ARBE λ*: A Deterministic Spectral Ordering Parameter for Atlas-Referenced Color Analysis

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Author Note: Norbert Woiwod is the author of this manuscript and the inventor of the ARBE λ* framework, including its atlas-only analytical architecture and the normative λ*_V2 method.

Abstract

ARBE λ* is introduced as a physical ordering parameter for atlas-referenced color analysis derived exclusively from measured reflectance spectra in the range 380–730 nm. The method is explicitly not a color space, not a color generator, and not an optimization system. Instead, it provides a deterministic analytical framework for revealing structure in existing references of an atlas-based system. The normative quantity λ*_V2 is defined as the unique root of an integral balance between absorption and reflection and is computed with Brent's method. This choice is methodologically binding because it is derivative-free, numerically stable on real atlas data, and deterministic. External inputs such as HEX, RGB, Lab, or textual color requests are treated only as queries and must be snapped to exactly one atlas reference by ΔE00 under D50/2° conditions. This preserves atlas identity and prevents interpolation, free-color generation, or visually approximate matching outside the atlas. Beyond the primary reference identity, ARBE λ* supports secondary descriptive attributes such as Lab values, λ*-related structure, and fixed spectral window states including calm, pull, tip, and break. Outputs are constrained by a compact schema and validation logic to ensure structural consistency, atlas existence, and physical plausibility. The resulting framework is intended for reproducible analysis, comparison, and explanation of measured spectral references rather than creative color production.

Keywords

spectral analysis; reflectance spectra; atlas-referenced color analysis; deterministic mapping; ΔE00; Brent's method; reproducibility

1. Introduction

Color description in science, industry, and digital workflows is often distributed across heterogeneous systems that serve very different purposes. Perceptual spaces such as CIE Lab support comparison under standardized viewing assumptions, device-oriented encodings such as RGB or HEX serve display pipelines, and semantic labels are useful for communication in design or commerce. However, these systems are frequently conflated in practice. As a result, measured physical structure, perceptual approximation, and application-driven color selection are often treated as if they were interchangeable. This becomes problematic whenever reproducibility, reference stability, and physically grounded comparison are required. [1,6,7]

The present work addresses this problem by introducing ARBE λ* as a strictly reference-based analytical framework derived from measured reflectance spectra. ARBE λ* is defined only for real spectral data in the range 380–730 nm and is explicitly not a color space, not a color generator, and not an optimization system. Its purpose is not to invent or improve colors, but to reveal structure in already existing references. This distinction is central: the system is analytical rather than generative, and physical rather than stylistic. [1,6]

A second foundational principle is the atlas-only constraint. In ARBE λ*, a color is not identified by a name, a HEX triplet, or a perceptual coordinate alone, but by a valid atlas reference of the form Hxxx_Lxxx_Cxxx. This reference is the primary identity of the color within the system. Without such a reference, there is no valid color entity for ARBE λ*. External inputs, including RGB, HEX, CIE Lab, XYZ, or textual descriptions, are therefore treated only as queries, never as final results. They must be deterministically routed to exactly one atlas reference by a nearest-match procedure based on ΔE00 under D50/2° conditions. This rule ensures that all outputs remain anchored in the same measured atlas and prevents interpolation, approximate free matching, or implicit color generation outside the reference set. [2,4,5]

Within that reference framework, ARBE λ* introduces a physically interpretable ordering parameter, λ*_V2, defined as the unique root of an integral balance between absorption and reflection. The method is normatively fixed: λ*_V2 is not an intuitive midpoint, a centroid, a quantile, or a visually plausible approximation, but a numerically determined balance point computed with Brent's method. This choice is methodologically important. Brent's method is derivative-free, convergent, and robust on real measured data, making it well suited for a deterministic and reproducible analysis pipeline. [3]

This paper positions ARBE λ* as a methods and framework contribution. It does not propose a new perceptual color space, nor does it optimize color choice for aesthetics, harmony, or preference. Instead, it establishes a physically grounded analytical system for the structured interpretation of existing atlas references.

