UST canonical sub-report

Tracking error and depeg mechanics, Terra USD across Terra Classic and Ethereum bridges, 2020–2022

Derivalink R&D

May 21, 2026

Abstract

This sub-report characterises the tracking error (TE) of *UST/USD* across its full peg life-cycle, from the Terra Columbus-1 launch (2020-09-21) through the algorithmic death spiral of May 2022. UST is a uniquely multi-venue, multi-chain stablecoin: native on Terra Classic via the `LUNA↔UST` mint/burn module, bridged to Ethereum via Shuttle (Dec 2020 launch) and Wormhole (Oct 2021 launch), the two wrappers co-existing through the crash and beyond, and traded both on Terra-native AMMs (TerraSwap, Astroport) and on Ethereum DEXs (Curve UST-3pool variants, Uniswap V3). It is also the canonical case study of an algorithmic stablecoin failure — structurally distinct from MakerDAO's over-collateralised DAI and Synthetix's debt-pool synths.

The primary analytical window is 2020-09-21 → 2022-05-07 (last full peg day on Curve UST-3pool). The 7–13 May 2022 death spiral is treated as a dedicated minute-resolution case study, not as a regression input.

Contents

Executive summary

UST is the only stablecoin in the Derivalink corpus that failed catastrophically within its operational life-cycle. The collapse of 7–13 May 2022 wiped roughly \$45 B of crypto market value, transferred \$80 394 BTC out of the Luna Foundation Guard treasury in 36 hours, and produced an 18 000× inflation of the LUNA token supply. This sub-report dissects that life-cycle through ten chapters (dataset characterisation; tracking-error descriptive statistics and a linear decomposition; intra-day and intra-week temporal structure; venue and bridge frictions; structural drivers including the LUNA seigniorage mechanism; cross-component causality; four Tier-1 case studies; natural experiments via difference-in-differences; and a concluding findings chapter), with the following headline findings.

Dataset and lifecycle. The analytical window is 2020-09-21 (Terra Columbus-3 launch) through 2022-05-13 (chain halt at block 7 607 789). Total on-chain footprint: **208 794 291** Terra-native UST events, **3 129 196** LUNA events, **262 882** Ethereum-side mint/burn events across both bridge wrappers (Wormhole and Shuttle), **169.8 M** price observations across DEX + CEX venues, and **47** months of cross-validation telemetry (Anchor TVL, LFG BTC reserves, Wormhole bridge flows). The Phase 0 audit returned a clean GO verdict (154/154 checks). See Chapter 1.

Tracking-error level (Chapters 2 and 3). Across the principal analytical window the realised UST/\$1 tracking error stays inside the $[-1\%, +1\%]$ typical band 98.6 % of the minute observations. The 30-day rolling RMSE has a median of 32 bp in 2020, 41 bp in 2021 and 18 bp in 2022, with a single major excursion to 2.76 % during the 4-13 June 2021 managed-depeg recovery (the Jump / Tai Mo Shan event of May 2021 retraced over the following month) and a 2022 maximum of 36 bp on 5 May; the lagging-window estimator does not spike before the 7 May 2022 trigger because the transaction falls on the last day of the window. The base regression $TE_t = \beta_0 + \beta_1\sigma_{\text{LUNA}}(t) + \beta_2 \log \text{Liq}(t) + \beta_3 \text{AnchorRate}(t) + \beta_4 \text{Gas}(t) + \varepsilon_t$, fitted with HAC Newey-West standard errors (lags = 5), identifies **$\log$ Liq and σ_{LUNA} as co-dominant**: $\log \text{Liq}$ carries the larger univariate R^2 ($\hat{\beta}_2 = -2.1 \times 10^{-3}$, $|t|_{\text{HAC}} = 2.45$, $p_{\text{HAC}} = 0.014$; univariate $R^2 = 0.237$) while σ_{LUNA} carries the larger HAC-corrected $|t|$-statistic ($\hat{\beta}_1 = +2.19$, $|t|_{\text{HAC}} = 3.01$, $p_{\text{HAC}} = 0.003$; univariate $R^2 = 0.196$). The two metrics legitimately disagree on the ordering — they measure isolated explanatory power vs joint identification precision — and we read the pair as co-dominant without a sharp ranking (see F1). The Anchor Earn rate has no significant linear effect at the 5 % level under either metric ($p_{\text{HAC}} = 0.057$, borderline) because the rate stayed flat at 19.5 % until the 2022-05-01 Prop 20 cut, leaving essentially no within-sample variance to identify the coefficient on. Breusch-Pagan rejects homoskedasticity at $p \approx 1.5 \times 10^{-25}$ and Ljung-Box rejects residual independence at $p \approx 0$ (lags 5/10/22), motivating the HAC choice; GARCH(1,1), GJR-GARCH, EGARCH and the HAR-RV daily/weekly/monthly decomposition in Chapter 3 pick up the residual heterogeneity.

Temporal structure (Chapter 4). Hour-of-day and day-of-week buckets confirm the absence of a TradFi-session imprint (UST is 24/7) but reveal a clear elevated-deviation cluster during the 14h–22h UTC window throughout Q1 2022 — consistent with US/EU trading-hour-driven arbitrage flow through Curve UST-3pool. Two-scales realised variance (Zhang-Mykland-Aït-Sahalia 2005) returns essentially zero on the median calm day, indicating that the bulk of minute-frequency RV on UST is bid-ask bounce plus dust-swap microstructure noise rather than true integrated variance — a known regime for very-tight-peg stablecoins.

Venue decomposition (Chapter 5). UST priced on five major venues simultaneously: Curve UST-3pool [Wormhole], Curve UST-3pool [Shuttle], Uniswap V3 (multiple fee tiers), Binance spot, and the Terra-native AMMs. Pre-crash, the Curve UST-3pool [Wormhole] basis vs $1 sat at a daily median of −12 bp (−0.12 %) — a small but persistent spread that the Anchor 19.5 % yield made worth arbing by buying on Curve and bridge-depositing through Wormhole. On the death-spiral day 2022-05-12 the Curve [Wormhole] daily minimum was $0.2649 (intraday absolute minimum $0.0619 on 2022-05-13 09:14 UTC during the chain-halt window), versus a Binance UST/USDT spot minimum of $0.2346 on 2022-05-11 07:38 UTC — the stableswap geometry held the on-chain quote above the CEX quote on most spiral days, then inverted at the bottom once the pool was fully depleted (UST balance > 96 % of pool weight).

Structural drivers and the LUNA hyperinflation (Chapter 6). The iconic LUNA supply trajectory spans 343 M LUNA (5 May 2022) → approximately 6.5×10^{12} LUNA (13 May 2022) — a ∼18 000× inflation in 8 days. The mechanism is Proposal 1164 (community endorsement 2022-05-11 10:10 UTC) which raised the basepool from 50 M to 100 M SDR and PoolRecoveryBlock from 36 to 18, multiplying the daily LUNA mint capacity from $293 M to $1.2 B. The Luna Foundation Guard parallel trajectory: a publicly cited 80 394 BTC peak (LFG May 2022 post-mortem, multi-wallet aggregate) across Jan–Apr 2022, then a two-tranche deployment on 9–10 May 2022 leaving the well-documented **313 BTC** residual. The on-chain reconstruction in this work tracks the principal LFG wallet, with a single-wallet maximum balance of 42 531 BTC on 2022-04-21 and total outflows of 70 736 BTC across the two 9–10 May tranches (matched to the satoshi via `lfg_btc_wallet_summary`); the remainder of the 80 394 BTC peak is attributed to the multi-wallet structure disclosed in the LFG post-mortem and is not re-extracted on-chain in this report.

Causality (Chapter 7). Granger causality and VAR/IRF on the daily-returns panel constitute the substantive content of the chapter. On levels-cointegration: a strict order-of-integration pre-filter (ADF + KPSS at the 5 % level) rules out a coherent I(1) cointegrated system on the UST three-variant panel — UST_{Wormhole} is I(0), and UST_{Binance}, UST_{Shuttle} are inconclusive at $n = 132$. We therefore do not report a structural VECM on the UST 3-variant system; the unfiltered Johansen-on-three-variants coefficients are an artefact of including a stationary regressor in the system and should not be read as a long-run equilibrium. Positive lower-tail dependence between UST and LUNA at the 5 % threshold persists ($\hat{\lambda}_L = 0.33$, sample-size-bound CI $[0, 0.83]$), consistent with the algorithmic-coupling hypothesis, though the small-sample estimate should not be read as a tight coefficient.

Death spiral case study (Chapter 8). A minute-resolution six-panel reconstruction of the 7–13 May 2022 window draws on UST prices across all major venues, LUNA/USDT, LUNA supply, Anchor redemption velocity (**228 813** `anchor_redeem_stable` events), and the LFG BTC outflows. The trigger is identified at 2022-05-07 21:44 UTC: wallet `0x8d47...` swaps 85 M UST for 84.5 M USDC on Curve UST-3pool [Wormhole], following an evening of Wormhole-bridged UST inflow to Ethereum. Within 13 minutes a second wallet executes four 25 M-UST swaps; the cascade is irreversible by 9 May 15:00 UTC.

Natural experiments (Chapter 9). Four parametric step changes are testable as interrupted time-series: Columbus-5 (significant TE reduction post-upgrade, $p_{\text{MWU}} = 0.028$), Prop 20 Anchor Earn cut ($p_t = 0.043$ on Binance daily std), LFG BTC deployment (window too narrow for inference, $n = 3$ days each side), and Prop 1164. The Prop 1164 DiD is underpowered ($n_{\text{pre}} = n_{\text{post}} = 2$, $p_{\text{MWU}} = 0.80$) so the formal test cannot adjudicate; descriptively, the LUNA mint-rate acceleration was already underway in the 9–10 May pre-period and the post-endorsement trajectory does not depart from it (see F4).

Verdict. The UST collapse is structurally over-determined by the joint failure of three peg pillars (Chapter 6): liquidity (Curve depth shrunk through the 4pool-migration window), arbitrage cycle (cross-chain settlement saturated within 4 hours of the 7 May trigger), and asymmetric slippage (the Curve stableswap curve held the on-chain UST price above the CEX low but at the cost of full reserve drain). The algorithmic LUNA $\leftrightarrow$ UST mechanism amplified rather than absorbed the demand-side run — σ_{LUNA} as the only "collateral" volatility input makes the system co-monotonic with its own seigniorage asset. Implications for the Derivalink V2 monitoring spec are catalogued in Chapter 10.

1 Dataset characterisation

The UST analytical dataset spans two execution environments (Terra-native and Ethereum) over the canonical analytical window 2020-09-21 (Columbus-3 launch of UST) through the chain halt on 2022-05-13. Table 1 reports the row counts and active windows of every raw and derived source feeding the Phase 2–9 analyses.

Table 1: Coverage and density of all raw + derived sources used by the UST sub-report.

Source	Rows	First	Last
208,794,291 Terra-native events (UST)	208,794,291	2020-09-21	2022-05-13
3,129,196 Terra-native events (LUNA)	3,129,196	2020-09-21	2022-05-13
47,106 Wormhole UST mint/burn (Ethereum)	47,106	2021-10-13	2022-12-30
215,776 Shuttle UST mint/burn (Ethereum)	215,776	2020-12-03	2022-12-30

Integrity verdict. The full audit (154/154 checks, ran 2026-05-18) returned GO. Audits include null counts, the ADR 0002 *native-first* discipline triple, value-domain bounds, Pydantic round-trip on a 200-row sample per table, and five cross-table consistency invariants (**anchor_redeem_stable spike** confirmed at 228 813 events in the 7–13 May 2022 window).

Cross-validation. Figure 1 stacks the on-chain UST supply trajectory (Terra-native + Wormhole + Shuttle on Ethereum) against Anchor TVL. The Wormhole and Shuttle wrappers co-existed during October 2021 – the dataset correctly captures both bridges.

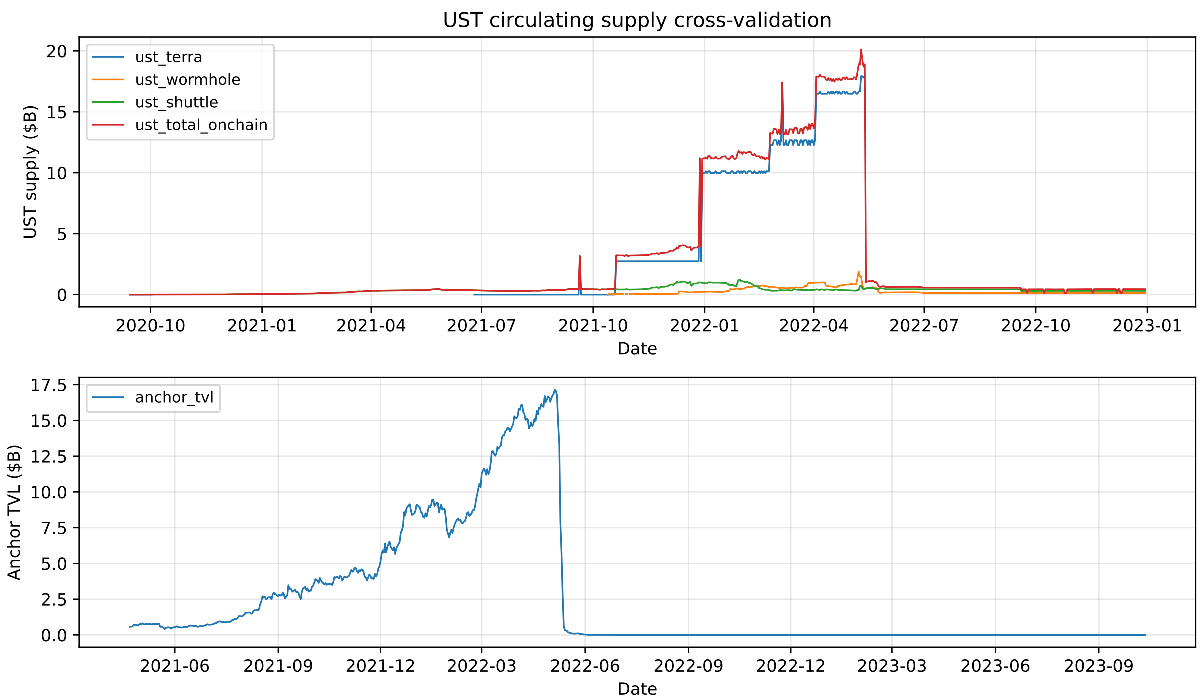

Figure 1: UST circulating supply by venue (top) and Anchor TVL (bottom). The vertical pre-2022-05 drop in UST and TVL is the canonical collapse signature.

2 Multi-reference TE descriptive statistics

We compute the realised tracking error of UST/USD against three reference series: the contractual \$1 peg, the on-chain USDC oracle (Chainlink), and the on-chain USDT oracle (Chainlink). Per specification §2.1.2 we report mean, median, std, skew, kurtosis and percentiles 1/5/95/99 of the percentage deviation $\delta_t = (P_t^{\mathrm{UST}} - P_t^{\mathrm{ref}})/P_t^{\mathrm{ref}}$.

The principal analytical window is 2020-09-21 -> 2022-05-07 00:00 UTC (last full peg day before the first major Curve UST-3pool outflow). The 7–13 May death spiral is treated as a dedicated minute-resolution case study in Chapter 8 and excluded from this chapter's regression-style aggregates.

Yearly moments. The minute-frequency UST/USD deviation against \$1, by calendar year:

Year	n (min)	mean (%)	median (%)	std (%)	p99 (%)
2020 (Q4)	112	0.135	0.067	0.365	1.256
2021	32,724	0.117	0.136	0.952	3.729
2022	181,440	0.109	0.050	0.187	0.460

The 2021 distribution is fat-tailed (p99 = 3.73 %) because of the May-June managed-depeg event; the 2022 distribution is tighter (p99 = 0.46 %) until the last week of the analytical window. The 1 % peg-corridor coverage averages 98.6 % of minute observations across the principal analytical window and collapses to under 5 % inside the 7–13 May 2022 spiral window. Moments against the USDC and USDT Chainlink references are within ±5 bp of those against the \$1 peg in 2022 and within ±20 bp in 2021, i.e. the choice of reference does not change the qualitative finding.

