

LED PAPI Calibration: Field Observations from UAV-Based Method

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Adam Rytter, Master of Engineering, Warsaw University of Technology, Faculty of Transport, Air Traffic Management specialization. Founder and leader of Airotec business and development activities. Director and initiator of the R&D unit. Defined and successfully completed €1M+ EU funded R&D project (2021-2023) for a UAV-based airport visual aids inspection.

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ABSTRACT

LED-based Precision Approach Path Indicator (PAPI) systems are becoming the standard at airports worldwide, replacing halogen units with improved energy efficiency and reduced maintenance. However, the transition zone characteristics of LED PAPI units differ from halogen systems due to the fundamentally different optical mechanism producing the color change. While ICAO Doc 9157 Part 4 recognizes unmanned aircraft systems (UAS) as an alternative method for PAPI setting measurement, the standard does not differentiate the assessment methodology by lamp technology.

This paper presents field observations from UAV-based measurements of LED PAPI transition zone behavior across multiple lateral observation angles. Using the Airotec DeFI drone-based inspection system, measurements were performed at EPRZ (Rzeszów) on an ADB Safegate LED PAPI installation, with supporting measurements at EPLL (Łódź) confirming the reproducibility of the observed patterns. The results reveal a consistent pattern of transition zone widening with increasing lateral observation angle, a characteristic that is not visible during standard aircraft-based flight inspection performed from the runway centerline. The transition zone boundary analysis shows that the widening is predominantly one-sided, causing the calculated measured angle to shift with lateral position. This paper presents these field observations and explores how extending beyond standard ICAO methodology can support more comprehensive LED PAPI assessment.

INTRODUCTION

Precision Approach Path Indicator (PAPI) systems provide essential visual guidance to pilots during the final approach phase. By displaying a combination of red and white light signals, PAPI enables pilots to assess their position relative to the desired glide path without reliance on cockpit instruments. The accuracy and reliability of these visual aids directly impact approach safety, making regular inspection and calibration a regulatory requirement for aerodrome operators.

Traditionally, PAPI systems have utilized incandescent (halogen) light sources, which have proven effective over decades of operational use. In recent years, however, airports have increasingly transitioned to LED-based PAPI units, driven by reduced energy consumption, lower maintenance requirements, and extended operational lifespan. This technological shift, while operationally beneficial, introduces different optical characteristics that affect how the transition zone appears to observers during visual assessment.

Recognizing the evolution of inspection technologies, ICAO Doc 9157, Part 4, has provided guidelines for unmanned aircraft systems (UAS) as an alternative method for measuring PAPI settings since 2021. The standard outlines positioning requirements and measurement procedures, establishing UAS-based inspection as a recognized approach for PAPI calibration. However, the methodology does not differentiate by lamp technology, applying the same procedures to both incandescent and LED systems regardless of their distinct optical properties.

This gap becomes increasingly relevant as LED technology becomes the industry standard. Visual inspection methods must account for how standard requirements manifest in LED optical behavior, yet the transition zone in LED units presents different visual characteristics compared to halogen systems. These differences raise practical questions about assessment consistency and interpretation. This paper presents field observations from operational testing at an airport with a commercial LED PAPI system and explores how extending beyond standard ICAO methodology can support more comprehensive LED-specific assessment. The findings offer practical insights for integrating UAS-based methods into LED PAPI maintenance workflows.

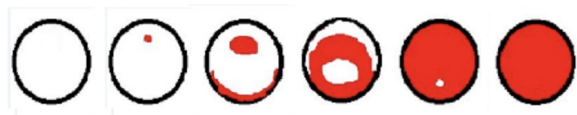
BACKGROUND

PAPI Unit Types

PAPI systems are designed to project a precisely defined light beam that transitions from red to white at specific vertical angles. The optical mechanism that produces this transition varies depending on the unit configuration. Transport Canada Advisory Circular AC 300-006 distinguishes between two primary designs: tandem configuration and single lens configuration.

In tandem configuration units, two or three separate light sources are arranged vertically within the housing. Each light source is filtered independently, with red filters positioned above white filters. As the observer's vertical angle changes, the proportion of visible red and white light shifts accordingly. This design produces a transition zone where both colors are partially visible, creating a characteristic mixed appearance during the transition phase.

Single lens configuration units achieve the same optical effect through a different mechanism, using a single optical assembly with integrated color filtering. In the case of a single lens PAPI light unit, the image is somewhat different in that the red first appears as a point and then expands around the lens. Regardless of configuration, both designs must meet the same ICAO requirements for transition zone characteristics, including the angular width of the transition and the sharpness of color change.