2. Scope and Normative Constraints

ARBE λ* is defined as a strictly constrained analytical framework for the interpretation of measured color references. Its scope is deliberately narrow. The system operates only on real reflectance spectra and only within the wavelength interval 380–730 nm. It is therefore a method for the analysis of existing physical references, not a general-purpose representation system for arbitrary color descriptions. In particular, ARBE λ* is not introduced as a perceptual color space, not as a rendering model, and not as a generative mechanism for proposing or synthesizing colors. [1,6]

A foundational normative constraint of the framework is the atlas-only principle. Every valid color entity in the system must be represented by a formally valid atlas reference of the form Hxxx_Lxxx_Cxxx. This reference is the sole primary identity of the color within ARBE λ*. Names, HEX values, RGB triplets, CIE coordinates, or textual descriptors may be useful as input or metadata, but they do not constitute color identity in the system. The framework therefore adopts a strict ontological rule: without a valid atlas reference, there is no valid color entity in ARBE λ*.

This identity rule has direct consequences for input handling. External representations such as HEX, RGB, sRGB, XYZ, or CIE Lab, as well as palette exports or textual color requests, are treated only as queries. They are not valid outputs in themselves and must never bypass atlas reference assignment. Any such input must be deterministically routed to exactly one atlas reference through a nearest-match procedure. The primary matching metric is ΔE00 under D50/2° conditions. This routing step is mandatory because ARBE λ* does not admit floating or unanchored color states. [1,2]

A further normative consequence is the exclusion of all operations that would create colors beyond the measured atlas. The framework therefore forbids interpolation between atlas samples, averaging or blending of references, optimization toward target color values, semantic color generation, and visually approximate matching without deterministic atlas snapping. These restrictions are not implementation preferences but methodological requirements. They preserve the closed-reference nature of the system and prevent the analytical layer from collapsing into a creative or heuristic color-production workflow.

The same principle governs the distinction between identity and attribute. In ARBE λ*, the atlas reference is the identity. All other quantities are secondary descriptors. These may include CIE Lab coordinates, λ*_V2, λ*_EE, Δλ*, or window-based structural interpretations such as calm, pull, tip, and break. Such descriptors may enrich the analysis, but they do not replace the reference and must not be treated as independent color entities.

3. Formal Definition of λ*_V2

Let R(λ) denote the measured reflectance spectrum of an atlas reference over the wavelength interval from 380 nm to 730 nm. In ARBE λ*, the quantity λ*_V2 is defined as a physical balance point between absorption and reflection, not as a perceptual midpoint and not as a descriptive heuristic. The method assumes real measured spectral data and operates only on existing reflectance references rather than on generated or interpolated color states. [1,6]

The formal definition is based on the balance function:

$$g(\lambda) = \int_{380 \to \lambda} [1 - R(\lambda')]\, d\lambda' - \int_{\lambda \to 730} R(\lambda')\, d\lambda'$$

The value λ*_V2 is defined as the unique wavelength for which this balance vanishes:

$$g(\lambda^*_{V2}) = 0$$

In this formulation, λ*_V2 represents an energetic equilibrium between the two opposed accumulations. It is therefore an ordering parameter derived from spectral structure itself rather than from appearance alone.

A central normative property of this definition is that λ*_V2 must be obtained through a deterministic root-finding procedure. The reference method fixed by the framework is Brent’s method. This requirement is not optional. Brent’s method is used because it does not require derivatives, is numerically stable on measured data, and guarantees convergence under the conditions relevant to the ARBE λ* pipeline. As a consequence, λ*_V2 is not merely a conceptual point on the spectrum; it is a reproducibly computable physical quantity whose numerical evaluation is part of the formal definition of the method. [3]

This numerical restriction also serves an important epistemic purpose. In ARBE λ*, differing λ*_V2 values for the same reflectance spectrum are not interpreted as alternative legitimate readings of the data. Rather, such discrepancies indicate a deviation in implementation or methodology.

The present definition further excludes a number of superficially similar substitutes. λ*_V2 is not a discrete sum heuristic, not an energy centroid, not a median of a cumulative distribution, not a quantile-based approximation, and not a visually plausible middle of the spectrum. The framework distinguishes λ*_V2 from λ*_EE, which describes an equal-energy or reflected-energy centroid. Their difference, $\Delta\lambda^* = \lambda^*_{V2} - \lambda^*_{EE}$, is interpretable as a structural asymmetry indicator rather than as numerical redundancy.

4. Reference Identity and Deterministic Input Routing

A central architectural principle of ARBE λ* is that reference identity precedes analysis. Before any structural attribute such as λ*_V2, λ*_EE, or a window state can be interpreted, the system must establish which atlas entity is being analyzed. In this framework, that entity is defined exclusively by a valid atlas reference of the form Hxxx_Lxxx_Cxxx. The atlas reference is therefore not one descriptor among others, but the primary and non-substitutable identity of the color object under analysis.