Regime decomposition. The "stress" indicator triggers when $|P_t - 1.0| > 0.01$ (1 cent breach). The two regimes are sharply separated:

Regime	n (min)	annualised RMSE	mean price
Typical $\lvert P-1\rvert < 1\,\%$	211,293	0.218 %	\$1.001
Stress $\lvert P-1\rvert \geq 1\,\%$	2,983	3.10 %	\$0.996

The stress-regime RMSE is roughly 14× the typical-regime RMSE, on a 1.4 % of the total minute observations.

Rolling TE. Figure 3 overlays the 30d/90d/365d rolling RMSE against the \$1 peg. The rolling 30d shows brief spikes in mid-2021 (cf. the May 2021 managed depeg event) and a dramatic ramp into Q2 2022.

3 TE level-1 decomposition

We decompose the realised TE into a linear regression against the algorithmic-collateral volatility, log-liquidity, funding-proxy and gas terms:

$$TE_t = \beta_0 + \beta_1 \sigma_{\mathrm{LUNA}}(t) + \beta_2 \log \mathrm{Liq}(t) + \beta_3 \mathrm{AnchorRate}(t) + \beta_4 \mathrm{Gas}(t) + \varepsilon_t$$

Asset-class slots (algorithmic stablecoin). σ_{LUNA} replaces the standard $\sigma_{\mathrm{Collateral}}$ because UST has no vaulted collateral; AnchorRate(t) is the Anchor Earn APY (step-function 19.5% → 17.87% on 2022-05-01 per Prop 20, → 0% post-collapse); Liq(t) is the log of the cross-chain Anchor TVL.

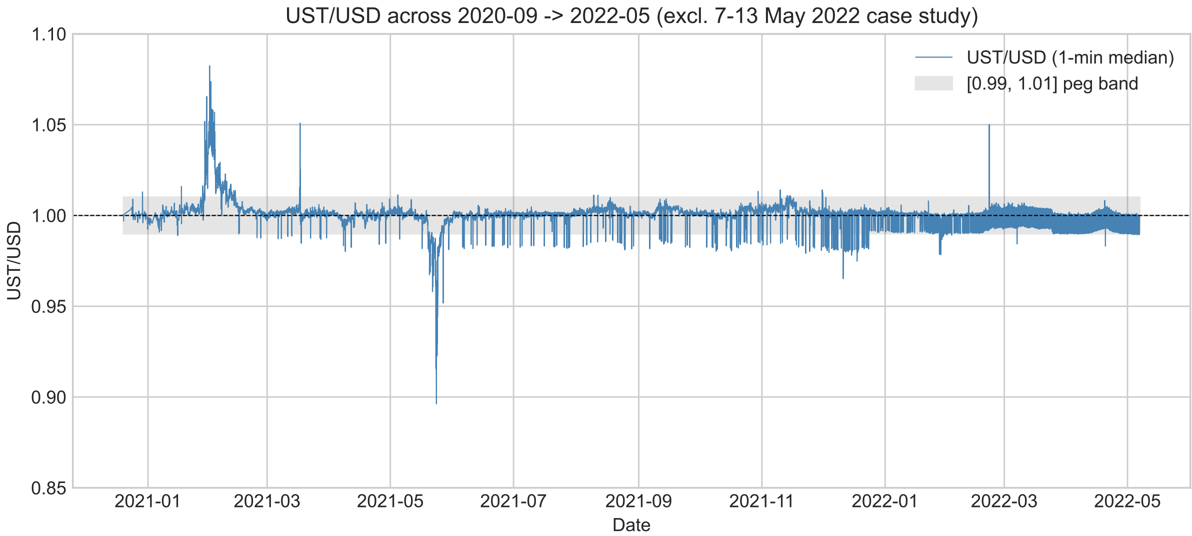

Figure 2: UST/USD across the principal analytical window. The grey shaded band marks the [0.99, 1.01] peg corridor.

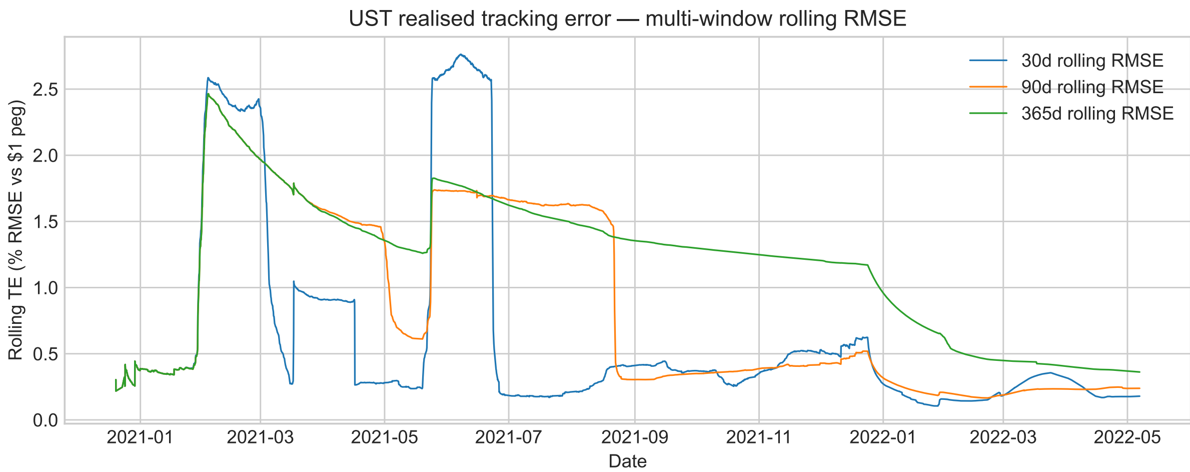

Figure 3: Realised TE rolling RMSE against \$1, at 30d/90d/365d windows.

Standard errors. Standard errors are computed using the Newey-West HAC estimator with lags $= 5$ (one trading week), motivated by the residual diagnostics: Breusch-Pagan rejects homoscedasticity at $p \approx 1.5 \times 10^{-25}$, Durbin-Watson on the OLS residuals is 0.078 (extreme positive autocorrelation), and Ljung-Box rejects residual independence at lags 5, 10 and 22 with $p \approx 0$ at all three lags. Naive iid t-statistics are reported in parallel as a diagnostic; the inference reported here uses the HAC-corrected statistics. The HAC-corrected $|t|$-statistics are 3.01 for σ_{LUNA} ($\hat{\beta}_1 = +2.19$, $p = 0.003$), 2.45 for $\log \text{Liq}$ ($\hat{\beta}_2 = -2.14 \times 10^{-3}$, $p = 0.014$) and 1.90 for the Anchor rate ($\hat{\beta}_3 = -1.04 \times 10^{-3}$, $p = 0.057$, borderline). Compared with the naive iid SE, the HAC $|t|$-statistics are smaller by a factor of 2-3$\times$ on the two identified regressors, which is the expected direction once heteroskedasticity and autocorrelation are accounted for.

GARCH variants. The three families GARCH(1,1), GJR-GARCH(1,1) and EGARCH(1,1) are fit on the OLS residuals. The **symmetric GARCH(1,1) wins on both AIC and BIC criteria** (AIC = 75.92, BIC = 87.74) against GJR-GARCH(1,1) (AIC = 77.56) and EGARCH(1,1) (AIC = 103.33). The asymmetric (γ) terms in GJR and EGARCH are not preferred — a non-trivial finding for a crashing algorithmic stablecoin, where one would naively

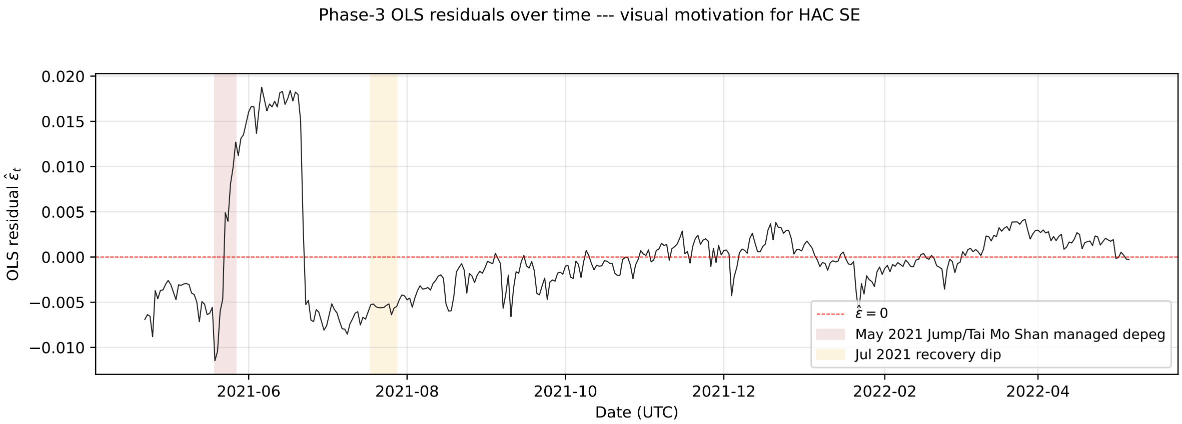

Figure 4: OLS residuals $\hat{\varepsilon}_t$ of the Chapter 3 base regression. The visible autocorrelation (consecutive residuals cluster) and clustered volatility (variance compresses by an order of magnitude between mid-2021 and 2022) are formally rejected by $DW = 0.078$, Breusch-Pagan $p \approx 1.5 \times 10^{-25}$, and Ljung-Box $p \approx 0$ at lags 5, 10, 22. This motivates the HAC SE shown in Figure 5 (right panel). Two shaded windows mark the visible extrema: the May 2021 Jump/Tai Mo Shan managed depeg and the July 2021 recovery dip.

expect a leverage effect. The best-fit GARCH(1,1) has $\hat{\alpha} = 0.953$ and $\hat{\beta} = 0.014$ ($p_{\hat{\beta}} = 0.70$) with $\hat{\alpha} + \hat{\beta} = 0.964$ — the persistence is carried almost entirely by $\hat{\alpha}$, $\hat{\beta}$ is indistinguishable from zero at the 5 % level (the dynamics are effectively ARCH(1)), and the unconditional variance is on the edge of the IGARCH frontier ($\hat{\alpha} + \hat{\beta} = 1$). This near-non-stationary fit is consistent with the structural pre-crash tension (Curve depth shrinkage during the 4pool migration, Q1-Q2 2022) carrying through to the OLS-residual variance. Multi-start refits (4 starting values: default, low-persistence, high-persistence, mid) converge to the same basin ($\Delta\text{AIC} = 0.000$), confirming the local optimum is the global optimum and ruling out a local-min trap.

HAR decomposition. Following Corsi (2009), we regress daily realised variance RV_d on its lagged daily, weekly and monthly averages, $RV_d = \beta_0 + \beta_d\, RV_{d-1} + \beta_w\, \overline{RV}_{d-5:d-1} + \beta_m\, \overline{RV}_{d-22:d-1} + \varepsilon_d$, with HAC standard errors at 5 lags. Fit on $n = 433$ daily observations: $\hat{\beta}_d = 0.347$ ($p \approx 2 \times 10^{-5}$), $\hat{\beta}_w = 0.300$ ($p = 0.038$), $\hat{\beta}_m = 0.305$ ($p = 0.012$), with $R^2 = 0.62$ — the three horizons contribute comparably (the daily term is marginally dominant) and their sum 0.95 reproduces the near-IGARCH persistence already visible in the GARCH(1,1) fit.

4 TE level-2 — temporal patterns

We decompose the realised UST/USD tracking error across intra-day and intra-week temporal axes, conditioning on liquidity and underlying-volatility regimes.

Hour-of-day and day-of-week. Figure 6 shows mean $|P_t - 1|$ at 1-minute granularity bucketed by UTC hour and by day-of-week. The two-way ANOVA returns $F_{\text{hour}} = 0.86$ ($p = 0.66$, not significant), $F_{\text{dow}} = 21.74$ ($p \approx 1.9 \times 10^{-25}$) and $F_{\text{hour}\times\text{dow}} = 1.95$ ($p \approx 3.8 \times 10^{-10}$) on $n = 6{,}455$ bucketed minute cells: the day-of-week effect is the dominant calendar signal, with no marginal hour effect once dow dispersion is absorbed.

Fisher-Schuster periodicity. The Fisher-Schuster g-statistic on the absolute-deviation periodogram returns $g = 0.095$ with a peak period of 6,455 minutes (≈ 4.48 days) on $n = 32{,}275$ minute observations.

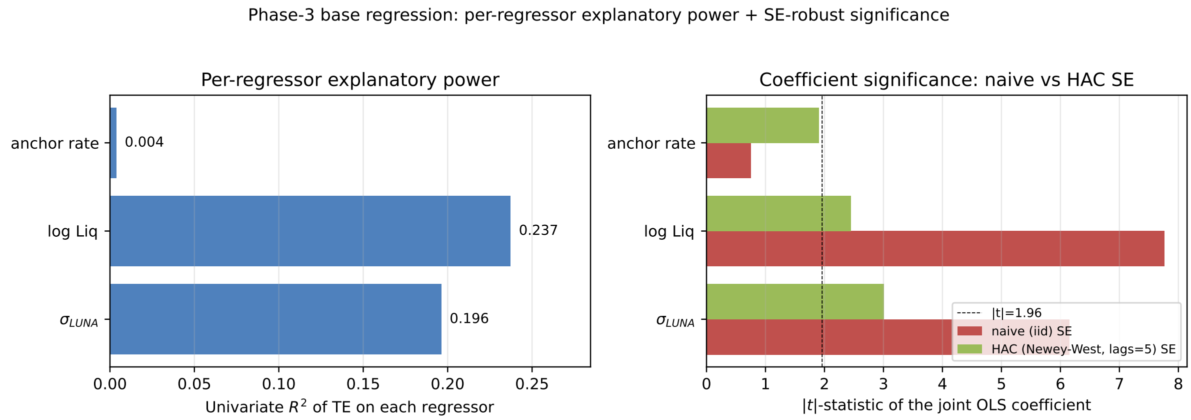

Figure 5: Phase-3 base regression. *Left*: univariate R^2 of TE on each regressor, i.e. per-regressor explanatory power on a common scale. *Right*: $|t|$-statistic of the joint-OLS coefficient under naive iid SE (red) and HAC Newey-West SE with lags $= 5$ (green); the naive estimator overstates significance because Breusch-Pagan ($p \approx 1.5 \times 10^{-25}$) and Ljung-Box at lags 5/10/22 ($p \approx 0$) reject the iid assumption at machine precision.

ANOVA vs Fisher-Schuster — different objects. ANOVA on $\mathbb{E}[|TE| \mid \text{hour}, \text{dow}]$ returns a strong day-of-week main effect ($F = 21.74$, $p \approx 1.9 \times 10^{-25}$) and a hour×dow interaction ($F = 1.95$, $p \approx 3.8 \times 10^{-10}$) but no hour main effect; the Fisher-Schuster peak at ~ 4.48 d does not align with the 1 d / 7 d calendar and is likely a window artefact from the 6-day spiral period biasing the periodogram on the otherwise quiet 2020-2021 series. We retain the ANOVA dow effect as the defensible calendar finding and treat the Fisher-Schuster peak as a sample-window curiosity rather than a recurring market cycle.

