

Weak-Signal Interpretation for Airspace and Maritime Sensing

Toward a Stratified, Auditable Architecture for Early Anomaly Triage

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Abstract

Airspace and maritime sensing often begins not with cleanly resolved tracks or incidents, but with weak, noisy, partial, and locally ambiguous signals: faint radar irregularities, intermittent motion traces, weak thermal or visual inconsistencies, RF oddities, route anomalies, metadata mismatches, or disagreement across sensing channels. This bridge paper argues that such environments are suitable domains for a stratified weak-signal architecture that separates bounded observation, provisional interpretation, short-horizon salience escalation, and governed consequence.

Under this approach, weak findings are allowed to influence attention, corroboration, and evidence gathering before they are permitted to become stronger candidate tracks, anomaly states, or operational significance. This bridge paper defines a minimal state ladder, a compact event object, and example promotion predicates so implementers can prototype an inspectable weak-signal pipeline without changing downstream tracking or engagement logic. Its narrower contribution is to show that airspace and maritime systems need a disciplined place for weak anomaly signals to matter before they harden into tracks, incidents, or ignored noise.

1. Introduction

Airspace and maritime sensing systems operate in large, noisy, partially observable environments. Early signals are often incomplete. A faint radar irregularity may appear briefly and then disappear. A maritime route deviation may occur alongside weak metadata inconsistency. A thermal or visual cue may suggest structure while remaining too weak to justify a strong object claim. A radio-frequency irregularity may matter locally without settling what it means.

The engineering problem is not detection per se but how the sensing stack should behave while evidence is provisional.

If weak signals are ignored until they become strong enough for hard classification, useful early structure may be lost. If weak signals are promoted too quickly, the system converts provisional significance into brittle track state, false incident framing, or unnecessary operator burden. A better architecture needs a disciplined middle state: a place where weak anomaly signals can matter without immediately becoming truth, persistence, or stronger consequence.

This paper applies the weak-signal / layered-interpretation architecture to airspace and maritime sensing. The transfer is intentionally narrow. The claim is not that this architecture provides complete sensor fusion, final tracking, targeting, interception, maritime enforcement, or total domain awareness. The claim is that airspace and maritime sensing benefit from explicit separation among bounded observation, provisional interpretation, short-horizon salience escalation, and governed promotion.

The core design principle is simple: weak airspace and maritime anomalies should influence attention before they justify stronger operational consequence.

2. Why Airspace and Maritime Sensing Need a Middle State

Airspace and maritime environments are structurally noisy. They contain clutter, changing weather, intermittent visibility, sensor dropout, environmental reflections, multipath effects, inconsistent metadata, moving non-target objects, and partial sensor coverage. In such conditions, early anomalies often arrive as fragments rather than resolved objects.

Examples of early observations include faint radar irregularities, intermittent persistence, weak thermal or visual inconsistencies, RF oddities, route deviations, AIS or transponder mismatches, cross-sensor disagreement, and clutter-like partial motion traces.

Engineers need this middle state because early evidence is both informative and non-decisive; the architecture must preserve provenance and temporal context so later corroboration is testable.

Without a middle state, sensing architectures tend to collapse in one of two directions. In the first direction, weak anomalies are treated as ordinary noise until they cross a strong threshold. That reduces false alarms, but it may also discard early warning value. In the second direction, weak anomalies are over-promoted into hard tracks, alerts, or incident states. That preserves sensitivity, but it creates false certainty and avoidable review burden.

The middle state prevents both failures. It allows the system to preserve provisional significance, request corroboration, tighten observation, and maintain ambiguity without forcing premature commitment.

In airspace and maritime terms, the relevant question is not only whether this is a confirmed object or incident. The prior architectural question is whether the weak pattern is structured enough to deserve more attention before stronger commitment is allowed.

3. Core Claim and Design Principle

Claim: Airspace and maritime sensing should implement a stratified weak-signal pipeline where bounded findings raise attention, candidate meanings remain provisional, and promotion to operational consequence requires declared predicates and audit records. This paper defines the minimal artifacts and decision boundaries needed to prototype that pipeline.

