Journal of Applied Sciences and Archaeology

Mini-Review

WRJASA-26-004

P.A.V.O.R.A.T: A Protocol for the Systematic Assessment of Orbital Phenomena and Anomalies in Unbound Trajectories: A Stepped Bayesian Framework for the Detection and Characterization of Infrastructure Techno Signatures in Interstellar Objects

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Citation: Nicolalde MIG (2026) P.A.V.O.R.A.T: A Protocol for the Systematic Assessment of Orbital Phenomena and Anomalies in Unbound Trajectories: A Stepped Bayesian Framework for the Detection and Characterization of Infrastructure Techno Signatures in Interstellar Objects. J Appl Sci & Archeaol 1: 04.

Abstract

The imminent detection of numerous Interstellar Objects (IOs) by the Vera Rubin Observatory requires a formal framework to prioritize observational resources and systematically evaluate potential infrastructure techno signatures. We present P.A.V.O.R.A.T, a stepped Bayesian protocol for Prevision, Alert, Vigilance, Observation, Review of Anomalies and Tactical Action. The core of the protocol is a Rarity Index (RI) formalized as the posterior probability of artificiality, calculated using likelihood ratios that compare natural and artificial models for multiple observables. We validate the framework through simulations of synthetic populations (AUC=0.94) and retroactive application to 3I/ATLAS (P(artificial) <0.01). We specify VOEvent standards for alerts and operational thresholds calibrated for <1% annual false alarms. The reference code is available under MIT license.

Keywords: Interstellar objects; Techno signatures; Bayesian inference; Vera Rubin; Scientific protocol; 3I/ATLAS

Received date: October 31, 2025; **Accepted date:** November 03, 2025; **Published date:** January 07, 2026

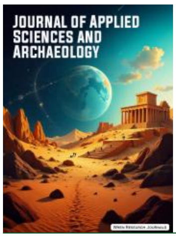
Introduction

The discovery of Oumuamua and subsequent Interstellar Objects (IOs) has established that these visitors are statistically common [1,2]. The upcoming Vera Rubin Observatory (LSST) is projected to discover dozens annually, exceeding our capacity for comprehensive follow-up observation [3]. This abundance presents both an observational challenge and a unique opportunity: the possibility of detecting infrastructure techno signatures on non-cooperative objects [4]. Traditional SETI approaches are insufficient for this scenario [5]. A framework is required that: (1) automatically prioritizes objects; (2) rigorously quantifies evidence of artificiality and; (3) efficiently scales observational responses. We present the P.A.V.O.R.A.T protocol, which integrates a non-cooperative behavior analysis within a Bayesian formalism for the evaluation of anomalies.

Methodological Framework: Bayesian Formalism

Definition of the Rarity Index (RI)

$$IR \equiv P(H_A \backslash D) = \frac{P(D \backslash H_A)P(H_A)}{P(D \backslash H_A)P(H_A) + P(D \backslash H_N)P(H_N)} \ldots (1)$$



Where H_N represents the natural hypothesis. The prior $P(H_A)$ is conservatively set at 10-4 based on Astro biological considerations, but is configurable [6].

Combined likelihood function

For N observables D={Di}, assuming initial conditional independence:

$$log_{\Lambda}(D) = \sum_{i=1}^{N} w_i \cdot log\left(\frac{P(D_i \backslash H_A)}{P(D_i \backslash H_N)}\right) \ldots (2)$$

The weights w_i are calibrated *via* mutual information on simulations. The final posterior probability is:

$$IR= [1+\exp(-(\alpha \log \Lambda - \beta))]^{-1} \ldots (3)$$

Where α, β are calibrated to control false positive rates.

The P.A.V.O.R.A.T Protocol: Implementation

Phase 1: Prediction and Alert (P-A)

- **Prediction:** Integration with LSST VOEvent streams. Real-time classification using Random Forest trained with synthetic data.
- **Alert:** Automatic activation for objects with eccentricity ≥ 1.1. Notification *via* IVOA-standard VOEvent with complete orbital metadata.

