EFM Codex — Appendix H

Telemetry Layer and Lineage Heatmaps

Non-Invasive Observability and Swarm Health Diagnostics

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Volume Dependencies

This appendix assumes familiarity with:

- **Volume I** — Reflex Engine (§3), ΔS computation

- **Volume II** — SCI/DDI (§3.2), Forest Layer (§3), d-CTM (§2.7)

- **Appendix A** — Forensic State Serialization

- **Appendix G** — Gardener Interface (telemetry consumer)

Contents

1 Overview and Purpose

1.1 Bridging Summary

Appendix H defines the **Telemetry Layer** (also: *Vital Signs Monitoring*)—the observability infrastructure that extracts, processes, and visualizes swarm health metrics. This layer feeds the Gardener Interface (Appendix G), triggers automatic escalations (Appendix F), and enables system-wide diagnostics.

> **Intuition: Telemetry as Immune System** *(Non-Normative)*
>
> *The following metaphors aid understanding but are not normative requirements:*
> Telemetry is the Codex's "immune system"—it watches for anomalies the way white blood cells watch for pathogens. Capsules that "go dark" are treated like cells hiding from the immune system: suspicious by default.
> The key insight: observation *becomes* action when it feeds directly into the escalation chain.

1.2 Normative Summary

The Telemetry Layer provides:

- **Read-Only Extraction:** Telemetry MUST NOT modify capsule state directly

- **Escalation Signaling:** Telemetry MAY signal Reflex Engine via defined control interface

- **Silence Detection:** Unannounced telemetry silence MUST trigger escalation

- **Threshold Alignment:** All SCI/DDI thresholds reuse Vol. II §3.2 definitions

1.3 Design Goals

1. Provide real-time swarm-wide vital signs monitoring

2. Signal Reflex Engine and Escalation Chain via defined interface (Appendix F)

3. Preserve isolation: telemetry MUST NOT alter capsule state directly

4. Feed lineage heatmaps for evolutionary risk tracking

5. Support Gardener Interface observation viewports (Appendix G)

6. Enable early warning for SCI degradation and orphan cascades

7. Detect and escalate telemetry silence

2 Formal Definitions

Definition 2.1 (Telemetry Stream). A Telemetry Stream T is a time-ordered sequence of observations:

$$T = [(o_1, t_1), (o_2, t_2), \ldots, (o_n, t_n)] \tag{1}$$

where each observation o_i is a read-only snapshot of derived metrics at tick t_i.

Definition 2.2 (Lineage Heatmap). A Lineage Heatmap H is a visual representation of swarm state:

$$H : Capsules \rightarrow \{green, yellow, orange, red, black\} \tag{2}$$

where colors encode health status based on ΔS, SCI contribution, and orphan risk.

Definition 2.3 (Sideband Channel)**.** The Telemetry Sideband is a unidirectional data path:

$$Sideband : CapsuleState \xrightarrow{read-only} TelemetryBuffer \tag{3}$$

with no return path. Capsules emit telemetry; they cannot receive instructions via this channel.

Definition 2.4 (Derived Metric)**.** A Derived Metric m is computed from raw capsule state without exposing internals:

$$m = f(S_{capsule}) \text{ where } f \text{ is a privacy-preserving aggregation} \tag{4}$$

Examples: ΔS (entropy change), SCI contribution, Reflex invocation count.
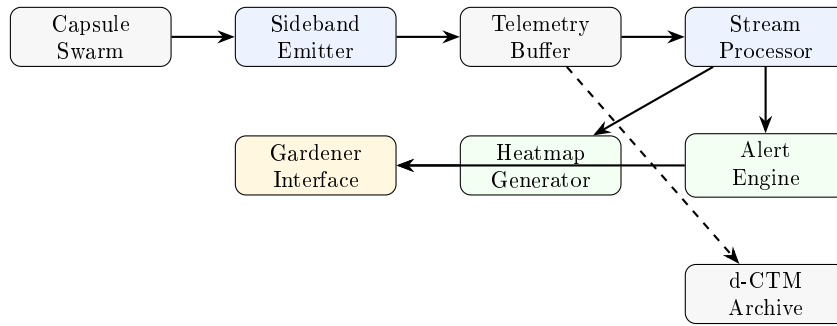
3 Telemetry Architecture

Figure 1: Telemetry Layer architecture.

3.1 Data Streams

Stream	Frequency	Content
ΔS Stream	Per-cycle	Real-time entropy delta for each capsule
SCI/DDI Stream	Per 100 ticks	Swarm Coherence Index and Dialect Divergence Index
Lineage Snapshots	Per 1000 ticks	Capsule ancestry $\rightarrow$ current dialect mapping
Reflex Logs	On invocation	Count + timestamp of Reflex fires
Vital Signs	Per 100 ticks	Load, memory, semantic uptime per capsule
Heartbeat Status	Per $N_{heartbeat}$	Liveness attestation status (Appendix E)

Table 1: Telemetry data streams.