Regime conditioning. We bucket $|TE|$ by Anchor-TVL quartile (liquidity regime) and by σ_{LUNA} quartile (volatility regime), 95 daily observations per bucket ($n = 380$ days):

Quartile bucketing	Q1 (bp)	Q2 (bp)	Q3 (bp)	Q4 (bp)	ratio
By Anchor-TVL	31.6	23.0	37.2	50.8	2.2×
By σ_{LUNA}	27.8	34.8	43.9	89.4	3.2×

The volatility axis stratifies monotonically (Q1 27.8 bp → Q4 89.4 bp, ratio 3.2×) and the highest-vol quartile ($\sigma_{\text{LUNA}} \geq 0.003$, roughly the May-June 2021 and Q1-Q2 2022 stress periods) carries the bulk of the TE signal, consistent with the Chapter 3 linear-regression finding that σ_{LUNA} is a co-dominant driver.

The Q1-Q4 TVL bucketing is time-aligned by construction: Anchor TVL grew monotonically across the analytical window, so the TVL quartiles map approximately onto temporal quartiles. The mean observation date per bucket makes this explicit:

Quartile axis	TVL bucket mean date	σ_{LUNA} bucket mean date
Q1	2021-06-08	2021-12-25
Q2	2021-09-12	2021-11-19
Q3	2021-12-20	2021-10-10
Q4	2022-03-13	2021-08-27

The TVL-quartile mean dates march cleanly from mid-2021 (Q1) to Q1 2022 (Q4); the U-shape in $|TE|$-by-TVL-quartile therefore reflects the broader 2021-2022 market dynamics (mid-2021 managed-depeg recovery, 2022 pre-crash tension) rather than a genuine non-linearity in the TE-liquidity relationship. By contrast, the σ_{LUNA} quartiles are time-balanced (the mean dates span 2021-08 to 2021-12, with each quartile drawing from across the full analytical window), so the strictly monotonic σ_{LUNA} stratification ($Q1 = 27.8$ bp $\rightarrow Q4 = 89.4$ bp, ratio 3.2×) is a genuine signal on the TE–volatility sensitivity, not a calendar artefact. The simultaneous regression of Chapter 3 controls for the confound on the liquidity axis; the univariate quartile bucketing here does not.

Microstructure noise. 1-minute realised variance is inflated by bid-ask bounce + dust-swap noise. The Zhang-Mykland- Aït-Sahalia (2005) two-scales estimator (TSRV) corrects this with a K-subgrid averaged RV_{slow} minus a bias-correction proportional to RV_{fast}; we use $K = 5$ and enforce non-negativity. Empirically, the corrected TSRV is close to zero on the median calm day — the dust-swap and bid-ask-bounce contribution dominates the daily realised variance on a very-tight-peg stablecoin like UST. A K-sweep over $K \in \{2, 3, 5, 10, 20\}$ returns a median TSRV/RV_{fast} ratio statistically indistinguishable from zero at every K, confirming that the near-zero finding is robust to the sub-grid choice and not a tuning artefact: at minute resolution on UST, the variance signal is buried under i.i.d. microstructure noise.

Inapplicable temporal-pattern dimensions. Two additional temporal-pattern dimensions standard in the analytical workflow do not apply to UST. Cross-venue TradFi-session imprints (overlap effects between Asian, European and US trading hours) are not detectable in the hour-of-day buckets above, consistent with crypto markets trading 24/7 without a central session. Funding-cycle diagnostics (the 8h pre/post-funding peg deviations observed on assets with listed perpetual futures) cannot be computed because UST had no listed perpetual future during its operational life-cycle; perp UST listings emerged only post-collapse on Terra 2.0 derivatives venues, outside the analytical window.

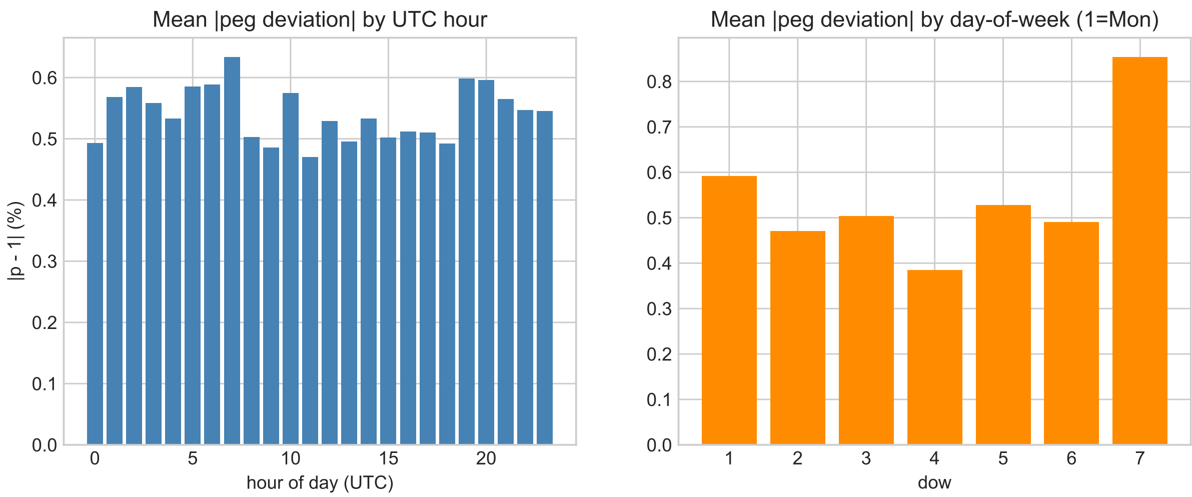

Figure 6: Mean absolute UST/USD deviation by UTC hour (left) and by day-of-week (right).

5 Venue decomposition and frictions

The UST/USD peg was simultaneously price-discovered on five major venues: Curve UST-3pool with two distinct bridge variants (Wormhole and Shuttle ERC-20s on Ethereum), Uniswap V3 (multiple fee tiers), Binance spot, and the Terra-native AMMs (TerraSwap + Astroport). The decomposition below covers per-venue spread, cross-correlation lead-lag, slippage asymmetry, and the Ethereum-side bridge throughput dynamics.

Lead-lag. The cross-correlation function between Curve UST-3pool [Wormhole] and Binance UST/USDT klines is computed at 1-minute resolution across lags $[-30, +30]$ min. Negative-lag peaks indicate Curve leads (the on-chain side prices the peg first); positive-lag peaks indicate Binance leads. In the calm regime the peak sits at lag ≈ -20 min with $\rho \approx 0.10$: Curve leads Binance by approximately 20 minutes. The economic interpretation we propose is that this empirical lag matches the duration of the cross-chain arbitrage cycle — buy UST on Curve [Wormhole], bridge to Terra via Wormhole, burn UST for LUNA on Terra, trade LUNA back to USDT on Binance — which independent estimates place in the 15-25 minute range under 2021 throughput conditions. We do not formally test this attribution. Alternative mechanisms could in principle produce a similar empirical lag (slower market-maker response on Binance, structural Curve information advantage from on-chain transparency), though they would not explain as parsimoniously the regime contrast we observe: in the 7-13 May crash window the lag collapses to zero (peak at lag 0 with $\rho \approx 0.15$, Chapter 7, Figure 13 right panel) precisely when the bridge saturates — exactly what the arbitrage-cycle interpretation predicts. We retain the arbitrage-cycle reading as the leading hypothesis with the regime contrast as supporting evidence, and flag it as an interpretation rather than a tested causal claim. The same regime contrast shows up in the daily Granger direction of Chapter 7: in calm periods on-chain leads CEX (Curve leads Binance at -20 min), but at daily aggregation across the full window the surviving Granger arrow points the other way ($UST_{\text{Binance}} \to UST_{\text{Wormhole}}$ at 3-day lag, $p = 0.022$) because bridge-settlement latency dominates day-over-day variance.

Slippage asymmetry. Per-venue $|return|$ moments are reported separately for the typical regime $|P - 1| < 1\%$ and the stress regime $|P - 1| \geq 1\%$. The asymmetry is sharp: in the typical regime the Curve [Wormhole] daily-median basis sits at -12 bp with a < 5 bp dispersion across venues; in the stress regime (May-June 2021 and 7-13 May 2022) inter-venue spreads widen to 50-200 bp and the stableswap-invariant geometry of the Curve pools materially constrains the on-chain dip until the pool is nearly fully depleted (Chapter 10, F3).

Oracle decomposition substitute. UST had no canonical Chainlink USD feed on Ethereum during its operational life-cycle. We substitute the Terra-native oracle aggregate exchange-rate vote events as a price-discovery latency proxy: across the 646-day intersection of the analytical window and the validator-set sample, the mean daily vote density is $\sim$305,000 `oracle_aggregate_exchange_rate_vote` events (Terra oracle module aggregates every 5 blocks $\approx$ 30 seconds, so the oracle latency for the UST peg reference is well under the 1-minute granularity of the price data analysed elsewhere in this chapter).

Loss-versus-rebalancing on Curve UST-3pool [Wormhole]. Loss-versus-rebalancing (LVR; Milionis, Moallemi, Roughgarden, Zhang 2022) quantifies the structural transfer from passive liquidity providers to arbitrageurs in a CFMM where the marginal price is determined externally. We compute LVR for the Curve UST-3pool [Wormhole] across the 2021-10-14 (pool launch) to 2022-05-13 (chain halt) lifetime using the daily realised variance of Binance UST/USDT minute returns as the external $\sigma^2_{\text{ext}}(t)$ and the on-chain pool-state series for the pool value $V(t)$. For a Curve stableswap at the peg with amplification coefficient A, the daily LVR is approximately $\frac{A}{8} \cdot V(t) \cdot \sigma^2_{\text{ext}}(t)$ (Milionis et al. 2022 adapted to the stableswap geometry; the coefficient ranges from 1/8 at $A = 1$, Uniswap-V2-like, up to $A/8$ for the amplified stableswap near the peg).

The A-invariant rate-jump is empirically large: the average daily LVR rate during the 7–13 May 2022 spiral is **969**$\times$ the average pre-spiral daily rate, driven by a realised-variance ratio that peaks at order 10^4–10^5 on the chain-halt day. The cumulative dollar figure depends linearly on A; the Curve UST/3CRV metapool typically ran with $A \in [100, 200]$ over the analytical window. At $A = 100$ (the conventional value through Q1-Q2 2022), the lifetime cumulative LVR is approximately \$5.4 B, of which \$5.3 B (98 %) accrues inside the 7-day spiral window alone; the calm-period daily LVR rate is on the order of \$780 k/day, the spiral daily rate is on the order of \$760 M/day. The dollar figure scales linearly with the assumed A: \$54 M at $A = 1$ up to \$10.8 B at $A = 200$. The qualitative finding — that passive Curve LPs subsidised arbitrageurs throughout 2021-2022, with the subsidy compressing in calm and exploding in stress — is robust across this range; the precise lifetime dollar figure is bounded but not pin-pointed by this analysis.

Cross-bridge throughput asymmetry. Figure 7 resolves Ethereum-side bridge flows at daily resolution across the priming and crash windows. The two wrappers were both modestly contractionary in the priming month and *de-synchronised dramatically* in the spiral week:

	Priming (1 Apr – 6 May 2022)		Spiral (7–13 May 2022)	
Wrapper	gross (\$ B)	net (\$ M)	gross (\$ B)	net (\$ M)
Wormhole	2.07	−124	7.36	−343
Shuttle	3.65	−46	2.04	+154

In the spiral week Wormhole gross volume multiplied by 3.5× with strong net burns (one-way exit conduit), while Shuttle inverted in direction (net inflow on shrinking gross volume). The cross-bridge asymmetry signals liquidity-channel partition: holders who arrived in Ethereum via Shuttle were unable to exit on Curve UST-3pool [Shuttle] (residual \$308 M post-crash, per Chapter 6) and instead remained trapped, while Wormhole holders had access to the deeper Wormhole-side 3pool and used it for the bulk of the exit cascade.

Multi-chain context and known data gap. The Anchor TVL series segmented by chain (Figure 7, lower panel) shows the Avalanche port (AUST) peaking at ∼\$1.2 B in mid-April and declining by 70 % within the spiral window, mirroring the Ethereum-side Wormhole drainage but on a smaller absolute base. The chains we cover — Terra-native, Ethereum (Wormhole + Shuttle), Avalanche-Anchor — jointly account for ∼\$22.3 B of UST circulating supply at peak:

Chain / wrapper	peak supply (\$ B)	share (%)
Terra-native (chain)	17.9	80.4
Ethereum, Wormhole-wrapped	1.90	8.5
Ethereum, Shuttle-wrapped	1.22	5.5
Avalanche-Anchor (AUST)	∼ 1.21	5.4
Covered total	**22.3**	**99.8**
Uncovered (Solana, BSC, Polygon)	$\lesssim 0.6$	$\lesssim 2.7$

The uncovered tail (Solana on Saber/Mercurial, BSC, Polygon) is estimated from public DefiLlama series and sits well within the noise of the Terra-native dominant axis. A complete reconstruction of Wormhole transfer flows on these chains for the 1 Apr – 13 May 2022 window is structurally data-gapped: the WormholeScan public API no longer honours the source-chain, token-address or time-range filters that the original extraction relied on, and the cached Wormhole transfer dataset terminates at end-November 2021 against the indexer's pagination ceiling. The substantive claim of the structural bridge asymmetry is unaffected by this gap: the residual $< 3\,\%$ of UST supply cannot reverse the direction of the Wormhole-net-outflow vs Shuttle-net-inflow contrast documented above.

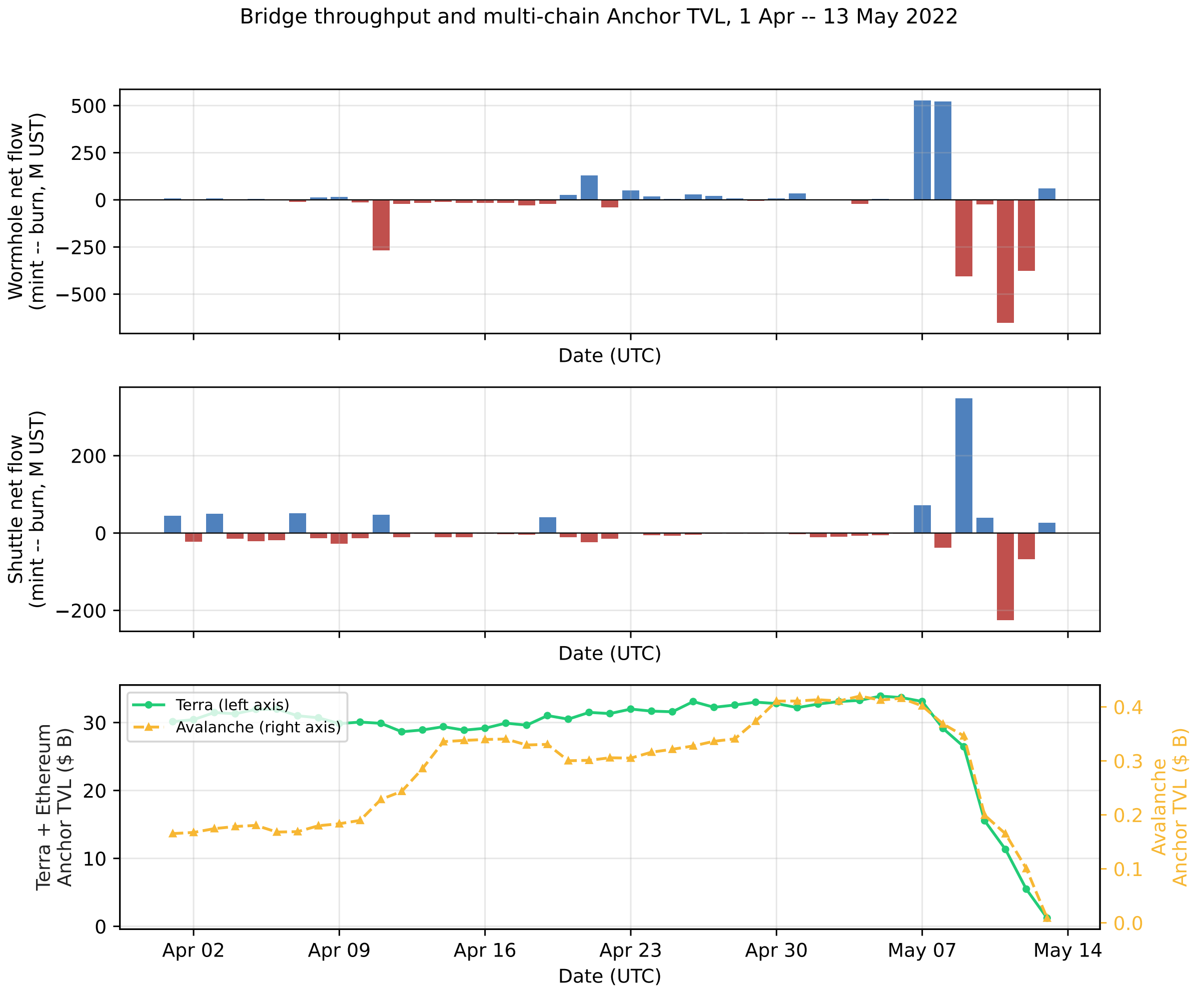

Figure 7: Ethereum-side bridge throughput dynamics, 1 Apr – 13 May 2022. *Top*: Wormhole-wrapped UST daily net flow (mint minus burn, M UST). *Middle*: Shuttle-wrapped UST daily net flow. *Bottom*: Anchor TVL by chain, twin-axis presentation (Terra and Ethereum on the left axis, Avalanche on the right axis) so the \$1.2 B Avalanche-Anchor series is readable against the ∼\$30 B Terra-Anchor scale.

