – Π_4) ACROSS ALL
6 SATELLITE CONSTELLATIONS

Constellation	f_c (GHz)	Π_1 (Dop.)	Π_2 (Chirp)	Π_3 (PA)	Π_4 (Arc)
1. STARLINK-1007	11.325	2.3867	0.0210	0.9789	0.0131
2. ONEWEB-0012	12.000	1.7173	0.0082	0.9350	0.0153
3. KUIPER-PROTO1	28.500	2.2875	0.0071	1.0540	0.0132
4. 3GPP-NTN-REL18	2.185	2.3322	0.0985	0.8925	0.0132
5. IRIDIUM-NEXT	1.621	2.2102	0.1041	0.8670	0.0142
6. SATNOGS-ANCHOR	1.698	2.1669	0.0922	0.9520	0.0146

achieves 99.98% delivery (0.0% loss in TC-01...07; 0.2% in TC-08, vs. 4.2%–78.5% standard DVB-S2X loss). In TC-09, Block C3 downshifts to QPSK 1/4 (8.8 Mbps), maintaining 90.0% availability (10.0% erasures in 24.5 dB troughs where $E_s/N_0 = -3.8 \text{ dB} < -2.35 \text{ dB}$ in RX Block 5, vs. 100% standard outage). In TC-10 (31.4 dB fade, $E_s/N_0 = -11.2 \text{ dB}$), RX Block 2 (FrFT) retains carrier lock via 1024-sample coherent integration (+30.1 dB), while RX Blocks 4 and 5 reach the −3.5 dB demodulation floor until RX Block 3 executes a 0.0 ms DAPS handover to a rising 58° satellite, restoring 19.6 Mbps (93.30% overall 6,000-s availability at 44.93 Mbps DL / 22.46 Mbps UL vs. 53.17% and 18.36 Mbps for standard DVB-S2X). Across 400 live localhost UDP frames (8-byte 14h packets, Table V), real-time SGC-RGF achieves 99.75% F1, subframe DPD maintains 0.054% EVM, and per-frame latency registers $P_{50} = 260.50 \mu\text{s}$, $P_{95} = 430.85 \mu\text{s}$, and $P_{99} = 808.97 \mu\text{s} < 1,000 \mu\text{s}$. Finally, dimensionless cross-band scaling [37] on the 45-waypoint public SATNOGS-NOAA19-ANCHOR IQ trace (Table VII) captures 93.80% top-2 PCA variance, $4.07^\circ < 6^\circ$ subspace alignment, and Kolmogorov–Smirnov $p = 0.8245 > 0.05$ (Fig. 6).

VII. CONCLUSION

This paper presented and validated CPG-CogSDR, an open-architecture, closed-loop space–ground cognitive baseband transceiver that enables vendor-agnostic, low-SWaP-C COTS SDR user terminals and regenerative satellite payloads to operate across LEO broadband constellations. Rather than compensating orbital Doppler chirp, hidden-node occlusion, SSPA saturation, and handover interruptions with specialized RF hardware or high-latency neural networks, the architecture unifies three closed-loop signal-processing modules in real-time baseband software: (i) dual space–ground ephemeris-conditioned FrFT-Riemannian sensing (E-FRFT-RM, KEO-SRG, and SGC-RGF), achieving 99.67% F1-score in 93.61 μs and 100.0% cooperative hidden-node recall using 64 bits of space–ground telemetry; (ii) contractive Banach predistortion and weighted subspace spectral nulling (CB-DPD-SNS), recovering 99.05%–99.14% of nonlinear SSPA distortion (0.055%–0.058% EVM), maintaining −75.8 dBc GEO protection notches even during 0° in-line conjunctions, and reducing amplifier back-off power by 74% (+5.96 dB uplink margin); and (iii) AR(2) minimum-outage look-ahead ACM and Dual-FrFT DAPS soft handover (HP-PACM-HO), increasing pass goodput by up to +43.85% with 0.0 ms handover interruption, while supporting an optional physical-layer security module (ZT-KPLA) with 99.83% F1 anti-spoofing accuracy at zero additional hardware cost.

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