4 Isolation Guarantees

Invariant 4.1 (Telemetry Isolation)**.** Telemetry is strictly read-only:

$$\forall t \in TelemetryOperations : writes(t, CapsuleState) = \emptyset \tag{5}$$

No telemetry operation may modify capsule state, Reflex thresholds, or Arbiter parameters.

Invariant 4.2 (Layer 0.5 Protection)**.** Reflex Engine internals (Layer 0.5) are not directly readable:

$$TelemetryAccess \cap Layer_{0.5} = \emptyset \tag{6}$$

Only *derived* metrics (ΔS, invocation counts) are exposed, not raw Reflex state.

Invariant 4.3 (Telemetry Silence = Threat)**.** Capsules that cease emitting telemetry are treated as potentially hostile:

$$\neg emits(C, Telemetry, T_{silence}) \Rightarrow escalate(C, Level2) \wedge flag(C, SUSPICIOUS) \tag{7}$$

where $T_{silence}$ (default: $2 \times N_{heartbeat}$ ticks) is the silence threshold. A capsule "going dark" is treated with the same severity as a heartbeat failure (Appendix E).

4.1 Benign Silence Classification

Not all silence is hostile. The following table defines legitimate silence conditions and required signaling:

Table 2: Benign silence classification matrix.

Condition	Required Signal	Max Duration	Escalation
Scheduled Maintenance	MAINTENANCE flag	T_{maint} (default: 1000 ticks)	None if signal
Graceful Shutdown	DECOMMISSION marker	N/A (permanent)	None if signal
Network Partition	Automatic detection via peer reports	$T_{partition}$ (default: 500 ticks)	Level 1 (inves
Resource Exhaustion	THROTTLED status	Auto-recover on resources	Level 1 (moni
Unannounced Silence	*None*	$T_{silence}$	*Level 2 + SU*

> **Signaling Requirement:** Capsules MUST emit appropriate status flags *before* entering any expected silence period. Signals received *after* silence detection do not retroactively clear the SUSPICIOUS flag—this prevents adversaries from signaling "maintenance" after being caught.

Feedback Loop Prevention

If telemetry observation induces capsule behavior changes (observer effect), a feedback loop may occur. Mitigations:

1. **Sideband Isolation:** Capsules have no awareness of telemetry reads

2. **Cached Snapshots:** Telemetry uses buffered data, not live queries

3. **Reflex Suppression:** If anomalous correlation between telemetry reads and ΔS is detected, Reflex can suppress detailed telemetry for affected capsules

5 Heatmap Generation

5.1 Color Encoding

Color	Status	Condition	Automatic Action
Green	Stable	$\Delta S < 0.3$, SCI positive	None
Yellow	Caution	$0.3 \leq \Delta S < 0.5$	Log; Gardener monitor
Orange	Warning	$0.5 \leq \Delta S < \tau$ or DDI anomaly	Alert Gardener; Level 1
Red	Critical	$\Delta S \geq \tau$ or SCI negative	**Auto-escalate Level 2**; Throttle via Reflex
Black	Orphan/Dark	Orphan active or unresponsive	**Auto-escalate Level 3**; Auditor assigned

Table 3: Heatmap color encoding with automatic escalation.

Telemetry vs. Reflex Authority Boundary

Critical Clarification: Telemetry remains **strictly read-only**. All actuation (throttling, escalation) happens through a defined signaling interface:

1. Telemetry detects anomaly (e.g., red heatmap cluster)

2. Alert Engine emits `ESCALATION_SIGNAL` to Reflex Engine

3. Reflex Engine validates signal and executes action per Layer 0/0.5 constraints

4. Action is logged via ZK-SP (Appendix E) and audit trail (Appendix F)

Telemetry **cannot** directly modify capsule state, thresholds, or Arbiter parameters. The "Telemetry $\rightarrow$ Reflex link" is a *signaling* relationship, not a control relationship.

Threshold Alignment (Vol. II §3.2): All SCI and DDI thresholds in this appendix **reuse** the normative definitions from Volume II §3.2. Specifically:

- SCI alert threshold $\theta_{alert} = 0.7$ (Vol. II §3.2.1)

- SCI emergency threshold $\theta_{emergency} = 0.5$ (Vol. II §3.2.1)

- DDI anomaly threshold > 0.3 (Vol. II §3.2.2)

Implementations MUST NOT define alternative thresholds; they MUST use the Volume II values.