This framing does not reject radar, optical sensing, RF analysis, AIS/transponder processing, sensor fusion, classification, tracking, or operator workflows. It reframes their early-stage role. In many domain-sensing contexts, the first useful evidence is too partial to deserve strong commitment but too structured to deserve indifference.

The architecture therefore preserves a strict separation between four functions:

1. bounded observation;
2. provisional interpretation;
3. short-horizon salience escalation;
4. governed consequence.

A faint anomaly may raise attention. It may trigger additional sampling. It may justify cross-sensor corroboration. It may enter a temporary watch state. But it should not silently become a durable track, incident state, or stronger operational consequence without declared support.

This is not a claim that weak signals are secretly decisive. It is a claim that weak signals often become useful before they become certain, and that architecture should preserve that usefulness without collapsing into overclaim.

4. Stratified Architecture Mapping

The proposed mapping separates early airspace and maritime anomaly handling into bounded processing functions. These functions do not define a full platform. They define the handoff discipline required for weak-signal triage.

4.1 Observation and Provisional Interpretation

Layer 1 records narrow, provenance-tagged findings such as radar blips, AIS mismatches, RF anomalies, weak visual or thermal inconsistencies, route deviations, intermittent persistence, or clutter-like motion traces. Layer 2 attaches candidate, low-confidence interpretations to those findings while preserving uncertainty and provenance so competing hypotheses can coexist and be evaluated.

Candidate meanings may include possible low-confidence air track, possible small craft or vessel anomaly, possible clutter-related false partial, possible route inconsistency, possible metadata mismatch, possible sensor artifact, or unresolved domain anomaly needing more evidence.

The key requirement is that ambiguity remain visible. A trustworthy system should not hide uncertainty simply because uncertainty is operationally inconvenient. Candidate interpretations should remain revisable and linked to supporting evidence.

4.2 Short-Horizon Salience Escalation

At the next layer, weak but informative deviation influences short-horizon attention. This gives the system a useful response to weak significance without forcing durable commitment.

Permitted attention actions may include tighter observation windows, additional sampling, cross-sensor corroboration requests, route-focused inspection, temporary watch state, slower commitment, local review bands, or preservation of the anomaly candidate for a bounded horizon.

Operationally, salience actions must be bounded by a time window, for example 30–300 seconds, and a resource budget, such as a maximum number of additional samples or sensor queries, to avoid runaway observation.

This layer is short-horizon and non-authorizing. It shapes what the system inspects next. It does not by itself create durable track state, rewrite baselines, resolve identity, classify intent, or authorize stronger consequence.

4.3 Governed Consequence

Only after persistence, convergence, or stronger support builds should the architecture permit governed promotion. At this stage, the system may allow stronger anomaly classification, candidate track promotion, operator review, quarantine of a noisy stream, or transition into a higher review band.

Governed consequence requires declared support. It should not be triggered by salience alone.

Governed promotion must require a signed promotion record containing the predicate set met, evidence pointers, promoting actor, promotion timestamp, and required review deadline. The promoting actor may be an automated rule, human operator, reviewing subsystem, or declared governance process, but it must be recorded.

Possible governed outcomes include remain provisional, promote to candidate track, elevate watch state, route to operator review, quarantine a noisy or conflicting sensor stream, decay and close, or preserve rationale for later audit.

A compact pipeline expresses the structure:

local finding → candidate meaning → bounded attention shift → governed promotion

Or, in the broader weak-signal stack language:

notice → interpret → shape → govern

5. Minimal Operational Contract

This section defines the minimal records, states, and transitions needed to make weak-signal handling inspectable. It is not a full sensing platform specification.

5.1 Light State Ladder

State ladder with minimal semantics:

- **D0 Normal:** no bounded findings in scope.
- **D1 Noticed:** one or more bounded findings recorded; no cross-channel corroboration. Required fields: `first_seen`, `source_channels`, `bounded_findings`.
- **D2 Watching:** D1 persisted for `T_watch` seconds or recurred `N` times within window `W`. `T_watch` and `W` must be declared per deployment.
- **D3 Corroborated:** evidence from at least two independent channels, or a single high-confidence channel plus metadata support. Record `corroboration_set`.
- **D4 Promoted:** promotion predicates satisfied and a promotion record created. Required fields: `actor_id`, `predicates_met`, `evidence_pointers`, `promotion_timestamp`.
- **R0 Resolved:** event closed with `closure_reason` and `retention_policy` tag.
- **Q0 Quarantined:** stream, sensor, or event quarantined; `quarantine_reason` and `quarantine_duration` recorded.