Transition of a single lens PAPI (source tc.canada.ca)

Redundancy and Unit Configuration

A critical distinction between PAPI configurations lies in how redundancy is achieved, which directly affects the physical arrangement of optical components and their susceptibility to leveling errors.

In **tandem halogen** installations, two or three incandescent bulbs are housed within a single PAPI enclosure. Each bulb operates independently with its own filtering, providing lamp-level redundancy: if one bulb fails, the remaining

bulb(s) continue to produce the required signal. The bulbs are mechanically coupled within the housing, so they share the same physical alignment.

In **single lens halogen** installations (such as those manufactured by Research Engineers), two or three independent PAPI units are mounted on a common platform to serve a single approach position. Redundancy is provided at the unit level: each unit is a complete, independent optical system. If one unit fails, the others maintain the signal. Because the units are separate physical devices on a shared mount, each unit's internal alignment is independent.

LED PAPI installations typically use a single unit per approach position, with four individual units comprising the complete PAPI system. Redundancy is provided not through duplicate optical assemblies but through the electronic architecture: multiple LED driver circuits, power redundancy, and monitoring systems ensure continued operation despite component failures. This means each approach position relies on a single optical assembly, making the alignment and leveling of that individual unit more critical than in configurations where multiple units provide redundancy.

This structural difference has practical consequences for inspection. In tandem halogen systems, the inspector observes multiple lamps within one housing, each providing a visible reference point during transition. In single lens systems (both halogen and LED), the observer sees a single optical aperture transitioning as a unified field. The visual assessment approach is similar for single lens halogen and LED units; the key difference is that LED arrays produce the transition through a shifting ratio of diode intensities rather than a mechanical color filter boundary.

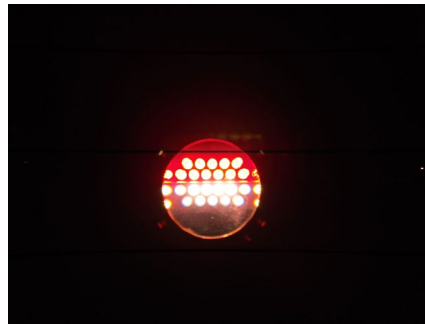


Image of red and white LED arrays inside of PAPI unit (source: internal)

Transition Zone and Leveling Relationship

The transition zone width is directly related to the optical alignment of the PAPI unit. A properly leveled unit presents a uniform color change across its entire aperture. All points of the lens assembly transition simultaneously, producing a sharp, well-defined boundary between red and white. When a unit or any of its components are not levelled, the left and right edges of the optical assembly sit at slightly different vertical angles. This causes one side to transition before the other, extending the total angular range over which the observer sees a mixed color signal.

In halogen tandem units, leveling errors produce an asymmetric transition that is detectable by observing which individual lamp changes first. The inspector can directly relate the visual observation to the mechanical condition of the unit. In LED and single lens halogen units, leveling errors manifest as a widened transition zone without individual lamp reference points. The transition simply appears less defined, making it more difficult to distinguish between a narrow transition zone caused by precise leveling and a wider one caused by a leveling offset.

This relationship provides the foundation for using lateral measurements as a diagnostic tool. When observed from directly in front (0° lateral angle), the unit presents its optical axis characteristics. A leveled unit is expected to produce a symmetric transition zone profile when observed from equal lateral angles on both sides (e.g. -8° and $+8^\circ$ from the

optical axis). A larger transition zone width on one side compared to the other indicates that the unit or its optical components may be tilted in the horizontal plane, with the wider side corresponding to the direction of the tilt.

Optical Beam Analysis vs Mechanical Position

A fundamental distinction exists between measuring the mechanical setting of a PAPI unit and analyzing its actual optical output. Conventional calibration tools approach this challenge differently, each with specific limitations.

Clinometers and spirit levels measure the physical orientation of the PAPI housing or mounting platform. These instruments provide accurate readings of mechanical position but do not account for internal optical alignment. A unit may show perfect level on a clinometer while its internal lighting assembly produces a misaligned beam. This distinction becomes particularly relevant in LED units, where the relationship between housing position and optical output depends on the internal arrangement of the diode array.

Theodolites offer optical beam analysis capability, measuring the actual light output rather than mechanical position. However, theodolite measurements are performed from ground level, observing the PAPI from below its operational angle range. This perspective differs from the pilot's viewpoint during approach.