This identity-first logic determines how all external inputs are handled. Values such as HEX, RGB, sRGB, XYZ, or CIE Lab, as well as palette tokens or textual color descriptions, may enter the system

as requests, but they do not enter it as valid identities. In ARBE λ*, an external specification is therefore treated as an inquiry that seeks a corresponding atlas reference, not as a final color state. [1,2]

The required transition from external request to internal identity is implemented through a deterministic nearest-match routing rule. All admissible inputs must be snapped to the nearest atlas sample using ΔE00 under D50/2° conditions. The mapping is explicitly defined as always deterministic and never generative. Its task is not to invent a plausible approximation, but to assign exactly one existing atlas reference as the canonical target of the query. [1,2]

The insistence on determinism has several methodological consequences. First, the mapping must terminate in exactly one atlas reference. Second, the same input under the same conditions must always yield the same result. Third, the routing stage must not introduce latent creativity through interpolation, semantic guessing, or visually close free matching. These restrictions follow directly from the atlas-only rules, which prohibit free colors, interpolation, and generation outside the official atlas.

Once routing occurs, the atlas reference becomes the only valid identity for downstream analysis. Any subsequently reported quantities, such as Lab values, λ*_V2, or structural window labels, are attributes of that reference, not attributes of the original external request.

5. Secondary Attributes and Structural Interpretation

Once atlas identity has been established and the reference has been assigned a valid Hxxx_Lxxx_Cxxx code, ARBE λ* permits the attachment of a set of secondary analytical attributes. These attributes enrich the interpretation of a reference, but they do not alter its identity. This distinction is fundamental to the framework: the atlas reference remains the sole primary identifier, whereas all further quantities serve descriptive and explanatory purposes only.

Among the most important of these secondary quantities are λ*_V2, λ*_EE, and Δλ*. λ*_EE describes a reflected-energy centroid, whereas λ*_V2 describes an energetic equilibrium. The difference between them, Δλ*, is therefore not a numerical artifact but a structurally meaningful indicator of asymmetry and possible metameric sensitivity. In the methodological language of the present paper, λ*_V2 belongs to the normative core of the analysis, while λ*_EE and Δλ* provide additional descriptive resolution for comparing how energy is distributed around that balance point.

This attribute logic is extended by the use of fixed spectral windows. Local spectral structure may be classified into the states calm, pull, tip, and break. These windows are designed to explain local behavior in the spectrum rather than to determine the final result. They are states, not judgments. Window analysis supports interpretation without becoming a hidden decision engine that could override the measured reference or the primary analytical quantities.

The interpretive role of these window states can be summarized as follows. A calm window indicates relative local stability; pull suggests directional tendency or local attraction; tip indicates a critical or transition-like local condition; and break marks a stronger discontinuity or rupture in local spectral organization. Even where these labels carry intuitive meaning, they remain analytical descriptors rather than evaluative categories.

The framework remains deliberately conservative in output logic. Attributes such as Lab values, λ*-related measures, and window states may be reported only within a constrained format that preserves the primacy of the reference identity and the consistency of the analytical record.

6. Output Schema, Validation, and Reproducibility

The analytical claims of ARBE λ* depend not only on the formal definition of λ*_V2 and the atlas-only routing logic, but also on a constrained output layer that makes results inspectable, verifiable, and reproducible. For this reason, the framework does not treat reporting as a neutral presentation step. Instead, output structure is itself part of the method. [8,9]

A result is not considered valid merely because it appears plausible or because it contains familiar descriptive quantities. It must satisfy a formally specified structural contract. In the current working schema, the output object is defined with required fields such as Sample, HEX, Lab_D50, and λ*_V2, while unconstrained field expansion is disallowed. This restriction prevents silent drift in the reporting layer and ensures that every valid record remains machine-checkable and suitable for downstream auditing.

Validation in ARBE λ* is multi-layered. The current rule set distinguishes four checks: V1 Schema, V2 Atlas existence, V3 Physical plausibility, and V4 Prompt logic. Together, these checks show that validity is not exhausted by syntactic well-formedness. Schema validation ensures structural conformity, but this alone would not guarantee that a reported reference actually exists in the atlas, that the attached analytical values remain physically meaningful, or that the request-to-reference logic has respected the normative constraints of the system.