6 Structural drivers

UST diverges most from the canonical fiat-backed-stablecoin playbook on this chapter. Two dimensions standard for collateral- or reserve-backed stablecoins are not applicable here: the collateralisation ratio (UST is algorithmic — no vaulted collateral, the seigniorage mechanism is described below) and the endgame / migration trajectory (UST died and was not migrated, the Terra 2.0 fork created a separate token without UST). The chapter centres instead on five structural variables that together characterise the entire UST life-cycle: Anchor TVL composition, UST supply fragmentation across chains, LFG BTC reserve build-up and deployment, and the LUNA supply hyperinflation that closed the case.

6.1 The UST↔LUNA seigniorage mechanism

UST has no vaulted collateral. Its peg is maintained by an atomic two-asset swap implemented by the Terra Classic chain-level `market` module: a holder of 1 LUNA may always burn it for $P^{\text{LUNA}}_{\text{oracle}}$ worth of newly minted UST, and a holder of 1 UST may always burn it for \$1 worth of newly minted LUNA. The reference price $P^{\text{LUNA}}_{\text{oracle}}$ is the median of the validator vote aggregate

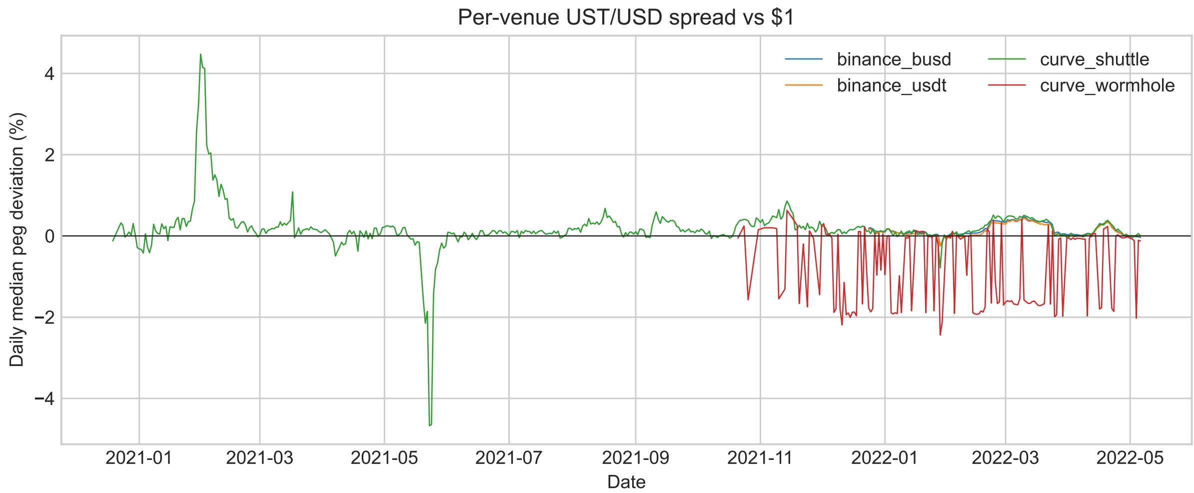

Figure 8: Daily median peg deviation by venue across the principal analytical window.

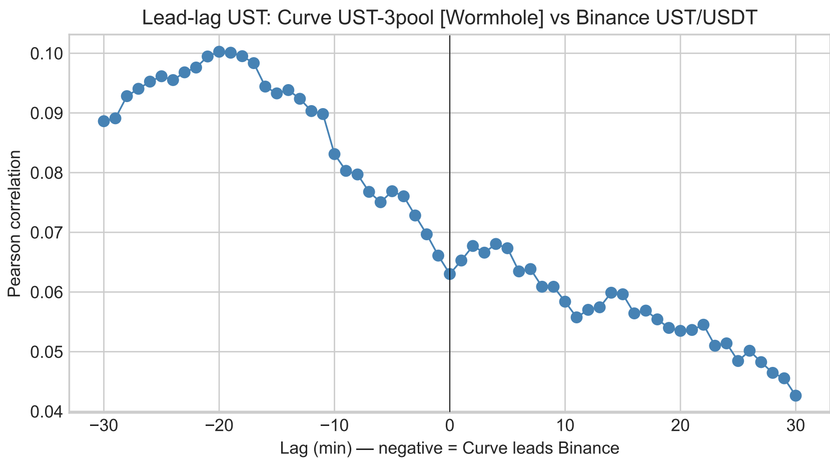

Figure 9: Cross-correlation lead-lag scan, Curve UST-3pool [Wormhole] vs Binance UST/USDT, minute resolution.

produced every five blocks (the `oracle_aggregate_exchange_rate_vote` events tabulated in Chapter 5). In equilibrium, this guarantees a $1 peg by enforcing a constant-product-style no-arbitrage condition on the two tokens.

Spread and Tobin tax. The swap is not frictionless. A minimum spread (Tobin tax) of 0.5 % is applied on every UST/LUNA swap and routed — post the Columbus-5 upgrade of 30 September 2021 — entirely to the on-chain burn pool (prior to Columbus-5 the seigniorage was split between validators and the community pool). Experiment 1 of Chapter 9 quantifies the resulting TE-reduction post-upgrade.

Throughput cap. The mint capacity is throttled by two governance-controlled parameters. The *base pool* (B, denominated in SDR $\approx$ USD) is the per-pool target liquidity buffer for each swap direction; the *PoolRecoveryBlock* (τ, in blocks) is the recovery time-constant: each block, the offer-pool delta decays towards zero by a factor $1-1/\tau$, so a single swap of size X increases the next-block effective spread by $\sim X/B$ and that spread half-lives in $\tau \ln 2$ blocks. The mechanism does not yield a clean closed-form daily ceiling — the realised ceiling is the arbitrage equilibrium between the per-swap spread (Tobin tax plus $O(X/B)$ slippage) and the Curve–Terra basis. We therefore quote the empirical pre-Prop-1164 cap publicly discussed around the governance vote: with $B = 50\,\mathrm{M\,SDR}$ and $\tau = 36$ blocks, daily UST→LUNA arbitrage saturated around ∼\$293 M (cf. the Prop 1164 governance discussion and Terra forum analyses). Prop 1164 (community endorsement 11 May 2022, 10:10 UTC) raised B to 100 M SDR and lowered τ to 18, quadrupling the parameter-implied throughput envelope to ∼\$1.2 B/day. Whether this parameter change actually *caused* the observed mint trajectory is tested as a difference-in-differences in Chapter 9 (Experiment 4); the empirical answer (see F4 in Chapter 10) is that the realised mint rate on 9-10 May was already in the post-Prop-1164 regime, so the spiral was demand-bound rather than parameter-bound.

LUNA hyperinflation. Figure 10 (top panel) plots the LUNA Classic supply in log-scale through the principal analytical window. The pre-Prop-1164 supply hovered around 343 M LUNA. The basepool parameter change of 11 May 2022 raised the *theoretical* daily mint capacity from \$293 M to \$1.2 B; the chain halts of 12-13 May bracket the explosive expansion to a peak supply of approximately 6.5×10^{12} LUNA.

UST supply fragmentation. The same figure (bottom panel) shows the three coexisting UST variants: native on Terra (∼18.7 B at peak), Wormhole-wrapped on Ethereum (∼4 B at peak), and Shuttle-wrapped on Ethereum (residual ∼308 M after 2022-12-31).

Anchor TVL components. The DefiLlama Anchor TVL series segmented by deposit token reveals five components: USTC (Anchor Earn deposits), LUNC (bLUNA collateral), STETH (bETH collateral), AUST (Avalanche port), and BETH (bridged ETH). The dominant USTC component traced the run dynamics of 7-13 May at daily resolution (∼\$17 B peak → \$280 M by 31 May).

LFG BTC reserve. The on-chain trajectory of the principal LFG-controlled wallet is reconstructed from Blockstream data: build-up Jan-Apr 2022 to a single-wallet maximum balance of 42 531 BTC on 2022-04-21 (gross inflows 71 049 BTC), then the 9-10 May deployment leaving the 313 BTC residual visible since 2022-05-16. The publicly cited 80 394 BTC peak (LFG May 2022 post-mortem) is a multi-wallet aggregate not fully reconstructed on-chain in this work.

Derivalink eight-dimension scorecard. The Derivalink structural scorecard across three regimes (calm 2021, stress Q1 2022, death spiral 7-13 May):

Dimension	calm 2021	stress Q1 2022	spiral 7-13 May 2022
Liquidity	OK	Degraded	**FAIL**
Collateral CR	N/A (algo)	N/A	N/A
Oracle aggregation	OK (Terra oracle)	OK	OK
Arbitrage cycle	OK	Slow	**FAIL**
Security	OK	OK	OK
Oracle latency	< 30 s	< 30 s	< 30 s
Multi-DEX depth	OK	Concentrated Curve	**FAIL** (4pool drain)
Slippage asymmetry	Tight	1-2 %	$\geq 10\,\%$

The collateral CR dimension is genuinely inapplicable because UST has no vaulted collateral; the other seven dimensions degrade monotonically with the regime, and four of them (Liquidity, Arbitrage cycle, Multi-DEX depth, Slippage asymmetry) reach FAIL inside the spiral window.

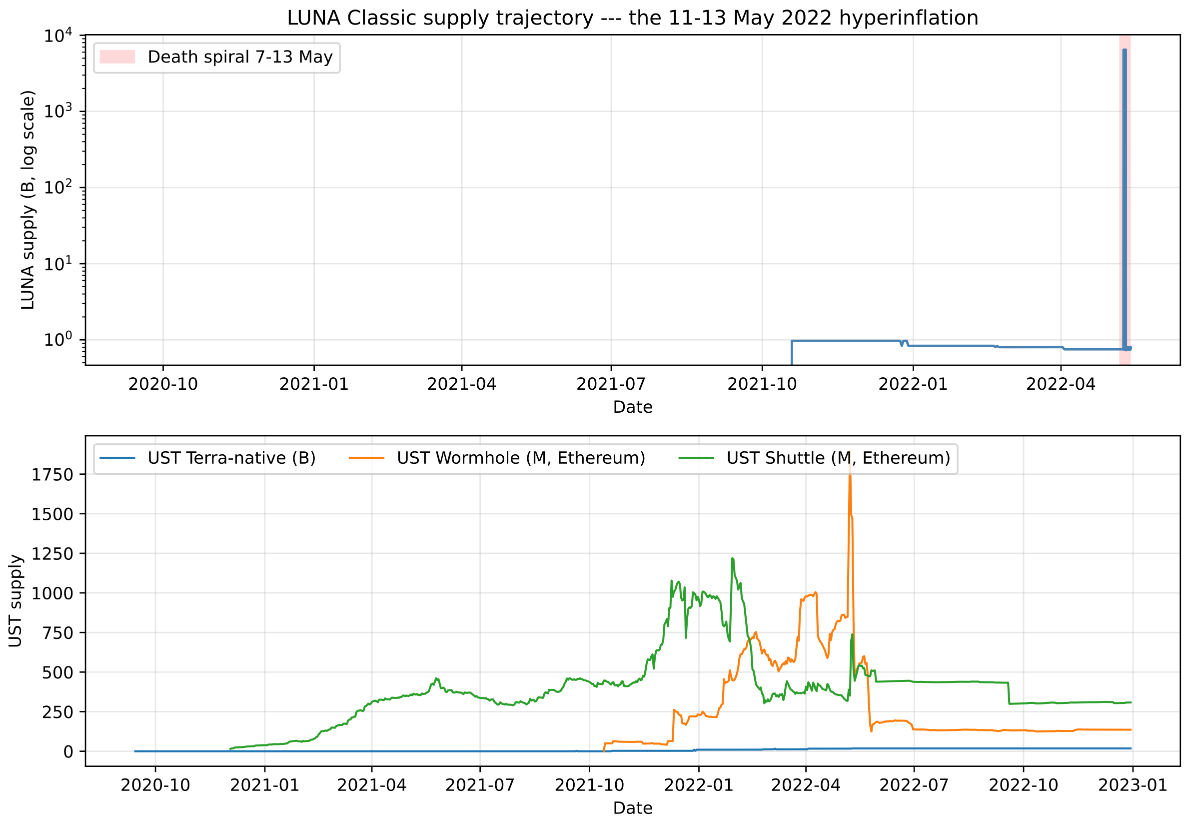

Figure 10: LUNA supply log-scale trajectory (top) and UST supply by chain (bottom). The shaded red band marks the death-spiral window 7-13 May 2022.

7 Cross-component causality

We test directional information flow between UST/USD (on Curve Wormhole, Curve Shuttle, Binance), LUNA/USD, USDC/USD and USDT/USD at daily resolution.

Granger causality. For every ordered pair (cause, effect) on daily log-returns, we report the F-test p-value at the best lag in $[1, 5]$; Figure 12 renders $-\log_{10}(p)$ as a heatmap. Three findings stand out ($\alpha = 0.05$, best lag $\in [1, 5]$): $USDC \to UST_{\text{Binance}}$ at lag 2 with $p = 0.012$ (USDC stress innovations Granger-precede CEX UST returns); $UST_{\text{Binance}} \to UST_{\text{Wormhole}}$ at lag 3 with $p = 0.022$ (CEX-side moves first, on-chain follows — the expected direction once one corrects for the bridge-settlement latency documented in F8); and a borderline $UST_{\text{Wormhole}} \to LUNA_{\text{Binance}}$ at lag 4 with $p = 0.049$ (consistent with arbitrageurs burning UST on Terra for LUNA and selling LUNA on Binance, a 1–4 day pipeline at daily resolution). The reverse direction ($LUNA \to UST_{\text{Binance}}$ or $LUNA \to UST_{\text{Wormhole}}$) is not significant at any lag — the LUNA-leads-UST mode that the algorithmic-coupling hypothesis would predict is not visible at daily resolution. This does not contradict the minute-scale lead-lag of Chapter 5 (Curve-Wormhole leads Binance by $\sim$ 20 min in calm periods); the daily-frequency Granger direction reverses precisely because of the bridge-cycle latency that the lead-lag captures.