UAS-based inspection provides a third approach that combines optical beam analysis with aerial perspective. The drone observes the PAPI from within the operational angle range at a distance of 300 m, well within the far-field photometric region where the beam pattern is fully formed and stable. This method captures the actual visual transition rather than inferring it from mechanical measurements or ground-level observations.

The distinction between housing level and lighting assembly level becomes critical when interpreting inspection results. PAPI systems may consist of a single housing containing multiple lighting units, or separate housings mounted on a common platform. What the clinometer measures in each configuration differs and what constitutes "level" for the housing may not correspond to optimal optical alignment of the beam.

AIRCRAFT VS UAS OBSERVATION ANGLES

Standard Approach Profile

A flight inspection aircraft on the runway centerline observes each PAPI unit at a lateral angle determined by the unit's distance from the centerline and the aircraft's distance from the PAPI.

Lateral observation angles: aircraft vs UAS					
Observer	Distance	Unit A	Unit B	Unit C	Unit D
UAS UAS 300m (PAPI axis)	300m	2.67°	1.34°	1.34°	2.67°
UAS UAS 400m (PAPI axis)	400m	2°	1°	1°	2°
FIS Aircraft 1 NM	1852m	1.79°	1.58°	1.36°	1.14°
FIS Aircraft 2 NM	3704m	0.9°	0.79°	0.68°	0.57°
FIS Aircraft 3 NM	5556m	0.6°	0.53°	0.45°	0.38°
FIS Aircraft 4 NM (FIS typical)	7408m	0.45°	0.39°	0.34°	0.29°
FIS Aircraft 5 NM	9260m	0.36°	0.32°	0.27°	0.23°

FIS aircraft vs UAS lateral positioning to PAPI units (source: internal)

UAS Observation Perspective

A drone positioned on the PAPI system axis at 300 m observes the units at lateral angles of 1.34° to 2.67°. While larger than the aircraft angles, these are still relatively close to the optical axis. The lateral scanning method extends this to the full range from 0° (directly in front of a unit) to beyond 10°, covering the angular range specified by ICAO for transition zone conformity assessment.

This comparison does not suggest that aircraft-based inspection is insufficient for its purpose. The aircraft confirms the aiming angle and verifies that the PAPI signal is visible and functional from the pilot's perspective. The lateral scanning method provides complementary diagnostic information that supports maintenance decisions.

METHODOLOGY

Equipment and Setup

The measurement system consisted of the Airotec DeFI software platform and a DJI Matrice 4 Enterprise (M4E) drone equipped with an RTK positioning module. Precise altitude determination was achieved through RTK NTRIP corrections provided by the ASG-EUPOS reference station network, with a target altitude standard deviation of less than 8 cm (recommended: below 3 cm). The drone's integrated camera recorded the PAPI signal during vertical inspection flights.

Before the lateral scanning session, the setting angle of each PAPI unit was verified using a PAPI built-in clinometer and level sensor. The clinometer and level readings served as the mechanical angle reference against which the optically measured angles were compared.



Clinometer and level sensor readings - EPRZ PAPI 27 (source: internal)

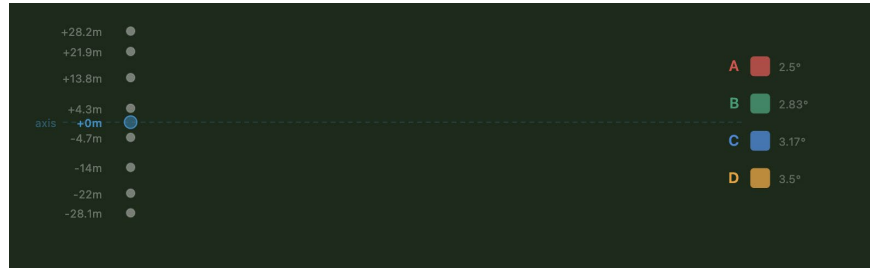
Supporting Dataset

A supporting dataset was collected at EPLL (Łódź) in April 2025 on PAPI system RWY 25 equipped with ADB Safegate LED Gen 1 units. This dataset consisted of 11 measurement positions at approximately 300 m using the same equipment and methodology. Initial observations at EPLL revealed the transition zone widening pattern with lateral angle, which motivated the assessment at EPRZ in April 2026 using the ICAO angle-driven measurement grid described below. While the EPLL measurement grid used arbitrary lateral spacing, it provided a basis for verifying the reproducibility of the observed patterns across different installations.

Measurement Grid Design

The measurement position grid was designed around the ICAO angular specification for transition zone requirements, not arbitrary meter spacing. ICAO stipulates that the transition zone shall not exceed 3 arc-minutes (0.05°) within $\pm 8^\circ$ of lateral observation angle, with a limit of 5 arc-minutes (0.083°) at or beyond $\pm 8^\circ$.