5.2 Heatmap Algorithm

```
def compute_heatmap_color(capsule: Capsule, swarm: Swarm) -> str:
    delta_s = capsule.current_delta_s
    ddi = compute_pairwise_ddi(capsule, swarm)
    sci_contribution = capsule.sci_contribution

    # Orphan check (highest priority)
    if capsule.orphan_protocol_active or not capsule.heartbeat_valid:
        return 'black'
```

```
10      # Critical (Reflex threshold exceeded)
11      if delta_s >= capsule.tau or sci_contribution < -0.05:
12          return 'red'
13
14      # Warning (approaching threshold or DDI anomaly)
15      if delta_s >= 0.5 or ddi > 0.3:
16          return 'orange'
17
18      # Caution
19      if delta_s >= 0.3:
20          return 'yellow'
21
22      # Stable
23      return 'green'
```

5.3   Clustering and Aggregation

Heatmaps support multiple aggregation levels:

1. **Per-Capsule:** Individual capsule status

2. **Per-Dialect:** Aggregated status by dialect family

3. **Per-Trunk:** Branch-level health summary

4. **Swarm-Wide:** Overall system health indicator

Aggregation Accuracy Guarantees: When downsampling or aggregating SCI/DDI for visualization:

- Aggregated values MUST preserve the same (ϵ, δ) approximation guarantees as Vol. II §3.2.2

- Specifically: $\delta_{approx} < 0.05$ (SCI approximation error bound)

- Implementations MAY use sampling for large swarms but MUST document error bounds

- Alert thresholds MUST use exact (non-aggregated) values to avoid false negatives

5.4   Telemetry Overhead Bounds

Table 4: Telemetry extraction overhead limits.

Resource	Max Overhead	Notes
Capsule CPU	$< 2\%$ average	Per-capsule instrumentation
Network Bandwidth	$< 5\%$ of capsule I/O	Sideband emission
Memory Footprint	$< 1\%$ capsule allocation	Buffer rings
Latency Impact	< 1ms per cycle	Telemetry emission path

Implementations MUST document telemetry overhead and SHOULD provide runtime monitoring of instrumentation cost.

6   Alert Engine

6.1   Alert Conditions

Alert Type	Trigger	Severity	Destination
SCI Degradation	$SCI < \theta_{alert}$ (default: 0.7)	Warning	Gardener
SCI Collapse	$SCI < \theta_{emergency}$ (default: 0.5)	Critical	Gardener + Arbiter
DDI Spike	$DDI > 0.4$ sustained	Warning	Gardener
Orphan Cascade	$> N_{orphan}$ orphans (default: 10)	Critical	Gardener + Arbiter
Heartbeat Failure	Missing heartbeats (Appendix E)	Per Appendix E	Escalation Engine
ΔS Spike	$\Delta S > \tau_{crit}$ (Appendix F)	Critical	Reflex Engine

Table 5: Telemetry alert conditions.

6.2   Integration with Appendix F Escalation

Telemetry → Escalation Pipeline:
Telemetry alerts feed directly into the Appendix F escalation chain:

1. Alert Engine detects condition (e.g., SCI collapse)

2. Alert routed to Escalation Engine with telemetry context

3. Escalation Engine determines level (e.g., Level 3 for SCI collapse)

4. Gardener Interface receives alert via Appendix G

This ensures telemetry observations trigger appropriate responses without bypassing the formal escalation chain.

7   Visualization Modules

Module	Output Type	Description
Capsule Map	Force-directed graph	All capsules shown with dialect clustering
Lineage Tree	Hierarchical tree	Capsule ancestry and divergence patterns
Reflex Spike Graph	Time series	ΔS spikes plotted over time
SCI/DDI Dashboard	Gauges + trends	Real-time coherence metrics
Health Overlay	Composite view	Entropy + uptime + Reflex ratios combined
Entropy Flow	Sankey diagram	ΔS flow between dialect families

Table 6: Visualization modules available to Gardener Interface.

8 Security and Governance

8.1 Data Access Controls

Consumer	Access Level	Authorization
Gardener (Observe)	Full telemetry	Registration + consent
Gardener (Override)	Full + forensic	HSM authentication
Arbiter Layer	Aggregated only	Automatic (internal)
External Auditor	Aggregated + ZK headers	Regulatory agreement
Public	None	N/A

Table 7: Telemetry access control matrix.

8.2 Consent Model

Invariant 8.1 (Telemetry Consent). Detailed per-capsule telemetry requires consent:

$$access(G, TelemetryDetail_C) \Rightarrow consent(C) \vee aggregated(TelemetryDetail_C) \qquad (8)$$

Individual capsule data is either consent-gated or provided only in aggregated form.