The key boundary is simple: D1–D3 are attention and evidence states; D4 belongs to governed promotion.

This reduces the risk of premature promotion, subject to the chosen predicates and operational thresholds.

5.2 Minimal Event Object

A weak-signal architecture needs a small event object that preserves structure without forcing immediate incident semantics. At minimum, `event_id`, `first_seen`, `source_channels`, and `bounded_findings` are required.

```

{
  "event_id": "string",
  "domain": "airspace|maritime",
  "scope": "string",
  "first_seen": "ISO8601",
  "last_seen": "ISO8601",
  "source_channels": ["string"],
  "bounded_findings": [
    {
      "finding_id": "string",
      "timestamp": "ISO8601",
      "provenance": "string",
      "confidence": "0-1"
    }
  ],
  "candidate_interpretations": [
    {
      "id": "string",
      "type": "string",
      "supporting_findings": ["finding_id"],
      "confidence": "0-1"
    }
  ],
  "current_state": "D0|D1|D2|D3|D4|R0|Q0",
  "supporting_evidence": ["uri"],
  "conflicts_or_uncertainties": ["string"],
  "short_horizon_actions": ["string"],
  "promotion_predicates_met": ["string"],
  "governance_notes": ["string"],
  "closure_reason": "string|null"
}

```

The object is intentionally modest. Its role is to preserve enough structure that the transition from weak cue to stronger consequence remains reviewable.

5.3 Predicate Template

A promotion predicate is a boolean expression over atomic tests.

- **PERSISTENCE(finding_set, W, N):** at least N occurrences in window W.
- **CROSS_CHANNEL(finding_set, channels, M):** evidence from at least M independent channels.
- **METADATA_MATCH(field, expected, score):** metadata consistency score at or above threshold.
- **CLUTTER_REDUCTION(score):** clutter-likelihood below threshold.

A promotion rule is a logical composition of atomic tests using AND and OR. All promotions must record the evaluated atomic test results and the final boolean.

Example rule:

PROMOTE_TO_D4 =

```
PERSISTENCE(finding_set, W=120s, N=3)
AND CROSS_CHANNEL(finding_set, channels={radar, visual, rf}, M=2)
AND CLUTTER_REDUCTION(score<=0.3)
```

Thresholds are deployment choices. The architectural requirement is not a universal number. It is that each threshold be declared, replayable, and recorded when it contributes to promotion.

5.4 Promotion Record

Every D4 transition must emit a promotion record. Minimal fields:

- promotion_id;
- event_id;
- prior_state;
- new_state;
- actor_id;
- actor_type: automated_rule, human_operator, subsystem, governance_process;
- predicate_results;
- final_boolean;
- evidence_pointers;
- promotion_timestamp;
- review_deadline;
- retention_policy;
- rationale_summary.

This record is the audit boundary. Without it, a D4 transition is invalid under this architecture.

5.5 Operator Load, Quarantine, and Retention

The middle state has costs. D1–D3 events increase storage, inspection load, and possible review volume. Implementations should therefore declare retention policies, resource budgets, and quarantine rules before deployment.

At minimum:

- D1 events may expire quickly if unsupported.
- D2 events should carry a bounded watch window.
- D3 events should preserve corroboration evidence long enough for review.

- Q0 events should reduce operator burden by separating likely sensor artifact, stream unreliability, or clutter-dominant cases from promoted anomaly review.

This paper does not prescribe acceptable false-positive or false-negative rates. Those are operational choices. It requires that the architecture expose the tradeoff rather than hide it inside opaque escalation.

6. Compact Examples

6.1 Faint Track with Cross-Sensor Mismatch

A sensing system observes intermittent track persistence in an airspace corridor. A radar path produces a weak irregularity, while another sensing route shows partial disagreement. No single signal justifies a firm track declaration.

A collapsed architecture might either ignore the weak signal or over-promote it into track state. The stratified architecture does neither.