The curated dataset consisted of 9 distinct lateral positions at a measurement distance of approximately 300 m from the PAPI system, covering offsets from -28 m to +28 m relative to the PAPI system axis. Key angular targets included: 0° lateral to each unit (drone in front of the unit), the PAPI axis (0 m offset), and positions reaching approximately 8° lateral to the outer units.



Achieved measurement grid- EPRZ PAPI 27 (source: internal)

Measurement Procedure

At each lateral position, the drone performed a standard DeFI vertical inspection flight: an ascending pass through the full angular range of the PAPI system. Flight duration at each position was approximately 15 to 20 seconds. The recorded video was processed through the DeFI software, which allowed the user to analyze the color transition for each unit in every position.



DeFI vertical inspection flight representation (source: internal)

Transition Zone Determination

ICAO Doc 9157, Part 4, Section 8.3.44 describes the UAS-based measurement procedure: the UA is positioned at least 300 m downwind of the PAPI system, and performs vertical scanning that enables the operator to determine heights h_1 and h_2 , which are the upper and lower limits of the transition zone from red to white.

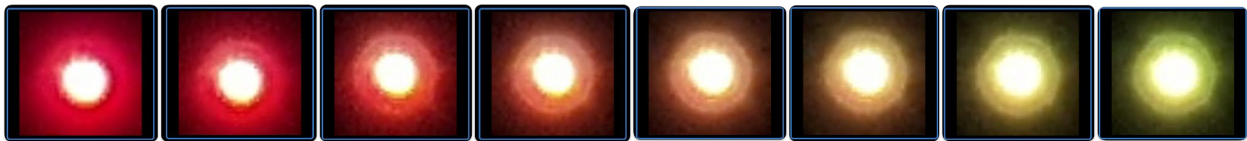
The transition zone boundaries in the results were determined by visual assessment of the recorded video through the DeFI software interface. The operator defined the transition start as the point where a visual change in lamp color behavior from red to white was first observed. The transition end was defined as the point where the unit no longer

displayed any visually recognized red color within the light beam. The transition zone width was calculated as the angular difference between these two boundaries.

This assessment method captures the operational visual appearance of the transition zone as it would be perceived by an observer. It differs from photometric measurement in that it relies on the camera sensor's color response and the operator's visual judgment rather than calibrated candela values. The ICAO transition zone specification indirectly references photometric measurement methods, defining the zone through candela values for the red and white areas. A direct comparison between visually assessed and photometrically measured transition zones is an area for further investigation.



Transition representation for 2-lamp tandem halogen unit across consecutive frames in DeFI software



Transition representation for single LED unit across consecutive frames in DeFI software

Lateral Angle Calculation

Lateral angle computation used a coordinate-based vector projection method. The GPS positions of all four PAPI units were surveyed (WGS84). For each measurement, the lateral angle to each unit was calculated as the angle between the unit axis direction and the vector from the unit to the drone position. Validation against the simplified offset-based method confirmed agreement within 0.02° across all measurement positions.

RESULTS

Measurement Overview

The lateral beam profile assessment was performed at EPRZ (Rzeszów) on PAPI system RWY 27 equipped with ADB Safegate LED units (April 2026). The curated dataset consisted of 9 measurement positions covering offsets from -28 m to +28 m relative to the PAPI system axis at 300 m distance.

PAPI unit specifications: A (2.50°), B (2.83°), C (3.17°), D (3.50°).

Built-in clinometer readings: A= 2.47° , B= 2.81° , C= 3.17° , D= 3.49° .

Measurement in front of each PAPI unit

In front of each unit (0° lateral)

Datasets: P05, P06, P12, P14

Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
■ Unit A	2.5°	2.47°	2.48°	-0.02°	0.1° (front)	0.11°	6.6'
■ Unit B	2.83°	2.81°	2.84°	+0.01°	0.04° (front)	0.12°	7.2'
■ Unit C	3.17°	3.17°	3.22°	+0.05°	0.04° (front)	0.18°	10.8'
■ Unit D	3.5°	3.49°	3.55°	+0.05°	0.05° (front)	0.12°	7.2'

Measurement results in front of each PAPI unit (source: internal)

Units A and B measured angles closely match clinometer readings, confirming consistency between mechanical and optical alignment. Unit C and Unit D show a measured angle approximately 0,05° above its design value despite the clinometer reading matching the design, suggesting an offset between mechanical and optical alignment.