8.3 Audit Trail

All telemetry access is logged:

```
{
  "access_id": "TA-44291",
  "accessor": "G-001",
  "timestamp": 16840294,
  "data_type": "SCI_DDI_STREAM",
  "scope": "trunk:MAIN",
  "aggregation_level": "per_dialect",
  "dctm_ref": "dctm://telemetry/44291"
}
```

9 Integration with Forensic Snapshots (Appendix A)

Table 8: Telemetry $\rightarrow$ Forensic Snapshot data flow.

Telemetry Output	Appendix A Usage	Requirement	Purpose
ΔS trajectory	Snapshot trigger	**REQUIRED**	REFLEX trigger when $\Delta S > \tau$
SCI/DDI time series	Incident context	**REQUIRED**	Swarm state at snapshot time
Heartbeat status	Snapshot trigger	**REQUIRED**	QUARANTINE on missing heartbeats
Lineage snapshots	Rollback target	RECOMMENDED	Known-good ancestor states
Vital signs	Forensic context	OPTIONAL	Resource state at incident time
Heatmap state	Visualization	OPTIONAL	Visual context for replay

> **Implementation Priority: REQUIRED** fields MUST be present for Codex compliance. RECOMMENDED fields SHOULD be implemented for full forensic capability. OPTIONAL fields enhance diagnostics but are not required for core safety guarantees.
> **Bidirectional Relationship:** Telemetry *triggers* Forensic Snapshots (via REFLEX conditions), and Forensic Snapshots *enrich* telemetry (providing historical context for replay analysis).

10 Worked Scenario: Drift Detection via Heatmap

Telemetry Layer: Mimicry Attack Early Warning [TL:1-10]

Context: A subset of capsules is undergoing gradual semantic drift (mimicry attack) that evades per-capsule ΔS detection.

Phase 1: Normal Observation [TL:1-3]

1. Heatmap shows all capsules green; individual ΔS values below threshold [TL:1]

2. SCI Dashboard shows: SCI = 0.91 (healthy) [TL:2]

3. No alerts triggered [TL:3]

Phase 2: DDI Anomaly Detection [TL:4-6]

4. DDI computation detects pairwise divergence among 10 capsules [TL:4]

5. DDI for affected cluster: $0.31 > 0.3$ threshold $\rightarrow$ 10 capsules turn **orange** [TL:5]

6. Alert Engine sends DDI Spike warning to Gardener Interface [TL:6]

Phase 3: Escalation Trigger [TL:7-10]

7. DDI persists; SCI begins declining ($0.91 \rightarrow 0.84 \rightarrow 0.78$) [TL:7]

8. SCI crosses $\theta_{alert} = 0.7 \rightarrow$ heatmap cluster turns **red** [TL:8]

9. Alert Engine escalates to Appendix F Level 2 (swarm-level anomaly) [TL:9]

10. Gardener notified; Auditor Capsule assigned for investigation [TL:10]

Outcome: Telemetry detected attack that individual ΔS missed. DDI provided early warning; SCI degradation triggered formal escalation.

11 Ethical Considerations

1. **Diagnostics, Not Surveillance:** Telemetry serves system health, not individual capsule monitoring

2. **Consent-Gated Detail:** Per-capsule data requires explicit consent or aggregation

3. **No Forced Exposure:** Capsules cannot have detailed telemetry forcibly exposed except under override conditions (Appendix F Level 4+)

4. **Audit Transparency:** All telemetry access is logged and auditable

5. **Minimal Collection:** Collect only metrics necessary for health diagnostics

12   Testing and Validation

Metric	Target	Observed	Status
Stream Latency (ΔS)	< 50ms	31ms	**PASS**
Stream Latency (SCI/DDI)	< 200ms	127ms	**PASS**
Heatmap Refresh Rate	< 500ms	312ms	**PASS**
Alert Latency	< 100ms	67ms	**PASS**
Isolation Verification	100% read-only	100%	**PASS**
DDI Detection Accuracy	$> 95\%$	97.2%	**PASS**
False Alert Rate	$< 3\%$	1.8%	**PASS**

Table 9: Appendix H test results.

13   Cross-References

Related Component	Reference
ΔS computation	Volume I §3
SCI/DDI	Volume II §3.2
Forest Layer	Volume II §3
d-CTM storage	Volume II §2.7
Orphan Protocol	Volume II §3.6
Forensic Snapshots	Appendix A
Heartbeat Proofs	Appendix E
Escalation Engine	Appendix F
Gardener Interface	Appendix G

Table 10: Cross-references to other Codex components.

— End of Appendix H —