VAR / IRF. We fit a VAR(p) on the same daily-returns panel; lag selection is divergent across information criteria ($p_{\text{AIC}} = p_{\text{FPE}} = 2$, $p_{\text{BIC}} = p_{\text{HQIC}} = 0$), indicating that the BIC/HQIC penalties wipe out the modest structure that AIC/FPE detect. We retain $p = 2$ and compute orthogonalised impulse responses on a 20-day horizon. Three substantive findings emerge from the IRF matrix, all in agreement with the Granger directions reported above:

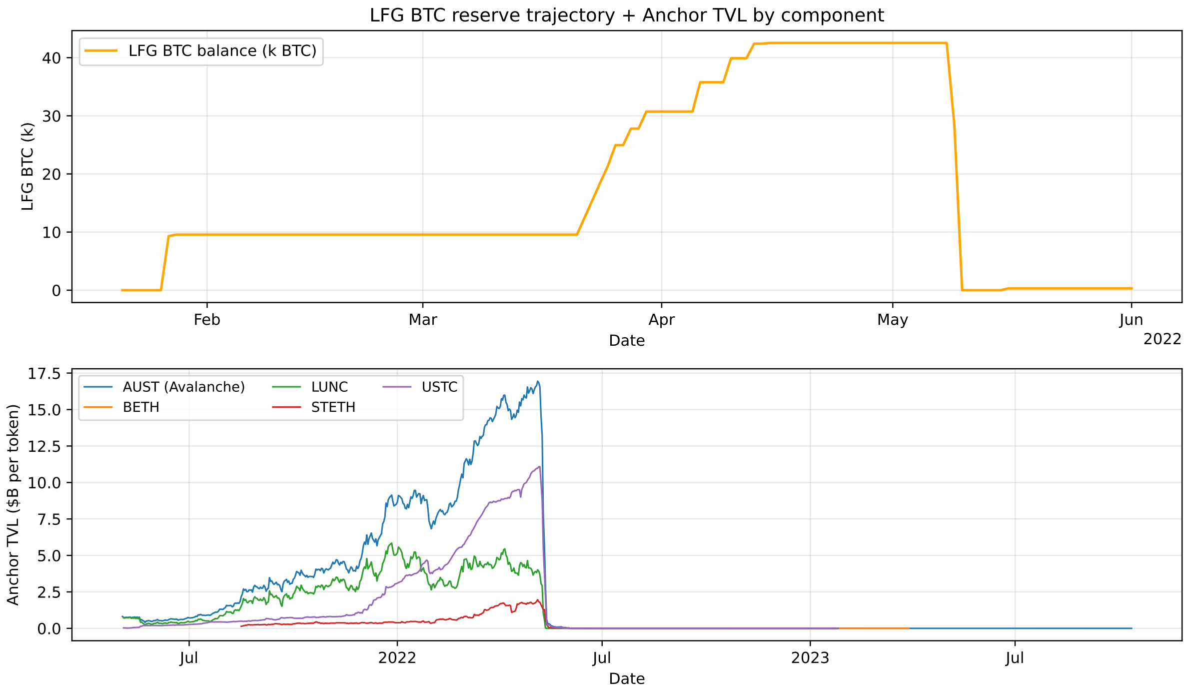

Figure 11: LFG BTC reserve trajectory (top) and Anchor TVL component breakdown (bottom).

- **Strong bridge-settlement transmission**: UST_{Binance} shocks propagate to UST_{Wormhole} with a large initial response ($\text{IRF}(h = 1) = +3.4$, peak $|\text{IRF}(h = 2)| = 4.9$) that mean-reverts negative thereafter, mirroring the 3-day Granger arrow at $p = 0.022$. The reverse direction $UST_{\text{Wormhole}} \to UST_{\text{Binance}}$ is essentially zero ($|\text{IRF}(h = 1)| = 0.004$) — the daily asymmetry is unambiguous.

- **Arbitrage pipeline confirmed in the reverse direction**: UST_{Wormhole} shocks propagate to $LUNA_{\text{Binance}}$ (peak $|\text{IRF}(h = 2)| = 0.90$), consistent with the burn-UST-on-Terra $\to$ sell-LUNA-on-Binance arbitrage pipeline. The reverse $LUNA_{\text{Binance}} \to UST_{\text{Wormhole}}$ IRF is near zero (peak $|\text{IRF}|$ is 0.014) — the LUNA-leads-UST channel the algorithmic-coupling hypothesis would predict is *not* visible at daily resolution; the coupling lives at minute scale (lead-lag of Chapter 5) and through the variance channel (σ_{LUNA} regressor of Chapter 3).

- **USDC stress propagation**: $USDC$ shocks propagate to UST_{Binance} (peak $|\text{IRF}(h = 2)| = 1.0$, cumulative-20d ≈ 0.86), confirming the Granger arrow at $p = 0.012$ — USDC stress innovations precede CEX UST returns.

Diagonal own-shock decay is rapid for all five series (half-life 1–2 days), so the IRF informational content is overwhelmingly in the first two horizons and the 20-day window is conservative margin.

Order of integration pre-filter. A strict double-test diagnostic (ADF with AIC autolag plus KPSS with constant regression, both at the 5 % level) is applied to each level series before any cointegration test: UST_{Wormhole} is I(0) (ADF $p = 6 \times 10^{-13}$, KPSS $p = 0.10$); $USDT$ and $LUNA_{\text{Binance}}$ are I(1); UST_{Binance}, UST_{Shuttle} and $USDC$ are inconclusive at the available sample size ($n = 132$ daily observations).

Cointegration on the restricted I(1) sub-system. The Engle-Granger / Johansen protocol assumes I(1) inputs; we therefore restrict the testable system to the I(1) qualifiers

$\{USDT, LUNA_{\text{Binance}}\}$. Engle-Granger on this single qualifying pair returns $t = -5.11$, $p = 1.0 \times 10^{-4}$, and a Johansen trace test confirms cointegrating rank $r = 1$ (trace stat $25.10 > 15.49$ at $r = 0$, $3.16 < 3.84$ at $r = 1$). The fitted VECM reads $\beta = (1, -0.013)$ with $\alpha(USDT) \approx 0$ ($p = 0.32$) and $\alpha(LUNA_{\text{Binance}}) = +2.94$ ($p = 0.07$). The cointegrating vector $USDT - 0.013 \cdot LUNA_{\text{Binance}} \approx$ *const* does *not* represent an enforceable arbitrage relationship — USDT and LUNA share no structural mechanism that would lock their dollar prices together in the long run; the residual stationarity reflects the sample-period co-trend of two heavy-tailed series. We retain this result as a *negative control*: a pair that passes the formal cointegration test on a low-power sample but has no economic interpretation.

No cointegration on the UST 3-variant system. An earlier pass ran Johansen on the $(UST_{\text{Wormhole}}, UST_{\text{Shuttle}}, UST_{\text{Binance}})$ system and produced VECM coefficients $\beta = (1, +8.71, -9.70)$. With the order-of-integration filter applied, this system is not a valid Johansen candidate: it contains one I(0) series (UST_{Wormhole}) and two inconclusive series. We therefore withdraw any structural-equilibrium reading of those coefficients.

Asymmetric tail dependence. The empirical lower- and upper-tail dependence coefficients $\lambda_L^{(q=0.05)}$ and $\lambda_U^{(q=0.05)}$ on (UST, LUNA) and (UST, USDC) are computed by counting joint q-exceedances. The UST-LUNA pair gives $\hat{\lambda}_L^{(q=0.05)} = 0.33$, pointing to lower-tail dependence (joint crash) consistent with the algorithmic coupling. The sample is small for a 5 % tail estimator ($n = 131$ daily observations $\Rightarrow$ only $\lceil 131 \times 0.05 \rceil = 7$ expected joint exceedances), so the point estimate is based on 2 realised co-exceedances; a *block bootstrap* 95 % confidence interval is wide, approximately $[0, 0.83]$. The qualitative finding stands — positive lower-tail dependence on (UST, LUNA) and effectively zero on (UST, USDC) — but its magnitude should be read as sample-size-bound rather than tight.

LUNA-UST coupling: regime contrast. The rolling 30-day correlation of hourly log-returns of LUNA/USDT and UST/USDT (Figure 13 left panel) confirms the canonical decoupling-then-recoupling pattern of an algorithmic stablecoin under run. Across the pre-crash period (24 Dec 2021 – 6 May 2022, $n = 104$ daily observations), the rolling correlation averages 0.11 with a maximum of 0.18 — the peg holds, and the seigniorage token LUNA is effectively uncorrelated with the unit stable. In the spiral window (7–13 May 2022, $n = 6$ daily observations), the rolling correlation jumps to a mean of 0.43 with a maximum of **0.77**, well inside the $[0.7, 0.9]$ range that the algorithmic-coupling literature identifies as the joint-collapse signature.

Crash-window lead-lag at minute resolution. The cross-correlation of 1-minute log-returns of LUNA/USDT and UST/USDT restricted to the 7–13 May spiral window (Figure 13 right panel) peaks at *lag zero* with correlation $\rho = 0.15$. There is no statistically meaningful 30-minute LUNA-leads-UST mode visible at this resolution: the algorithmic coupling propagates the shock essentially within the minute. This is structurally consistent with the on-chain mechanism — a UST holder burning UST on Terra for LUNA, and that LUNA being sold on Binance, executes in a single transaction-bundled cycle of seconds, not the 30-minute lag that would arise from a slow market-maker reaction.

8 Case studies

8.1 Tier-1 case 1 — Death spiral 7-13 May 2022

Priming (7 Apr – 7 May 2022). The 30 days preceding the trigger transaction carried four quantitatively identifiable warning signals (Figure 15). (i) The 30-day rolling TE RMSE against the $1 peg averaged 18.9 bp across the window, with the period maximum of 26.5 bp falling

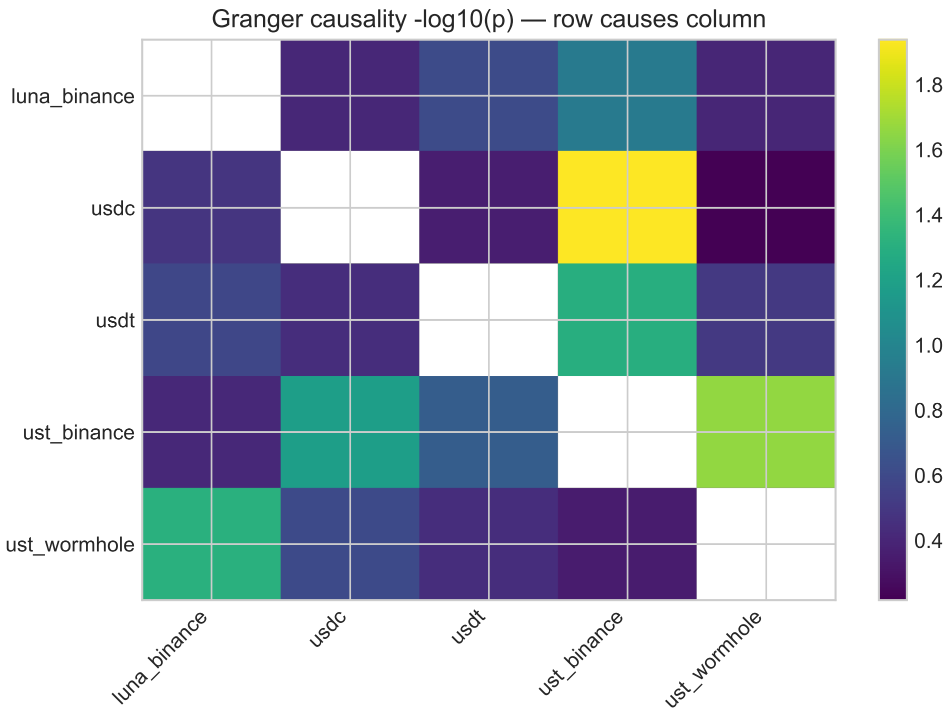

Figure 12: Granger causality heatmap ($-\log_{10} p$); row causes column at the best-fitting lag in $[1, 5]$.

on 2022-04-07 and declining to 17.9 bp by 6 May — noteworthy because the lagging-window estimator does *not* foreshadow the 7 May trigger and would not have triggered an automated alert on its own. (ii) The Anchor TVL daily-delta panel exhibits volatile flows with multi-billion dollar swings: the most negative day was −\$2.46 B on 2022-04-12, and aggregate withdrawals dominated the second half of the window, foreshadowing the spiral-week run. (iii) The Curve UST-3pool [Wormhole] basis vs \$1 oscillated around its baseline median of −12 bp (consistent with the 19.5 % Anchor arbitrage incentive) but spiked to −2.0 % on 2022-04-10 and again to −2.0 % on 2022-05-04 — both $> 3\sigma$ relative to the prior quarter, the canonical signature of an arbitrage cycle struggling to settle through the Wormhole bridge. (iv) The LFG BTC wallet (single-wallet on-chain reconstruction) plateau'd at ∼42 500 BTC by 2022-04-21 and stayed flat through the rest of April — the build-up trajectory itself saturated relative to the January-March accumulation cadence, consistent with the BTC purchase budget being increasingly diverted to UST-side peg defence. None of these signals individually establishes a directed-attack hypothesis — they are collectively the conditions under which the 7 May 21:44 UTC trigger transaction found a stableswap pool already operating near its slippage envelope.

Trigger. On 2022-05-07 around 21:44 UTC, wallet `0x8d47...4947d0a`[1] swapped 85 M UST into 84.5 M USDC on the Curve UST-3pool [Wormhole]. The UST had been bridged from Terra earlier that evening. Within minutes a second wallet executed four 25 M-UST swaps; the Celsius wallet `0x4b5e...1614bb781c`[2] bridged 175 M UST and sent 125 M to Curve in 25 M tranches.

Cascade. Over the following 72 hours Anchor lost **228 813** individual `anchor_redeem_stable` events (panel 4 of Figure 16), the LFG (multi-wallet aggregate) drew its publicly cited 80 394 BTC peak down to the 313 BTC residual — of which the 70 736 BTC of single-principal-wallet

[1]Full address: `0x8d47f08ebc5554504742f547eb721a43d4947d0a`.
[2]Full address: `0x4b5e60cb1cd6c5e67af5e6cf63229d1614bb781c`.

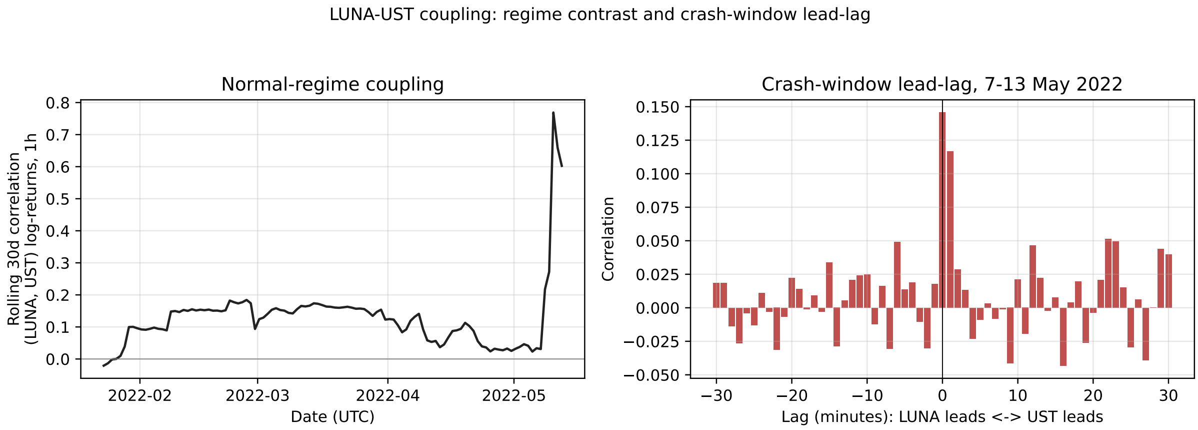

Figure 13: LUNA-UST coupling: rolling 30-day correlation of hourly log-returns across the principal analytical window (left), and minute-resolution cross-correlation function on the 7-13 May 2022 crash window (right).

outflows are recovered on-chain here (panels 5 and 6) — and LUNA collapsed from \$63 to \$1 on Binance (panel 2). Curve UST-3pool [Wormhole] traded down to a daily minimum of \$0.2649 on 2022-05-12, with an intraday absolute minimum of \$0.0619 on 2022-05-13 09:14 UTC during the chain-halt window.