Measurement at the PAPI system axis

At 0 m offset, lateral angles to each unit range from 0.9° (inner units) to 2.6° (outer units). Transition zone widths at this position ranged from 0.07° to 0.1° across the most units besides unit C.

PAPI system axis

Dataset P11 · 009-0001 · offset +0.2m

Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
■ Unit A	2.5°	2.47°	2.47°	-0.03°	2.61° (right)	0.1°	6'
■ Unit B	2.83°	2.81°	2.84°	+0.01°	0.9° (right)	0.07°	4.2'
■ Unit C	3.17°	3.17°	3.275°	+0.1°	0.82° (left)	0.17°	10.2'
■ Unit D	3.5°	3.49°	3.55°	+0.05°	2.55° (left)	0.1°	6'

Measurement results at PAPI system axis (source: internal)

Measurement at matched lateral angles

When multiple units are observed at similar lateral angles from different drone positions, their transition zone behavior can be compared directly. This comparison removes the variable of lateral angle and isolates differences between individual units.

Matched lateral angle -1.6° right Units A, B, C, D at -1.6° right. Datasets: P06, P12, P14, P16							
Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
Unit A	2.5°	2.47°	2.445°	-0.06°	1.68° (right)	0.11°	6.6'
Unit B	2.83°	2.81°	2.825°	+0°	1.68° (right)	0.15°	9'
Unit C	3.17°	3.17°	3.22°	+0.05°	1.78° (right)	0.18°	10.8'
Unit D	3.5°	3.49°	3.57°	+0.07°	1.6° (right)	0.16°	9.6'

Matched lateral angle -1.6° left Units A, B, C, D at -1.6° left. Datasets: P03, P05, P06, P12							
Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
Unit A	2.5°	2.47°	2.49°	-0.01°	1.63° (left)	0.13°	7.8'
Unit B	2.83°	2.81°	2.825°	+0°	1.81° (left)	0.12°	7.2'
Unit C	3.17°	3.17°	3.27°	+0.1°	1.76° (left)	0.16°	9.6'
Unit D	3.5°	3.49°	3.56°	+0.06°	1.77° (left)	0.12°	7.2'

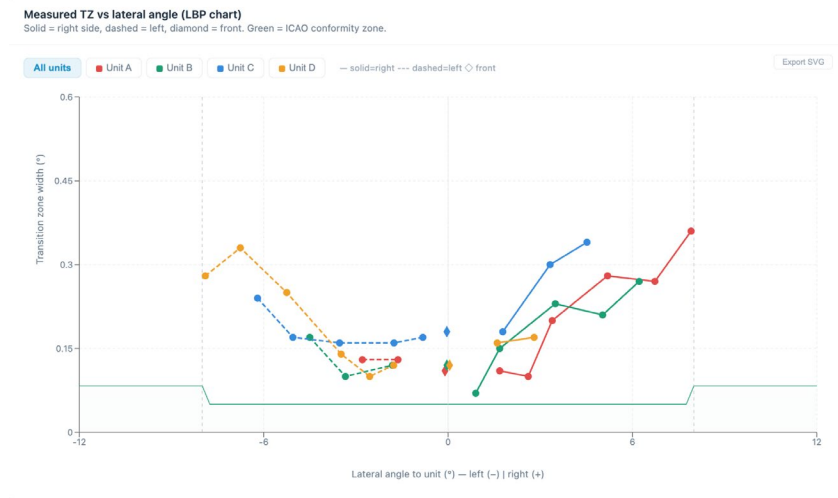
Matched lateral angle -3.3° right Units A, B, C, D at -3.3° right. Datasets: P12, P14, P16, P18							
Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
Unit A	2.5°	2.47°	2.52°	+0.02°	3.39° (right)	0.2°	12'
Unit B	2.83°	2.81°	2.87°	+0.04°	3.49° (right)	0.23°	13.8'
Unit C	3.17°	3.17°	3.21°	+0.04°	3.32° (right)	0.3°	18'
Unit D	3.5°	3.49°	3.56°	+0.06°	2.8° (right)	0.17°	10.2'

Matched lateral angle -3.3° left Units A, B, C, D at -3.3° left. Datasets: P02, P03, P05, P06							
Unit	Design	Clinometer	Measured	Δ design	Lat. angle	TZ (°)	TZ (arc-min)
Unit A	2.5°	2.47°	2.47°	-0.03°	2.79° (left)	0.13°	7.8'
Unit B	2.83°	2.81°	2.84°	+0.01°	3.34° (left)	0.1°	6'
Unit C	3.17°	3.17°	3.28°	+0.11°	3.53° (left)	0.16°	9.6'
Unit D	3.5°	3.49°	3.56°	+0.06°	3.48° (left)	0.14°	8.4'

Measurement results at matched lateral angles for each PAPI unit (source: internal)

Transition Zone Behavior Across Lateral Angles

The lateral beam profile charts show how each unit's transition zone width changes across the measured angular range. All four units show a consistent pattern: the transition zone widens progressively with increasing lateral observation angle. The rate of widening accelerates at larger lateral angles. This behavior is consistent across all four units.



