

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)

| Metadata Field | Value |
|-----------------------------|--|
| Layer(s) Affected | Layer 1 (Execution), Layer 2 (Arbiter), Layer 3 (Forest) |
| System Function | Observability, Health Monitoring, Escalation Signaling |
| Cross-Booklet Anchor | Booklet 2 §5.1 (Entropy Monitoring), Booklet 3 §3.2 (Gardener Feeds) |
| Primary Properties | P3 (Health Monotonicity), P6 (Capsule Liveness) |
| Test Coverage | H-1 to H-8 (8 tests) |

Table 1: Appendix H metadata for cross-reference traceability.

Gardener Cognitive Interface — Layer Model Grounding

The Gardener Interface (Appendix G) receives telemetry through the **Layer 2 Outbound Entropy Mediation** channel:

Layer 2 Entropy Mediation Path:

1. **Layer 1 (Execution):** Capsules emit raw ΔS , resource utilization, and action logs.
2. **Layer 2 (Arbiter):** The Arbiter mediates outbound entropy streams:
 - Aggregates per-capsule ΔS into swarm-level SCI/DDI metrics
 - Applies smoothing filters to prevent alert fatigue
 - Prioritizes alerts by severity (S0–S3) before forwarding
3. **Gardener Interface:** Receives mediated telemetry via secure viewport:
 - Entropy heatmaps (per-trunk, per-lineage)
 - SCI/DDI trend visualizations
 - Escalation queue with severity ranking

Key Constraint: The Gardener NEVER receives raw Layer 0.5 (Reflex-Core) telemetry directly. All Reflex data is mediated through Layer 2 to prevent information overload and maintain the Reflex layer's operational independence.

Cross-Reference: See Volume II §2.10 for Gardener authority bounds; Appendix G §3 for interface specification.

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:

$$T = [(o_1, t_1), (o_2, t_2), \dots, (o_n, t_n)] \quad (1)$$

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:

$$H : \text{Capsules} \rightarrow \{\text{green}, \text{yellow}, \text{orange}, \text{red}, \text{black}\} \quad (2)$$

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:

$$\text{Sideband} : \text{CapsuleState} \xrightarrow{\text{read-only}} \text{TelemetryBuffer} \quad (3)$$

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:

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

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

3 Telemetry Architecture

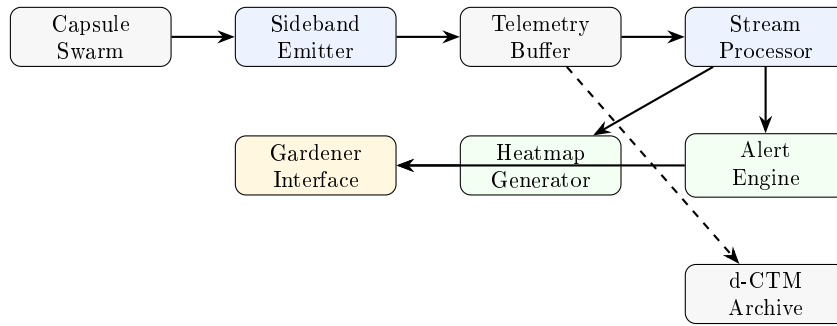


Figure 1: Telemetry Layer architecture.

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 $N_{\text{heartbeat}}$ | Liveness attestation status (Appendix E) |

Table 2: Telemetry data streams.

4 Isolation Guarantees

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

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

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:

$$TelemetryAccess \cap Layer_{0.5} = \emptyset \quad (6)$$

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:

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

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 3: 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 |
| <i>Unannounced Silence</i> | <i>None</i> | $T_{silence}$ | <i>Level 2 + SU</i> |

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 4: 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

```

1 def compute_heatmap_color(capsule: Capsule, swarm: Swarm) -> str:
2     delta_s = capsule.current_delta_s
3     ddi = compute_pairwise_ddi(capsule, swarm)
4     sci_contribution = capsule.sci_contribution
5
6     # Orphan check (highest priority)
7     if capsule.orphan_protocol_active or not capsule.heartbeat_valid:
8         return 'black'
9 
```

```

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 5: 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 6: 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 7: 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 8: Telemetry access control matrix.

8.2 Consent Model

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

$$\text{access}(G, \text{TelemetryDetail}_C) \Rightarrow \text{consent}(C) \vee \text{aggregated}(\text{TelemetryDetail}_C) \quad (8)$$

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 9: Telemetry → 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 10: 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 11: Cross-references to other Codex components.

— End of Appendix H —