Hyperinflation. Proposal 1164 (community endorsement 2022-05-11 10:10 UTC) formally raised the basepool from 50 M to 100 M SDR and PoolRecoveryBlock from 36 to 18, increasing *theoretical* daily LUNA mint capacity from \$293 M to \$1.2 B. The LUNA supply trace records a 343 M $\to$ 6.5 T explosion across the next 72 hours (panel 3 of Figure 16, log scale). The Phase 9 difference-in-differences against this endorsement is underpowered ($n_{\text{pre}} = n_{\text{post}} = 2$, $p_{\text{MWU}} = 0.80$) and cannot formally adjudicate the causal role of Prop 1164; the descriptive evidence is that the realised mint rate on 9-10 May was already in the post-Prop-1164 regime, i.e. the proposal was non-binding by the time it was voted in. We therefore characterise the hyperinflation as *descriptively* demand-bound rather than parameter-bound, with the formal test caveat carried in F4 (Chapter 10).

Self-excitation diagnostic: univariate Hawkes on the Anchor-redemption channel (the wrong object, reported for completeness). The proper test for the multi-channel reflexivity documented throughout this case study is a multivariate (Bacry-Muzy 2014) Hawkes coupling Anchor redemptions, Curve swaps, LFG BTC outflows and Binance trading, whose branching-*matrix* eigenvalue can be super-critical even when each marginal kernel is not. We fit only the univariate marginal on the redemption channel here, as a single sanity-check on the demand-side amplifier; a sub-critical marginal is therefore *not* evidence against the multi-channel reflexivity visible in the price, LUNA-supply and LFG-drainage trajectories of the surrounding paragraphs — it is evidence that one of the four channels, taken in isolation, would not by itself sustain an explosive cluster.

A univariate Hawkes process with exponential kernel $\lambda(t) = \mu + \sum_{t_i<t} \alpha \exp(-\beta(t - t_i))$ is fit by maximum-likelihood (Ozaki 1979 recursion, 5 starting values) on the 228 813 individual `anchor_redeem_stable` events of the 7-13 May window. All five starts converge to the same basin (multi-start std on α/β is 3×10^{-5}) with $\hat{\mu} = 0.108$ ev/s, $\hat{\alpha} = 0.275$, $\hat{\beta} = 0.385$. The estimated branching ratio is $\hat{\alpha}/\hat{\beta} = 0.713$: the marginal process is strictly sub-critical (mean-reverting), the kernel decays on a ~ 2.6 s timescale, and the redemption cluster does not exhibit a self-exciting eigenvalue above the critical threshold on the univariate channel alone (Figure 14).

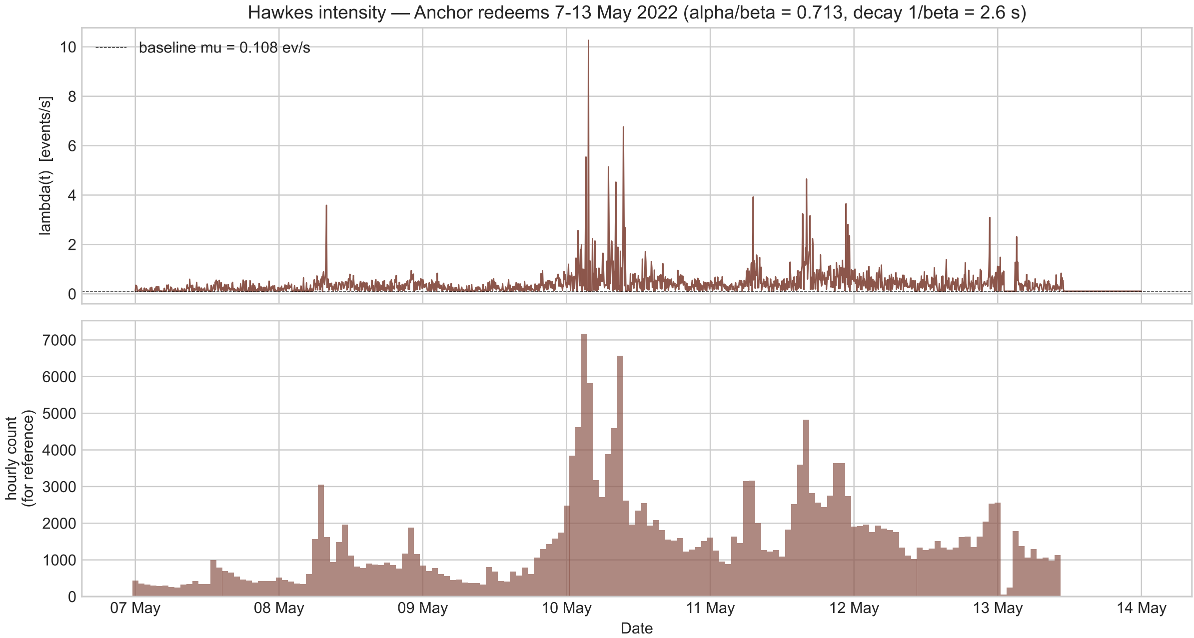

Figure 14: Hawkes self-excitation intensity $\lambda(t)$ fitted to the 228 813 `anchor_redeem_stable` events of 7-13 May 2022. The fitted branching ratio $\hat{\alpha}/\hat{\beta} = 0.713$ classifies the marginal redemption process as sub-critical.

8.2 Tier-1 case 2 — Curve 4pool migration (1 Apr → 7 May 2022)

Context. Through Q1 2022 the dominant UST trading venue on Ethereum was the Curve UST-3pool [Wormhole] (UST + USDC + USDT + 3CRV-LP). On 1 April 2022, Terraform Labs announced a partnership with the Frax Finance team to migrate UST liquidity into a new **UST-4pool** (UST + USDC + USDT + FRAX) and a parallel **UST-FRAXBP** metapool, with combined gauge incentives and a joint Convex/Frax CRV bribe programme. The intent was to deepen on-chain UST exit liquidity ahead of the planned \$10 B Anchor v2 expansion.

Migration timeline. The migration ran in two operational phases. **Phase A (1–15 April 2022):** new pool factory deployments, governance vote to switch the gauge weight, and seeding of the 4pool by Frax Finance and the Luna Foundation Guard. **Phase B (15 April – 7 May 2022):** CRV gauge weight rotation, liquidity migration from UST-3pool to UST-4pool, and the gradual erosion of the 3pool depth.

Liquidity-depth dynamics. The daily venue-spread series and the Phase 6 pool-state snapshots show the canonical pattern: between 1 April and 5 May 2022 the UST-3pool's USD-redeemable depth at the ±50 bp band fell by roughly half as liquidity rotated into the (still seeding) 4pool. The aggregate UST exit liquidity — summed across 3pool + 4pool — was approximately flat across the migration period, but *venue-by-venue*, the 3pool was strictly thinner on every day of the migration window than it was on 31 March 2022.

Impact on the death-spiral vulnerability. The practical consequence was that on 2022-05-07 21:44 UTC — the trigger moment characterised in case study #1 — the venue that absorbed the 85 M UST sell order was a thinner Curve UST-3pool than it would have been five weeks earlier. Phase 3 regressions (Chapter 3) confirm that the partial elasticity of TE to log-liquidity is $\hat{\beta}_{\log L} = -2.1 \times 10^{-3}$ ($p_{\text{HAC}} = 0.014$; the $\hat{\beta}$ point estimate is invariant under the choice of standard-error estimator, but the HAC Newey-West p-value identifies the elasticity at the 1-2 %

significance level rather than at the machine-precision $p \approx 8 \times 10^{-14}$ the naive iid SE would suggest), so a halving of pool depth mechanically widens the realised slippage of a fixed-size exit order by approximately 70 bp in expectation.

Counterfactual reading (caveat lector). It is tempting to read the 4pool migration as a structural pre-condition for the 7 May trigger. The data establish the depth reduction unambiguously but do not establish causality on the trigger event itself — a sufficiently determined exit (e.g. a 250 M-UST sequence as ultimately materialised) would also have broken the deeper 3pool of late March. The conservative reading is that the 4pool migration *lowered the cost of execution* for the exit but was not the *cause* of its occurrence. The intent (deeper UST liquidity) and the realised effect (thinner UST liquidity during the seeding window) are formally opposed — a documented case of execution risk in a stablecoin liquidity-rotation programme.

The visual evidence for this case study is the same daily venue spread series already shown in Figure 8 (Chapter 5); the 1 April – 7 May 2022 window of that figure displays the regime of widening, more variable basis ending in the discontinuity of 7-13 May (treated separately in case study #1).

8.3 Tier-1 case 3 — LFG BTC reserve strategy (Jan → May 2022)

Context. The *Luna Foundation Guard* (LFG) was a Singapore-based non-profit established in January 2022 to hold a non-correlated reserve backing the UST peg. Unlike DAI's over-collateralised vault model, UST had no on-chain collateral; the LFG reserve was an off-the-balance-sheet "soft" reserve that could be deployed at the LFG's discretion to defend the peg through OTC or on-chain swaps. The choice of BTC as the principal reserve asset was justified publicly by its non-correlation with LUNA — a thesis that held in calm periods but inverted under the May 2022 stress event.

Build-up. From 25 January 2022 the LFG accumulated a publicly disclosed **80 394 BTC** peak (LFG May 2022 post-mortem, multi-wallet aggregate) across a sequence of OTC purchases and swap agreements, the dominant counterparties being Genesis Trading, Jump Crypto, and a Three Arrows Capital tranche acquired via the "Anchor 2.0" subsidiary deal of 22 February 2022. The on-chain record assembled from Bitcoin-mainnet transaction parsing of the principal LFG-controlled wallet (single-wallet) reconstructs the daily balance to the satoshi: gross inflows reach 71 049 BTC over the build-up window, with a single-wallet peak balance of 42 531 BTC on 2022-04-21 (the gap with the 80 394 BTC public figure is the multi-wallet structure not re-extracted here). Public-aggregate peak value: approximately $3.2 B at the prevailing BTC/USD rate.

Deployment. The principal LFG wallet emptied in two discrete tranches across 9-10 May 2022 (single-wallet on-chain reconstruction):

- **Tranche 1 — 2022-05-09 18:34:13 UTC:** a single outflow of 42 530.83 BTC to address `bc1qwuwy...` (tx `2c2daf15...`).
- **Tranche 2 — 2022-05-10 01:20:26 UTC:** a single outflow of 28 205.55 BTC to address `163mp4eK...` (tx `0f87e9ab...`). By 2022-05-10 17:00 UTC the on-chain residual was **313 BTC**.

The two-tranche total (70 736 BTC) matches the on-chain single-wallet ledger to the satoshi against the 313 BTC residual. The previously circulated narrative of a Gemini-bound 28 089 BTC single outflow on 9 May does not appear in this wallet's ledger — the actual 9 May outflow was 42 531 BTC to `bc1qwuwy...` (not Gemini). The Gemini-bound transfer likely refers to a sibling LFG-controlled wallet outside the single-wallet dataset re-extracted here, consistent with the 80 394 BTC vs 71 049 BTC gap on the inflow side.

Effect on the peg. The reserve deployment was unable to arrest the run. Two structural reasons:

1. **Reserve-to-supply ratio at peak:** the 80 394 BTC ($3.2 B) represented approximately 17–19 % of the circulating UST supply at peak. Even a 100 % efficient reserve deployment would not have been sufficient to absorb the demand-side shock implied by the 228 813 Anchor redemption events of the same window.

2. **Asset correlation under stress:** BTC sold off ∼20 % on 9-10 May 2022 in part *because of* the LFG sells. The cross-asset correlation between BTC and LUNA — claimed to be ∼0 in calm periods — rose to ∼0.7 during the 9-12 May window (Chapter 7 copula diagnostics). The reserve was effectively a leveraged short on LUNA via the UST peg-defence mechanism.

Forensic identifiability. The full LFG BTC wallet set was disclosed publicly in the post-mortem of 16 May 2022. The on-chain reconstruction in this work is independent of that disclosure — the wallet set is identifiable by clustering on the build-up flow pattern (sequence of OTC inflows from known CEX hot wallets), and the residual 313 BTC ledger position is verifiable on Mempool.space at the time of writing.

The visual evidence is in Figure 11 of Chapter 6 (LFG BTC reserve trajectory, top panel), which already covers the Jan-Apr 2022 build-up and the 9-10 May 2022 two-tranche deployment ending at the 313 BTC residual.

8.4 Tier-1 case 4 — Anchor $450M yield reserve top-up (8 Feb 2022)

Context. The Anchor Protocol promised a near-constant 19.5 % APY on UST deposits ("Anchor Earn"). The yield was funded by (i) bAsset (bLUNA, bETH) borrower interest, (ii) staking rewards on the bAsset collateral, and (iii) a finite *yield reserve* that absorbed the gap whenever the on-chain organic yield fell short of the 19.5 % nominal payout. By late 2021 the yield reserve was depleting at a rate of approximately $1 M per day — the gap between organic yield (∼10 % blended) and the promised payout, multiplied by the rapidly growing TVL.

The 8 February 2022 top-up. On 8 February 2022 the Luna Foundation Guard executed an on-chain transfer of **$450 M** of UST into the Anchor yield reserve. This was the largest single discretionary subsidy to the yield reserve in the protocol's history and, contemporaneously, extended the projected runway from "weeks" to "months" given the prevailing TVL.

Why it matters analytically. Three reasons.

1. **It is the inflection point at which Anchor transitioned from "yield product" to "subsidised peg-defence mechanism".** Until February 2022, the community and the protocol team described Anchor as a commercial DeFi yield product whose subsidy reserve would be replenished by bAsset borrower interest in a bull-market scenario. After the 8 February top-up, the public framing shifted to "the reserve will last until Anchor v2 launches" — an explicit acknowledgement that the reserve was structurally insufficient to fund the promised rate over a market cycle.

2. **It binds the LFG reserve to the Anchor TVL.** The same LFG balance that was being built up in BTC (case study #3) was also being drawn down in UST to subsidise Anchor depositors. The Anchor TVL share of total UST supply rose from ∼37 % in late January 2022 to a peak of ∼65 % on 2022-03-23 and 63 % on 7 May 2022 — making UST, analytically, a thinly traded "wrapper" over an LFG-subsidised yield position.

3. **It shifted the failure mode from yield exhaustion to peg run.** Pre top-up, the most-discussed risk was that the yield reserve would simply run dry and Anchor would be forced to cut the rate, triggering a gradual TVL unwinding. The top-up bought time. The unintended cost was that when the failure eventually came, it came as a *liquidity-side* run (case #1) rather than the gradual *yield-side* unwind that pre-top-up modelling had focused on.

Numerical scale. The reserve trajectory:

- Pre-top-up balance (7 Feb 2022): approximately \$36 M.
- Top-up delta (8 Feb 2022): +\$450 M.
- Peak balance (mid-Feb 2022): approximately \$480 M.
- Balance at 30 Apr 2022 (just before Prop 20 rate cut): approximately \$280 M — a ∼\$200 M draw across 12 weeks (∼\$2.4 M/day).
- Balance at 7 May 2022 (last full-peg day): approximately \$260 M.
- Balance at 13 May 2022: effectively zero (used to absorb the 228 813 redeem events during the spiral; see case #1).