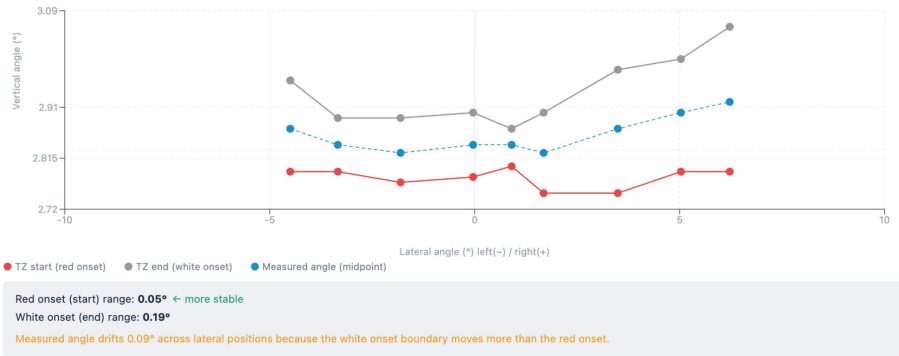
Measurement TZ results across lateral angles PAPI 27 (source: internal)

Transition Zone Boundary Behavior

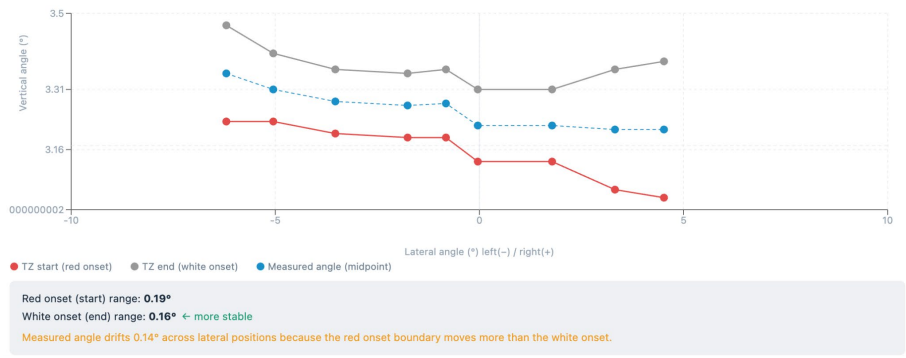
An examination of the individual transition zone boundaries reveals that the widening is not symmetric around the measured setting angle. The TZ start (the vertical angle where a visual change from red is first observed) and TZ end (the angle where no red is visible) behave differently as the lateral observation angle increases.

Taking Unit B as an example: at the frontal position (0° lateral), the transition zone extends from 2.78° to 2.90°, with the measured angle at 2.84°. As the observation moves to 6.22° lateral on the right side, the lower boundary (TZ start) remains at 2.79°, while the upper boundary (TZ end) moves to 3.06°. The transition zone widening is predominantly one-sided: the white onset boundary is more sensitive to lateral observation angle than the red onset boundary.

This one-sided boundary behavior causes the calculated angle (the midpoint between the two boundaries) to shift with lateral position, even though the physical setting of the unit has not changed. This is an important consideration when interpreting measured angles from off-axis observations: the apparent angle drift is a consequence of the asymmetric boundary movement, not a change in the unit's setting.



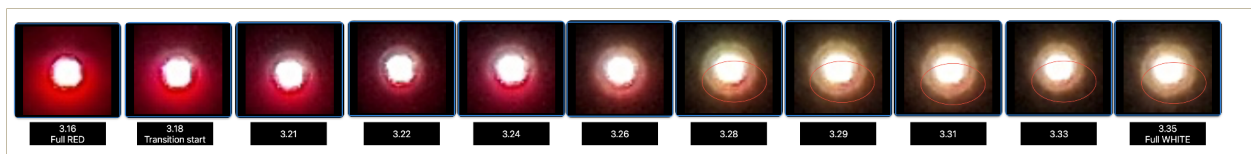
Transition zone boundary analysis PAPI unit B (source: internal)