Phase 2: Surveillance and Observation (V-O)

- Coordinated multi-wavelength observation (network of automated telescopes)
- **Acquisition of fundamental parameters:** High-precision astrometry (10 mas), multiband photometry, low-resolution spectroscopy.

Table 1: Likelihood functions for key observables.

Observable	***$P(D_i \backslash H_N)$***	***$P(D_i \backslash H_A)$***	**Parameters**
Non-gravitational acceleration	Degassing model [7]	Residual propulsion model	σ_{astrom}= 0.1
Isotopic composition	Solar distribution [8]	Anomalous mixture [9]	$\delta^{13}C$ precision 0.5
EM emission	Thermal noise	Narrowband coherent signal	S/N ¡ 7
Light curve	Chaotic rotation	Stabilized/controlled	χ^2 test

Phase 3: Anomaly Review (R) likelihood models

Phase 4: Tactical Action (A-T)

Activation when IR>0.85 (Phase 4a) or IR>0.95 (Phase 4b).

Observation with Level 2 resources (JWST, ALMA, ATA) according to pre-approved protocol.

Validation and Calibration

Population simulations

We generated 10^4 natural Interstellar Objects (OIs) with hyperbolic velocities normally distributed (mean=32 km/s, σ =8 km/s) and compositions based on solar abundances, along with 10^2 artificial objects with defined properties [10]. The pipeline shows:

- AUC=0.94 (95% CI: 0.92–0.96)
- **False alarm rate:** 0.8% per year (threshold IR = 0.85)
- **Sensitivity:** ≥ 90% detection rate for objects with ≥ 2 strong anomalies.

Retroactive application to 3I/Atlas

The Bayesian analysis applied to 3I/Atlas yields a Rarity Index of 0.008, indicating a 99.2% probability that the object is natural. This quantitative result rigorously confirms the qualitative conclusions of the scientific community, but on a solid and reproducible methodological basis.

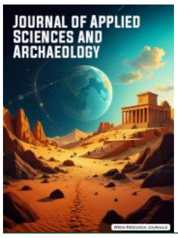
Table 2: Detailed Bayesian analysis of 3I/Atlas.

Observable	***$\log \Lambda_i$***	***w_i***
Trajectory (Δ_{vNG})	−2.1	0.25
Composition ($^{13}C/^{12}C$)	−0.8	0.2
Activity (Q–HO)	0.5	0.15
Structure (light curve)	−1.2	0.2
EM emission (no detection)	−1.5	0.2
Total: log Λ = −1.32 IR: 0.008 Interpretation: 99.2% probability of being natural		

Operational Implementation

Standards and formats

- **Alerts:** VOEvent schema extension for interstellar objects (OIs)



- **Data:** VOTable format with complete error metadata
- **Code:** GitHub repository with Docker container.

Governance and ethics

- **International review committee:** IAU/SETI/UNOOSA
- Cascade communication protocol for IR ≥ 0.85
- 72-hour embargo for independent verification.

Discussion and Limitations

The proposed protocol presents several advantages over ad-hoc approaches:

- **Reproducibility:** Quantitative criteria *vs.* committee decisions
- **Efficiency:** Optimized use of Level 2 telescopes
- **Robustness:** Explicit propagation of uncertainties.

Main limitations:

- Dependence on priors (attenuated through sensitivity analysis)
- Assumption of conditional independence (mitigated with correlation matrix)
- Computational complexity (addressed *via* precomputed models).

Possible false negatives for technologies radically different from current HA models.

Conclusion

P.A.V.O.R.A.T provides the first complete Bayesian framework for the evaluation of techno signatures of infrastructure in interstellar objects. Its implementation will allow the astronomical community to navigate the Rubin Observatory's discovery avalanche in a systematic, rigorous and efficient manner.

Acknowledgements

We thank the Interinstitutional Scientific Ethics Committee for its review and recommendations on public communication protocols for potential detections. This work used simulated data from the Rubin Observatory Technical Design Report (2020).

Code and Data Availability

The reference code is available at https://github.com/panivinux/pavorat-protocol under the MIT License.

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