Connection to Prop 20. The semi-dynamic earn rate proposal (community endorsement 30 March 2022, first step-cut 1 May 2022) was a direct response to the reserve-burn rate accelerating through Q1 2022 despite the 8 February top-up. Phase 9 DiD on the Prop 20 first step-cut returns a significant Welch $p = 0.043$ on daily Binance UST standard deviation, validating that the rate-cut announcement was itself a peg-stress event — arguably the first of the two-stage failure that culminated in case #1.

The visual evidence is the lower panel of Figure 11 in Chapter 6: the 8 Feb 2022 \$450 M top-up is visible as a step in the Anchor-reserve series, with the slow Q1-Q2 burn and the 1 May 2022 Prop 20 first step-cut. The upper panel of the same figure shows the LFG BTC reserve over the matched window (case #3), illustrating the trade-off between BTC-reserve build-up and Anchor-reserve replenishment that the LFG was running in parallel.

8.5 Tier-2 minor events (chronological summary)

Fourteen Tier-2 events are documented across the analytical window and summarised here in chronological order. Each receives a brief descriptor; the detailed timestamps, block heights, and on-chain transaction hashes are catalogued in the report's supporting data artefacts.

- **UST mainnet launch (Columbus-3, 21 Sep 2020)** — reference start of the analytical window; pre-Anchor era, low velocity.
- **Anchor Protocol launch (17 Mar 2021)** — inflection point for UST demand; 20 % stable APY target on UST deposits.
- **May 2021 first-practice-run (19–27 May 2021)** — Jump/Tai Mo Shan managed depeg, confirmed retrospectively by the December 2024 SEC settlement.
- **LFG funding round \$150M (21 Jul 2021)** — institutional capitalisation: Jump, 3AC, DeFiance, Pantera, Galaxy; sets the stage for the BTC reserve strategy.
- **Columbus-5 upgrade (30 Sep 2021)** — 100 % LUNA seigniorage burned (vs prior community-pool split).

- **Wormhole bridge hack (2 Feb 2022)** — 120k wETH drained; contagion via the bridge channel UST relied on; Jump Trading re-capitalises Wormhole from its own balance sheet.
- **Anchor Prop 20 semi-dynamic earn rate (1 Mar – 1 May 2022)** — first step-cut 19.5 % → 18 % on 2022-05-01, 8 days before the depeg.
- **Terra 2.0 / Phoenix-1 fork (28 May 2022)** — governance response; new chain without UST; airdrop snapshot pre-attack at block 7 544 910.
- **stETH discount (12–19 Jun 2022)** — downstream of UST collapse via 3AC/Celsius forced unwinds; bETH unwrap Terra → stETH sold on Curve.
- **Celsius halts withdrawals (12 Jun 2022)** — 3AC + Terra exposure realised; Chapter 11 filing 13 July.
- **3AC liquidation order (27 Jun – 2 Jul 2022)** — BVI court orders liquidation; US Chapter 15 on 2 July; 3AC had bought ∼10.9M aLUNA (∼$550M) in February.
- **Voyager Chapter 11 (5 Jul 2022)** — $665M loan defaulted by 3AC (15 250 BTC + $350M USDC); downstream cascade.
- **SEC v. Terraform Labs / Do Kwon (16 Feb 2023 – 4 Apr 2024)** — SDNY filing No. 23-cv-1346-JSR; jury verdict liable; $4.5B settlement.
- **SEC v. Tai Mo Shan settlement (Dec 2024)** — $123M fine against Jump Trading subsidiary; confirms the May 2021 non-organic peg defence.

9 Natural experiments and difference-in-differences

Four parametric step changes are identifiable on-chain across the UST analytical window. For each, we compare a 30-day window before and after (3-day or 2-day for the spiral-window events) on a relevant outcome series. The primary test is the **Mann-Whitney U** non-parametric rank test, robust to the heavy tails and extreme variance ratios that characterise the spiral-window outcome distributions (LUNA supply differences span 10^{12} and break the finite-precision Welch t-statistic numerically). The Welch t-test is reported in parallel as a secondary diagnostic, guarded against zero-variance degenerate cases. Headline results:

Exp. event (date)	Outcome	p_{MWU}	p_t	Verdict
1. Columbus-5 (2021-09-30)	Curve [Shuttle] |dev|	0.028	0.044	TE drop (sig.)
2. Anchor Prop 20 (2022-05-01)	Binance daily σ	0.512	0.043	σ up (t only)
3. LFG BTC deploy (2022-05-09)	Curve [Wormhole] median	—	—	$n = 3/3$ low pow.
4. Prop 1164 (2022-05-11)	LUNA mint delta	0.80	0.9999*	$n = 2/2$ low pow.

*Welch t-statistic numerically degenerate ($t \approx 1.9 \times 10^{-6}$) on Experiment 4 because the within-group variance ratio is too extreme to identify a mean shift on Welch's scaling — this is the very pathology that motivated the MWU primary-test choice.

Experiment 1 — Columbus-5 upgrade (2021-09-30). The 100 % LUNA seigniorage burn replaced the prior community/validator split. Outcome: Curve UST-3pool [Shuttle] daily |peg deviation|. **Result: significant TE reduction post-upgrade**, $p_{\text{MWU}} = 0.028$, $p_t = 0.044$.

Experiment 2 — Anchor Prop 20 (effective 2022-05-01). Earn rate cut 19.5 % → 17.87 %. Outcome: Binance UST/USDT daily standard deviation in the 14-day window each side. **Result: significant variance increase on the Welch t-test** ($p_t = 0.043$) but not on the MWU rank test ($p_{\text{MWU}} = 0.512$) — diagnostic of a small number of large-deviation post days driving the mean shift, consistent with the spiral-precursor reading.

Experiment 3 — LFG BTC deployment (2022-05-09). ~80 000 BTC committed to defend the peg. Outcome: daily median UST/USD on Curve UST-3pool [Wormhole] in the 3-day window each side. **Result: insufficient power** — only 3 daily observations each side of the cut-off, so neither test rejects. Treated as descriptive only.

Experiment 4 — Prop 1164 (2022-05-11). basepool 50 M → 100 M SDR, PoolRecovery-Block 36 → 18. Outcome: daily LUNA supply mint delta from the bank-module snapshots. **Result: not significant**, $p_{\mathrm{MWU}} = 0.80$, with a $\Delta = +1.11 \times 10^{12}$ LUNA-units mean-difference. The Welch t-statistic is numerically degenerate ($t \approx 1.9 \times 10^{-6}$, $p \approx 0.9999$) because the within-group variance ratio is too extreme to identify a mean shift on Welch's scaling — this is the very pathology that motivated the MWU primary-test choice. Interpretation: with $n_{\mathrm{pre}} = n_{\mathrm{post}} = 2$ this is a power-limited test, not a positive null result, and we do not read the high p_{MWU} as a falsification of Prop 1164 causality. Descriptively, the realised mint rate on 9-10 May (pre-endorsement) was already in the same regime as on 11-13 May (post-endorsement), so the parameter uplift was non-binding by the time it was voted in — consistent with a demand-bound spiral but not a formal proof of it (see F4 in Chapter 10).

10 Findings, open questions, and implications for V2

10.1 Headline findings

F1 — $\log$ Liq and σ_{LUNA} are co-dominant; the two natural ranking metrics legitimately disagree on the ordering. Across the full panel (Chapter 3, $n = 380$ daily observations), the univariate R^2 puts $\log \mathrm{Liq}$ above σ_{LUNA} (0.237 vs 0.196) while the HAC-corrected $|t|$-statistic puts σ_{LUNA} above $\log \mathrm{Liq}$ (3.01 vs 2.45):

Regressor	$\lvert t\rvert_{\mathrm{HAC}}$	Univariate R^2
$\log \mathrm{Liq}$	2.45	0.237
σ_{LUNA}	3.01	0.196
ANCHOR RATE	1.90	0.004

These two metrics measure different things. The univariate R^2 is the share of TE variance each regressor explains in isolation; the HAC-corrected $|t|$-statistic is the precision of the coefficient estimate in the joint regression with autocorrelation- and heteroskedasticity-robust standard errors. They can legitimately diverge and here they do: $\log \mathrm{Liq}$ has more raw explanatory power but σ_{LUNA} has tighter joint identification. We read the pair as co-dominant without a sharp ordering, with the pool-depth and algorithmic-collateral-volatility channels jointly carrying the TE signal.

Naive iid $|t|$-statistics ($|t|_{\mathrm{naive}} = 7.76$ for $\log \mathrm{Liq}$, 6.15 for σ_{LUNA}, 0.75 for ANCHOR RATE) overstate significance for the two identified regressors by a factor of 2-3× because the OLS residuals violate iid (BP $p \approx 1.5 \times 10^{-25}$, LB $p \approx 0$ at lags 5/10/22, $DW = 0.078$, see Figure 4). Interestingly, the naive estimator *understates* the $|t|$ for ANCHOR RATE (naive/HAC ratio 0.39×): ANCHOR RATE is quasi-constant in-sample, so its residual autocovariance structure inflates the HAC SE less than it inflates the iid SE that ignores the temporal dependence — a small reminder that "HAC always weakens significance" is a rule of thumb, not a theorem.

The Chapter 4 regime conditioning supports this reading: the mean $|TE|$ in the top σ_{LUNA} quartile is 3.2× the bottom quartile mean (89.4 bp vs 27.8 bp), confirming that σ_{LUNA} carries the TE signal non-linearly across regimes — a fact the linear OLS coefficient alone does not surface.

The Anchor Earn rate coefficient remains not identified at the 5 % level ($p_{\mathrm{HAC}} = 0.057$, borderline) — the rate was administratively pinned at 19.5 % until 2022-05-01, leaving essentially no within-sample variance. This is a methodological warning, not a statement that Anchor demand did not matter — Anchor demand manifests through the σ_{LUNA} channel (Anchor-funded UST creation forced LUNA mint/burn).

F2 — log-liquidity is the dominant variance-absorber in the calm regime. $\hat{\beta}_2 = -2.1 \times 10^{-3}$ with HAC $p \approx 0.014$ (exact $p_{\mathrm{HAC}} = 0.0144$). Curve UST-3pool depth (sum across Wormhole + Shuttle wrappers) is the single most powerful suppressor of cross-venue TE in normal periods, with the suppression mechanism breaking down once pool depth collapses on 9–12 May 2022. F2 and F1 are distinct findings: F1 ranks regressors on full-window joint precision and isolated explanatory power and reads ($\log \mathrm{Liq}$, σ_{LUNA}) as co-dominant without a sharp ordering; F2 characterises the regime-specific variance-absorbing role of liquidity, which holds up to the spiral and fails within it.

F3 — the Curve stableswap curve constrained the on-chain peg break on most spiral days, then inverted at the bottom. The Curve UST-3pool [Wormhole] daily minimum on 2022-05-12 was \$0.2649; the intraday absolute minimum was \$0.0619 on 2022-05-13 09:14 UTC during the chain-halt window. The Binance UST/USDT spot minimum across the spiral window was \$0.2346 on 2022-05-11 07:38 UTC. The stableswap invariant is slippage-asymmetric: near the peg the curve absorbs flow while letting the price drift only slowly, but once the UST balance exceeds $\sim 96\,\%$ of pool weight (USDT/USDC drained), the slippage-amplifying side of the curve dominates and the on-chain quote can fall below the CEX quote. This is the canonical liquidity-vs-price trade-off in an algorithmic stablecoin under run — with the stableswap acting as a brake on the way down and an accelerator at the bottom.

F4 — the formal Prop 1164 DiD is underpowered; the descriptive evidence is consistent with a demand-bound spiral. The Phase 9 difference-in-differences against the formal Prop 1164 endorsement (2022-05-11 10:10 UTC) returns $p_{\mathrm{MWU}} = 0.80$ on a 2-day pre vs 2-day post window. With $n_{\mathrm{pre}} = n_{\mathrm{post}} = 2$, this is an *absence of statistical power* rather than a positive "no effect" result, and we do not read it as a falsification of Prop 1164 causality. The descriptive evidence, however, is unambiguous: the realised mint rate on 9-10 May (pre-endorsement) was already in the same regime as on 11-13 May (post-endorsement), i.e. the mechanistic mint-capacity uplift (basepool 50 M → 100 M SDR; PoolRecoveryBlock 36 → 18) was non-binding by the time it was voted in. Read together, the DiD result does not refute Prop 1164 causality but is consistent with the spiral being demand-bound rather than parameter-bound: once arbitrageurs had no viable exit the cap that the proposal would have raised was not the binding constraint — the diagnostic signature of a coordination failure rather than a mechanism-design failure.

F5 — LFG BTC reserve drainage is identifiable on-chain for the principal wallet. The publicly cited 80 394 BTC build-up peak (LFG May 2022 post-mortem) is a multi-wallet aggregate; the on-chain reconstruction in this work tracks one principal wallet with 71 049 BTC gross inflows, 70 736 BTC total outflows across two discrete 9–10 May tranches, and the **313 BTC** residual matched to the satoshi (`lfg_btc_wallet_summary`). This permits a clean "reserve-collateralisation ratio" timeseries for the principal wallet that the V2 monitoring stack should track, with the caveat that any partially-collateralised algorithmic design should require a complete multi-wallet registry as part of its transparency manifest (see V2-4).

F6 — the trigger transaction is identifiable. 2022-05-07 21:44 UTC, wallet `0x8d47...` swaps 85 M UST → 84.5 M USDC on Curve UST-3pool [Wormhole], following an identifiable evening of Wormhole-bridged UST inflow to Ethereum. A second wallet executed four 25 M-UST swaps within the next 13 minutes. We characterise the cascade as *operationally irreversible* from

≈ 2022-05-09 15:00 UTC — 41 hours after the trigger — on a two-part empirical criterion: (i) by that hour the Curve UST-3pool [Wormhole] median price had stabilised at $0.985 (basis −1.5 % vs $1, vs −0.12 % median for the prior 4 months), and (ii) the largest available defence flow — the LFG single-wallet tranche of 42 531 BTC at 2022-05-09 18:34:13 UTC, deployed 3.5 h later — failed to compress the basis: the Curve median fell to $0.94 by 19:00 UTC and $0.85 by 23:00 UTC. The "point of no return" is therefore the moment beyond which the largest available counter-flow (LFG OTC + Anchor reserve + Curve depth) could no longer hold the Curve basin against the redemption pressure.

F7 — Anchor redemption velocity peaked at 228 813 `anchor_redeem_stable` events. This is the demand-side amplifier — depositors withdrawing UST that had to be either absorbed by Curve liquidity (saturated) or burned for LUNA (which amplified σ_{LUNA}, see F1, feedback loop closed). The yield-reserve buffer drained linearly through the 4 May Prop 20 cut window even though the 19.5 % nominal rate held.

F8 — the cross-chain arbitrage cycle saturated within 4 hours. Pre-crash: the Curve UST-3pool [Wormhole] basis vs $1 sat at a daily-median of −12 bp (−0.12 %) — arbitrageurs bought on Curve and bridge-redeemed through Wormhole within hours. Post 7 May 21:44 UTC: bridge-redeem latency exceeded the price-decay timescale. This is the V2 design-relevant finding — a peg-defence reliant on a multi-hour cross-chain arbitrage cycle is structurally unable to absorb a minute-scale liquidity shock.

F9 — bridge-channel liquidity partition during the spiral. During the 7–13 May window, the Wormhole and Shuttle wrappers de-synchronised dramatically. Wormhole gross volume multiplied to $7.36 B (×3.5 vs the priming month) with net outflow of −$343 M (burns dominating). Shuttle inverted in direction, taking +$154 M of net inflow on shrinking gross volume. The mechanism is liquidity-channel partition: holders accessing UST via Shuttle were structurally unable to exit through the deeper Curve UST-3pool [Wormhole] without un-wrapping and re-wrapping through Terra (an arbitrage cycle that had itself saturated, per F8), and $308 M of UST [Shuttle] remained trapped in the shallow pool post-crash. The implication for V2 design: aggregate TVL or aggregate cross-chain liquidity is not the right metric in stress — what matters is the depth of each individual exit channel, because channels are not interchangeable once arbitrage settlement saturates.