The requirement of atlas existence is especially significant in the context of the broader atlas-only architecture. Because ARBE λ* does not admit free-floating colors, a structurally valid record that refers to a non-existent or non-authorized reference would still be invalid. Likewise, physical plausibility guards against analytically inconsistent or impossible states, while prompt logic ensures that the system has not drifted from deterministic reference resolution into suggestive or generative behavior.

Reproducibility is strengthened further by an explicit provenance layer and checksum-based document integrity. In practical terms, the knowledge base can be treated as a versioned analytical artifact rather than as an informal set of notes. A reviewer, collaborator, or downstream implementer can verify whether the methodological documents used in an analysis correspond exactly to the released reference state. [8,9]

7. Demonstration / Worked Example

To make the analytical logic of ARBE λ* explicit, this section presents a compact worked example that follows the procedural order fixed by the project materials: λ*_V2 calculation, window analysis, aggregation, and valid output. The purpose of the example is not to establish a large empirical claim, but to show how the framework operates on a single atlas-grounded reference under reproducible rules.

Assume that a measured atlas reference S is available as a reflectance spectrum $R_S(\lambda)$ over the interval from 380 nm to 730 nm. Because ARBE λ* is an atlas-only system, the analytical object is not a free color description but an already existing reference-bearing sample. The first step is therefore not creative selection or optimization, but the identification of a valid reference entity to which all subsequent calculations will attach.

The first computational stage is the evaluation of the balance function:
$g(\lambda) = \int_{380 \to \lambda} [1 - R_S(\lambda')]\, d\lambda' - \int_{\lambda \to 730} R_S(\lambda')\, d\lambda'$

The value λ*_V2 is obtained as the unique root of this function using Brent’s method. At this stage, the analysis produces a first physically interpretable descriptor: the wavelength at which the

accumulated non-reflected portion below the point is balanced by the accumulated reflected portion above it.

The second stage is window analysis. Once λ*_V2 has been determined, the spectrum is examined in terms of fixed local structural states. In a concrete case, the analysis may reveal locally stable regions, directional tendencies, threshold-like transitions, or stronger discontinuities. These are then reported through the predefined window categories rather than through ad hoc narrative description.

The third stage is aggregation. At this point, the individual analytical descriptors associated with the reference are brought into a coherent result structure. Depending on the reporting level, this may include the atlas identity, a display-oriented surrogate such as HEX, perceptual coordinates such as Lab_D50, the normative λ*_V2 value, and any structurally relevant window interpretation.

The fourth and final stage is valid output formation. A minimal valid record may therefore take the following schematic form:

```
{
  "Sample": "Hxxx_Lxxx_Cxxx",
  "HEX": "#......",
  "Lab_D50": [L*, a*, b*],
  "λ*_V2": 5xx.x
}
```

Validation then applies as a final gate. In the current framework, schema validity, atlas existence, physical plausibility, and deterministic prompt logic must all succeed before the record belongs to the system in the strict ARBE λ* sense.

8. Discussion and Limits

The main contribution of ARBE λ* lies in the fact that it defines a closed, deterministic, and physically grounded analysis framework for existing color references rather than a flexible system for color invention. This is both its strength and its principal limitation. By restricting the method to measured reflectance spectra in the range 380–730 nm, and by explicitly excluding color generation, interpolation, and optimization, the framework gains conceptual clarity and reproducibility at the cost of broader descriptive freedom. [1,3,6]

A first strength of the framework is its ontological discipline. ARBE λ* does not permit color entities to float across names, device encodings, and perceptual coordinates without reference closure. Instead, every valid result must terminate in an atlas reference. This improves traceability and keeps the analysis anchored to a measured reference universe. At the same time, it limits applicability in contexts where no atlas reference is available or where the objective is to preserve an external representation without snapping it to a fixed atlas sample.

A second strength is the normative precision of λ*_V2. The quantity is fixed as the unique root of an integral balance between absorption and reflection and computed by Brent’s method. The corresponding limitation is that the framework depends on the availability and integrity of real spectral measurements. Where only display encodings, approximate perceptual values, or loosely specified palette descriptions exist, ARBE λ* can operate only indirectly through deterministic routing, not through direct spectral analysis.