Transition zone boundary analysis PAPI unit C (source: internal)

Visual Boundary Interpretation

Observation of the recorded vertical scans revealed that the visual transition from red to white is not always a single, uniform event. In a number of measurements the color change progressed through three distinguishable phases. The first phase is a gradual onset where a small portion of the lens area begins to show a subtle color shift while the majority of the disc remains in the original color. The second phase is a sharp color change in which the dominant color visibly switches across most of the aperture within a narrow angular range. The third phase is a residual tail where a small fraction of the disc, typically in the range of five to ten percent of the visible lens area, retains some of the original color before the transition completes. The detailed frame-by-frame record captured by the DeFI system makes this three-phase behavior visible and reviewable. Unit B at EPRZ provides an illustrative example.



Transition zone behavior of unit C measured at position in front of Unit B (source: internal)

The choice of boundary definition has a measurable effect on the reported result. If the gradual onset and the residual tail are both included within the transition zone, the width captures the full range of visible color change. If only the sharp color change is included, the width is narrower and the boundaries outside the sharp zone are not represented in

the result. The midpoint of the transition zone, which is used as the measured setting angle, also shifts depending on which definition is applied.

From the pilot's perspective, the gradual onset and residual tail are unlikely to affect approach guidance because the dominant color signal changes during the sharp color change phase. From a compliance assessment perspective, however, the choice of boundary definition can move a measurement from conforming to non-conforming. This is a standardization question rather than a measurement question: the UAS-based visual assessment method will benefit from a more explicit definition of what constitutes the start and end of the transition zone in the presence of gradual onset and residual tail behavior. A standardized definition of the visual transition boundaries for UAS-based assessment would allow results to be compared consistently across operators, installations, and tools

Symmetry Assessment

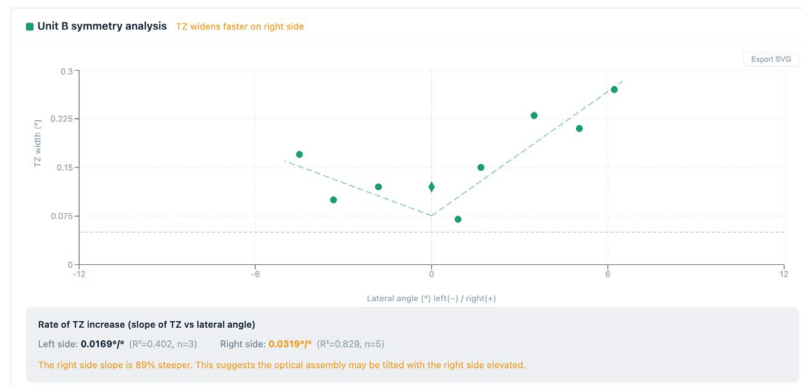
The lateral beam profile allows comparison of transition zone behavior when a unit is observed from equal lateral angles on opposite sides. The rate of transition zone increase (slope of TZ width vs lateral angle) was computed separately for left-side and right-side observations using linear regression.

Unit B exhibits notably different widening rates on the left and right sides. The built-in clinometer reading for Unit B indicates a horizontal offset of +0.1°, confirming that this unit is not perfectly level. The asymmetric widening pattern observed in the lateral beam profile is consistent with this clinometer reading.



Built-in clinometer reading for PAPI Unit B (source: internal)

The correlation between the clinometer offset and the asymmetric lateral beam profile supports the hypothesis that horizontal leveling affects the transition zone symmetry. However, establishing which direction of tilt produces which asymmetry pattern requires controlled calibration testing where a unit is deliberately tilted by known amounts in known directions.

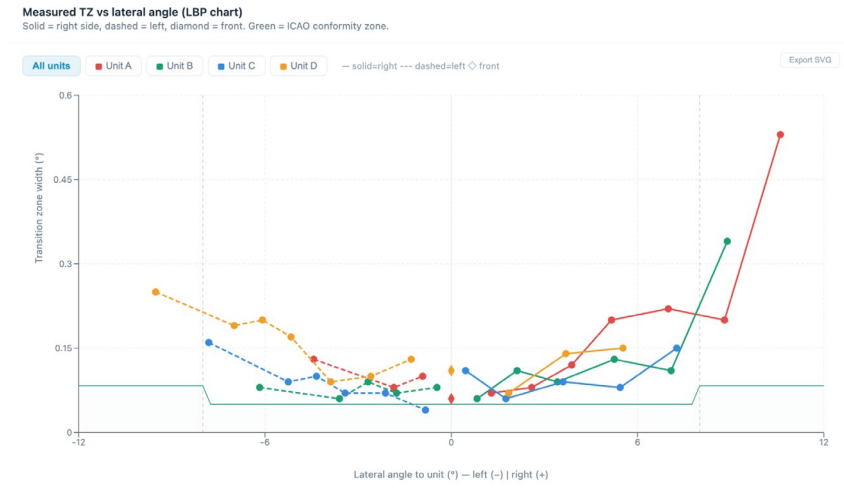


Symmetry analysis PAPI unit B (source: internal)