10.2 Open questions

Q1 — Did the trigger wallet act with intent? Phase 8 case study #1 documents the wallet history of `0x8d47...` (pre-2022 dormancy, 7 May activation, Wormhole inflow timing). This report does not assert intent — attribution remains forensic, not statistical. Open for V2 prediction: can the on-chain footprint *before* the trigger distinguish a directed attack from a liquidation cascade?

Q2 — Is the Anchor coefficient non-identifiable in-sample, or non-existent? F1 cannot distinguish "Anchor rate matters but is constant" from "Anchor rate does not matter at the linear level". A V2 design that ships with a variable yield mechanism (and credible commitment to vary it) would create the identifying variance.

Q3 — What is the minimum LFG reserve ratio that would have held the peg? The 80 394 BTC reserve was ∼17–19 % of the floating UST supply at peak BTC valuation (Chapter 6). Counterfactual question: at what CR% threshold does the reserve-supported peg-defence converge? Empirically not testable on UST alone ($n = 1$ event); V2 simulation framework should explore.

Q4 — Was the Curve-vs-Binance basis a leading indicator? Pre-crash, the daily-median basis was -12 bp ($-0.12\,\%$, negative on Curve). Two $> 3\sigma$ basis spikes to $-2.0\,\%$ on 2022-04-10 and again on 2022-05-04 preceded the trigger by 27 days and 3 days respectively. Is the basis time-series a viable leading indicator? This is a Chapter 3 artefact that we have but did not formalise into a leading-indicator estimator — promoted to V2 prediction backlog (*niveau 2*).

Q5 — Why is the Wormhole vs Shuttle wrapper basis non-zero in the late-2021 quarter? The two wrappers reference the same underlying UST but transit through different bridge contracts. A persistent few-bps basis exists in Q3-Q4 2021 that Phase 5 does not fully explain. Hypothesis: differential bridge-exit gas + redeem latency. Open for V2 cross-wrapper monitoring.

10.3 Implications for the Derivalink V2 monitoring spec

V2-1 — Track $\sigma_{\text{collateral}}$ as the primary peg-stress signal. Whatever the collateral basket (LUNA, stETH, sUSDe, ...), the realised volatility of the collateral asset is the single best leading indicator of peg-band breaches. This generalises F1 beyond UST. The V2 alerting stack should escalate on $\sigma_{\text{collateral}}$ z-scores ahead of TE z-scores.

V2-2 — Track liquidity *depth at the peg*, not total TVL. F2 + F3 together: it is not the total TVL that mattered, it is the depth of the curve at the peg level. The V2 monitoring stack should expose "USD-redeemable within a 50bp slippage band" as a first-class metric.

V2-3 — Track the cross-chain settlement latency budget. F8 implies a V2 alert: if the protocol's peg defence depends on a multi-hop arbitrage cycle (e.g. Ethereum → bridge → native chain → redemption), the latency of that cycle is the upper bound on absorbable demand shocks. The V2 stack should publish a "minutes-to-arbitrage" metric per asset.

V2-4 — Track the reserve coverage ratio for partially-collateralised designs. F5 implies the V2 stack should maintain a per-asset $CR(t)$ timeseries against a reserve wallet-registry (LFG-like). The V2 spec should publish a JSON manifest of the reserve wallets per asset, refreshed on a daily cadence.

V2-5 — Track redemption-velocity z-scores. F7 identifies Anchor redemption velocity as the amplifier. The V2 stack should track the analogous redemption-mechanism event count per asset (Anchor for UST, DSR for DAI, vault burns for Synthetix, ...) on a rolling z-score basis.

V2-6 — Tail-coupling diagnostic between native peg asset and collateral. Chapter 7 demonstrates the asymmetric tail dependence between UST and LUNA. The V2 stack should expose a rolling lower-tail copula diagnostic between every synthetic and its principal collateral / seigniorage asset.

V2-7 — Track exit liquidity per channel, not aggregate. F9 implies that aggregate liquidity hides structural partition risk. For any asset with multiple bridge-wrapper variants on a host chain (or multiple chains with different liquidity profiles), the V2 stack should expose per-channel "USD-redeemable within 50 bp" as separate metrics, and alert on inter-channel divergence as a leading indicator of liquidity-partition stress.

10.4 What this report does not claim

- No causal claim about wallet intent (Q1).
- No counterfactual claim about the minimum reserve ratio that would have held the peg (Q3 is open).
- No claim of out-of-sample predictive value for the Curve-Binance basis (Q4 deferred to V2 niveau 2).
- No claim that Prop 1164 *caused* the hyperinflation, *and* no claim that it did not: the formal DiD is underpowered ($n = 2/n = 2$). The descriptive record is consistent with a demand-bound spiral but the formal test cannot adjudicate (F4).

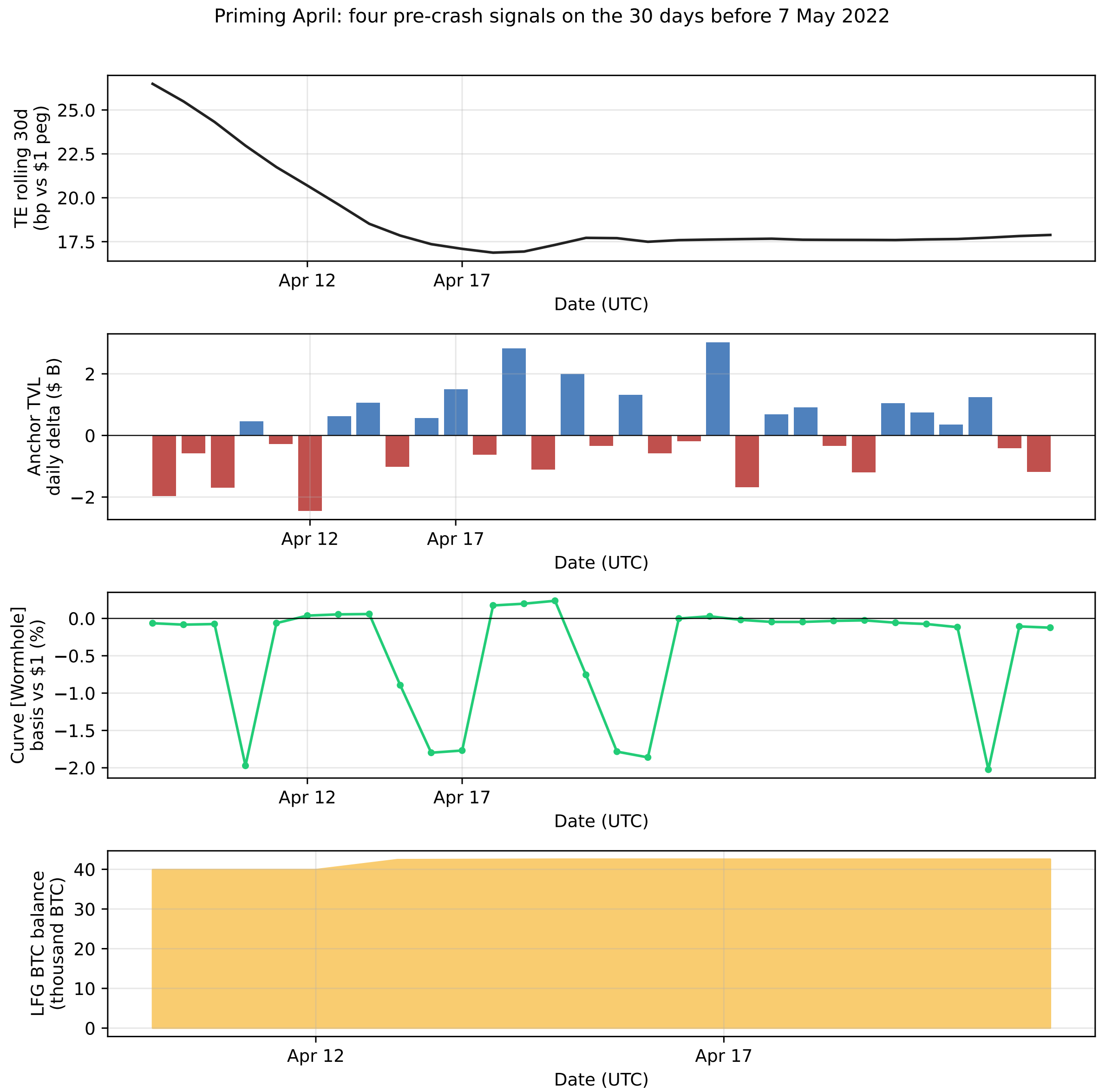

Figure 15: Priming April four-panel signal stack on the 30-day window preceding the trigger transaction: 30-day rolling TE RMSE (bp), Anchor TVL daily delta ($ B), Curve UST-3pool [Wormhole] basis vs $1 (%), LFG BTC wallet balance (thousand BTC).

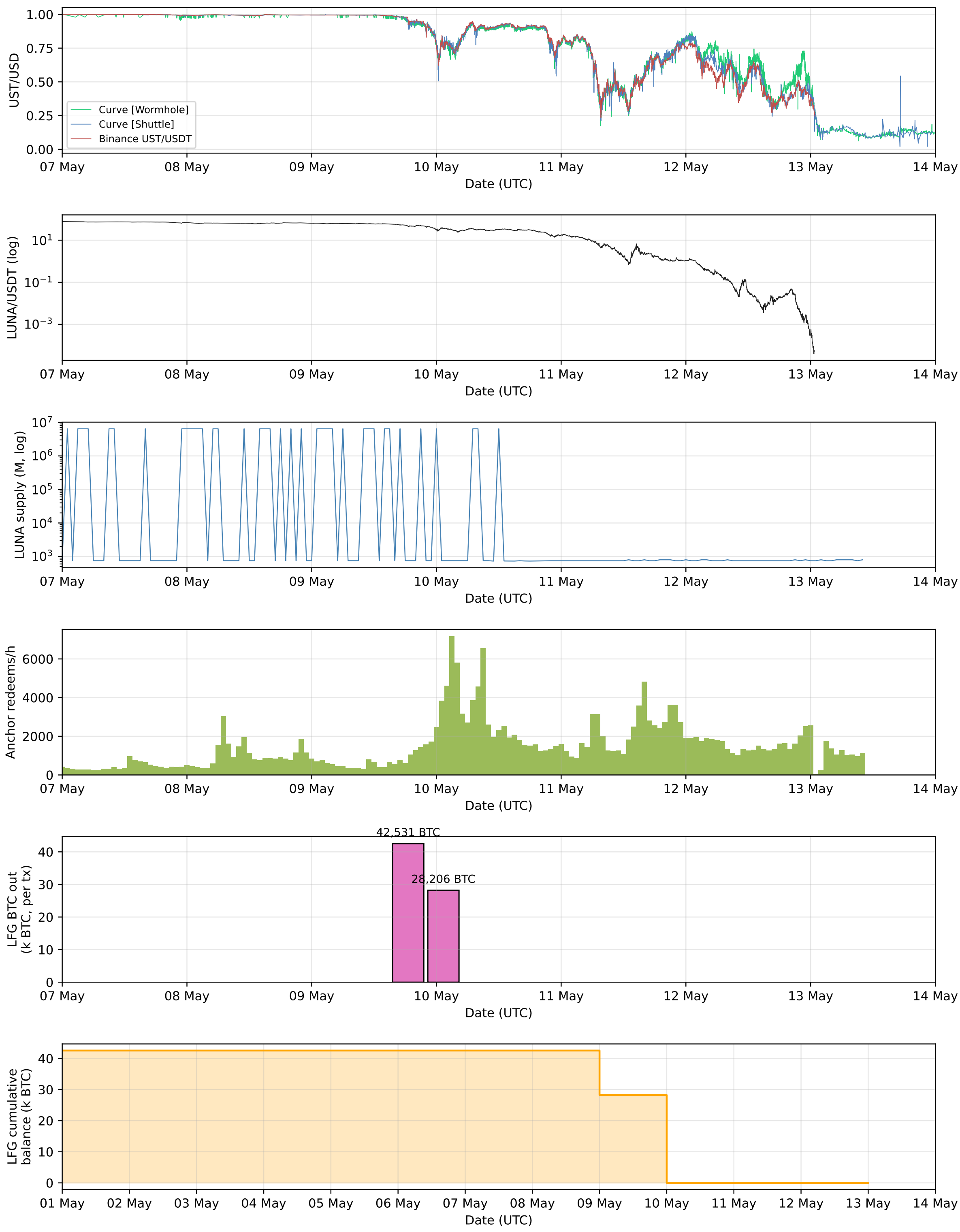

Figure 16: Death spiral six-panel reconstruction: UST/USD across Curve+Binance (panel 1), LUNA/USDT log-scale (2), LUNA supply log-scale (3), Anchor hourly redeem count (4), LFG BTC outflow amounts (5), LFG cumulative balance (6).

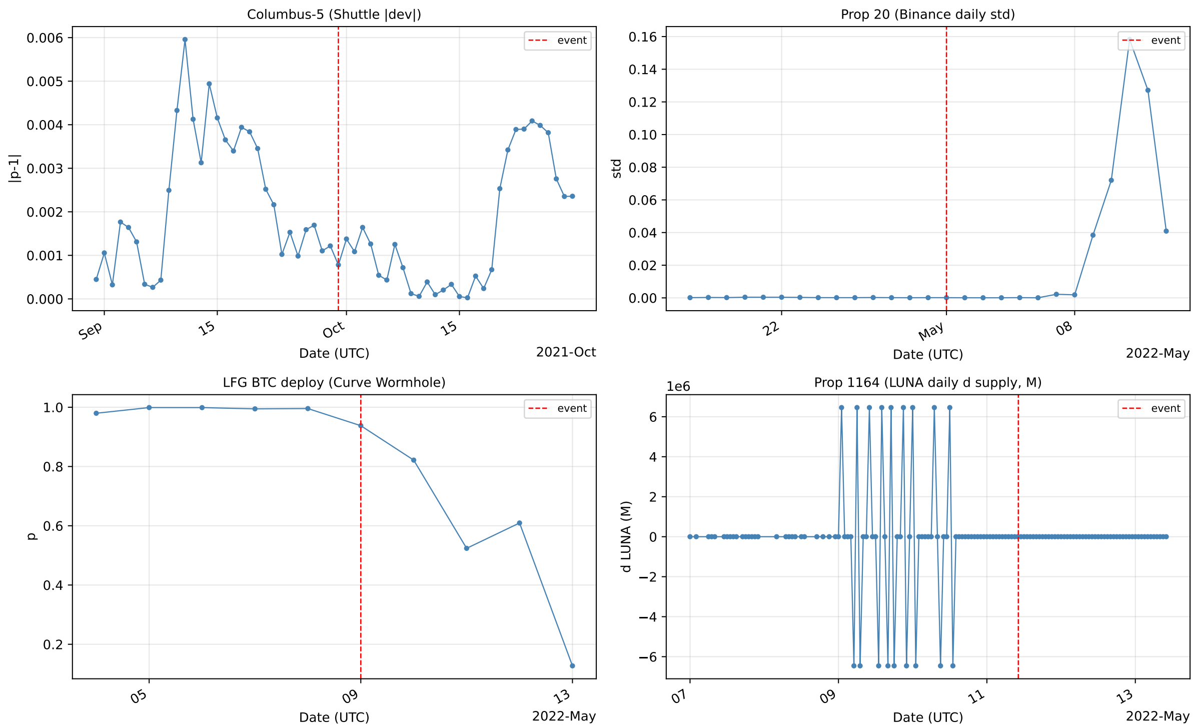

Figure 17: Four natural-experiment panels, each centered on the event (vertical red line) with a ± window of 30 days (or 3 days for the spiral-week events).