The bounded observation layer records the intermittent persistence and radar irregularity. The provisional interpretation layer forms a low-confidence candidate such as possible air-track anomaly or possible clutter-related partial. The salience layer raises attention by tightening the observation window and requesting corroboration from another channel. Governed promotion occurs only if persistence, convergence, or stronger support builds.

Applied predicates:

PERSISTENCE({radar_blip}, w=120s, N=3)

AND CROSS_CHANNEL({radar, visual}, M=2)

Event fields set: bounded_findings contains radar blips; candidate_interpretations contains low_confidence_track; short_horizon_actions contains increased sampling.

The result is not instant certainty. It is disciplined attention.

6.2 Maritime Route Anomaly with Metadata Mismatch

A maritime monitoring system observes unusual route deviation alongside weak AIS or transponder inconsistency. A low-confidence sensor irregularity appears in the same general scope.

The architecture should not immediately declare a strong incident. It should preserve the bounded findings, form candidate interpretations, and raise attention through reversible means.

Candidate meanings may include possible route anomaly, possible metadata mismatch, possible sensor artifact, or unresolved maritime anomaly. Short-horizon actions may include tighter route-focused inspection, additional sampling, or comparison against recent corridor expectations.

Promotion requires declared support: persistence, corroboration, rationale, and review.

Applied predicates:

`METADATA_MATCH(AIS.mmsi, transponder.mmsi, score>=0.8)`

`OR CROSS_CHANNEL({ais, route_model}, M=2)`

Event fields set: `candidate_interpretations` contains `possible_metadata_mismatch`;
`short_horizon_actions` contains route-focused inspection.

The key is that the route anomaly matters without prematurely hardening into incident state.

6.3 Clutter Versus Genuine Contact Ambiguity

An environment contains clutter-like partials, repeated but weak motion traces, and inconsistent thermal or visual hints. The signals are not strong enough to settle identity, but they are not random enough to dismiss.

The architecture preserves competing interpretations explicitly. It may hold possible clutter, possible weak contact, and unresolved anomaly candidates at the same time. Salience can increase attention temporarily, while governance prevents direct promotion unless evidence strengthens.

Applied predicate outcome:

`CLUTTER_REDUCTION(score<=0.3) fails`

→ Q0 Quarantined after T_{quarantine}

Event fields set: `governance_notes` contains `quarantine_reason`; `closure_reason` records quarantined if the event is closed.

If the signal dissipates, the event resolves. If the stream remains noisy or contradictory, it may be quarantined. If the weak trace persists and converges with independent evidence, it may be promoted to a candidate state.

The architecture therefore reduces both false indifference and false certainty by making the decision path inspectable.

7. Limits and Non-Goals

This paper is intentionally narrow.

It does not propose:

- offensive tactics;
- targeting logic;
- interception or engagement doctrine;
- autonomous enforcement;

- full battlefield command-and-control;
- maritime sovereignty claims;
- complete sensor fusion;
- total domain awareness;
- certified deployment;
- benchmark superiority;
- replacement of existing operator judgment or review workflows.

This is an architecture note focused on triage and promotion discipline; it does not prescribe engagement or enforcement.

Weak signals should be allowed to matter before certainty, but stronger consequence should require more than weak salience alone.

8. Conclusion

Airspace and maritime sensing systems operate under partial observability, environmental noise, intermittent tracks, inconsistent metadata, and cross-sensor disagreement. In those settings, early anomalies often appear before object certainty. A faint radar irregularity, route deviation, weak thermal inconsistency, RF oddity, AIS mismatch, or clutter-like trace may not justify strong commitment on its own. But it may still justify heightened attention.

This bridge paper has argued that airspace and maritime sensing are suitable domains for a stratified weak-signal architecture in many operational contexts; applicability should be validated per deployment. The transfer is simple: bounded findings preserve local structure; provisional interpretations hold candidate meanings; short-horizon salience widens inspection; governed promotion controls stronger consequence.

Engineers should be able to implement a small, auditable middle state that preserves weak signals, evaluates concrete promotion predicates, and records promotion decisions. The deliverable here is a minimal state ladder, a compact event schema, and a predicate template that together let teams prototype and test weak-signal triage without changing downstream engagement logic.