Supporting Observations from EPLL

A similar lateral beam profile assessment was performed at EPLL (Łódź International Airport) on PAPI system RWY 25 equipped with ADB Safegate LED Gen 1 units in April 2025. Initial observations at EPLL revealed the transition zone widening pattern, which motivated the systematic assessment at EPRZ in April 2026 with the ICAO angle-driven measurement grid. The measurement grid at EPLL consisted of 11 positions with offsets from -38 m to +44 m.

The EPLL data confirms the same fundamental patterns observed at EPRZ: transition zone widening with increasing lateral observation angle across all four units. The symmetry analysis shows position-dependent asymmetry consistent with the geometric effect of each unit's location within the PAPI row: units on the left side of the system (A and B) show steeper widening toward the right, while units on the right side (C) show steeper widening toward the left. Unit D shows approximately symmetric behavior.



Measurement TZ results across lateral angles PAPI EPLL (source: internal)

CONCLUSIONS

The lateral beam profile assessment at EPRZ with supporting observations from EPLL, reveals several findings about LED PAPI transition zone behavior when assessed using the UAS-based visual inspection method.

Observed transition zone values exceed ICAO specifications. The visually assessed transition zone widths consistently exceed the ICAO values of 0.05° (3 arc-min) within $\pm 8^\circ$ and 0.083° (5 arc-min) at $\pm 8^\circ$, even at optimal observation positions directly in front of each unit. These results reflect the visual assessment method used, where the operator marks the first visible color change as the transition start and complete absence of the other color as the transition end. The ICAO specification defines the transition zone through candela values measured with calibrated photometric equipment. The relationship between visually assessed and photometrically measured transition zones is an open question that has implications for how UAS-based visual assessment results should be interpreted against photometric specifications.

The transition zone widens with lateral observation angle. All four units at both airports show progressive TZ widening with increasing lateral angle. This behavior is not visible during aircraft-based flight inspection, where the lateral angles to each unit remain below 0.5° at typical inspection distances. A standard 300 meters UAS inspection at the PAPI axis observes the units at 0.9° to 2.6° lateral, also relatively close to the optical axis.

Transition zone widening is predominantly one-sided. The boundary analysis at EPRZ reveals that the TZ start (red onset) remains relatively stable across lateral positions, while the TZ end (white onset) moves significantly. This asymmetric boundary behavior causes the calculated midpoint (measured angle) to shift with lateral position. A measured angle that varies across lateral positions does not indicate a change in the unit's physical setting but reflects the one-sided nature of the transition zone widening.

Asymmetric widening correlates with clinometer readings. Units with measurable clinometer offsets (such as Unit B at EPRZ with $+0.1^\circ$) show asymmetric lateral beam profiles. Establishing which direction of tilt produces which asymmetry pattern requires controlled calibration testing with deliberately tilted units, which is a direction for further research.

Findings are reproducible across installations. The same transition zone widening pattern was observed at two different airports (EPRZ and EPLL) with different LED PAPI installations. This confirms that the observed behavior is reproducible and not an artifact of a specific installation or measurement session.

Open questions for further research. How should the start and end of the transition zone be defined when the visual color change exhibits a gradual onset phase and a residual tail in addition to the sharp color change phase? A practical distinction exists between these boundary definitions: one captures the full range of any visible color change, while the other captures only the dominant color switch that is relevant to the pilot's perception. Applying different definitions to the same measurement can move the reported transition zone width from exceeding the ICAO specification to conforming with it and shifts the calculated setting angle. A standardized definition of the visual boundaries for UAS-based assessment would allow measurement results to be compared consistently across operators and installations. How does the visually assessed transition zone, once its boundaries are standardized, relate to the photometrically measured transition zone defined in ICAO specifications? What is the relationship between the direction of horizontal tilt and the direction of asymmetric TZ widening? Is the observed widening a property of the LED optical assembly behavior, or is it specific to the UAS-based visual assessment method? Answering these questions would strengthen the interpretation of lateral beam profile measurements and support the development of standardized assessment criteria for LED PAPI systems.

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