A third strength is the clean separation between identity and attribute. Atlas reference codes define what the entity is; λ*_V2, λ*_EE, Δλ*, and local window states describe how that reference is structurally organized. The limitation is that users expecting a more expressive or design-oriented color system may perceive the framework as intentionally restrictive. ARBE λ* does not attempt to

answer questions such as which color is aesthetically better, trend-appropriate, emotionally fitting, or commercially preferable.

A particularly important limitation concerns the relationship between normative spectral ARBE λ* and didactic or image-based analogies. Image workflows may be useful for pedagogy, visualization, or adjacent analytical applications, but they are not equivalent to λ*_V2 as defined in this paper. For publication purposes, this distinction must remain explicit.

9. Conclusion

This paper introduced ARBE λ* as a deterministic, atlas-bound, and physically grounded framework for the analysis of measured color references. The method is defined on real reflectance spectra over 380–730 nm and is explicitly framed not as a color space, not as a generator, and not as an optimization system. Its purpose is narrower and more rigorous: to reveal structure in existing references rather than to produce new colors. [1,3,6]

At the center of the framework is λ*_V2, defined as the unique root of an integral balance between absorption and reflection and computed with Brent's method. This gives the method a fixed numerical core and makes reproducibility a property of the definition itself rather than an implementation afterthought. Combined with the atlas-only identity rule and deterministic ΔE00-based routing of external requests to exactly one atlas reference, ARBE λ* establishes a closed analytical system in which reference identity, spectral structure, and downstream interpretation remain tightly aligned.

A further contribution of the framework is the explicit separation between identity and attribute. The atlas reference defines what the analyzed entity is; quantities such as λ*_V2, Lab values, and other structural descriptors explain how that reference is organized. This separation is reinforced by a constrained output layer in which valid results must conform to a controlled schema. The accompanying validation logic and provenance materials strengthen auditability and make the framework suitable for settings in which methodological traceability matters.

Taken together, these elements position ARBE λ* as a methods and framework contribution: a disciplined spectral analysis system built on real references, deterministic computation, and formally validated output. Within that scope, it provides a strong basis for future empirical studies, comparative evaluations, and application-specific extensions that remain faithful to the atlas-only principle and the normative definition of λ*_V2.

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Declarations

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Conflicts of Interest

The author declares no conflict of interest.

Data Availability

The materials associated with this work are available via Zenodo at https://doi.org/10.5281/zenodo.18644381.

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During the preparation of this manuscript, the author used the custom GPT "ARBE λ*" within ChatGPT for editorial assistance, structural drafting, and language refinement. All generated text was reviewed, revised where necessary, and validated by the author. The author takes full responsibility for the final content.

Code Availability

No separate code repository is associated with this study beyond the archived project materials available via Zenodo.

Author Contributions

Norbert Woiwod: conceptualization, methodology, formal analysis, validation, writing - original draft, writing - review and editing.

Ethics Statement

Not applicable.

References

1. Commission Internationale de l'Éclairage (CIE). CIE 015:2018 Colorimetry. 4th ed. Vienna: CIE; 2018.

2. Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Res Appl. 2005;30(1):21-30. doi:10.1002/col.20070.

3. Brent RP. Algorithms for Minimization without Derivatives. Englewood Cliffs, NJ: Prentice-Hall; 1973.

4. freieFarbe e.V. Home – freieFarbe e.V.; HLC Colour Atlas XL. Available at: https://freiefarbe.de/en/home/. Accessed 2026-03-08.

5. DIN. DIN SPEC 16699:2019-04. Open Colour Communication; Text in German and English. Berlin: DIN Media; 2019.

6. Hunt RWG, Pointer MR. Measuring Colour. 4th ed. Chichester: John Wiley & Sons; 2011. doi:10.1002/9781119975595.

7. Wyszecki G, Stiles WS. Color Science: Concepts and Methods, Quantitative Data and Formulae. 2nd ed. New York: Wiley; 2000.

8. Wilkinson MD, Dumontier M, Aalbersberg IJJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data. 2016;3:160018. doi:10.1038/sdata.2016.18.

9. Sandve GK, Nekrutenko A, Taylor J, Hovig E. Ten simple rules for reproducible computational research. PLoS Comput Biol. 2013;9(10):e1003285. doi:10.1371/journal.pcbi.1003285.

10. HelabHLC. HelabHLC/arbe-lambda: ARBE λ*_V2 - Formal Specification 1.0.0 (lambdaV2-1.0.0). Zenodo; 2026. doi:10.5281/zenodo.18644381.