# Advancing Heliostat Field Measurement and Characterization: Insights from International Collaboration and Workshop Outcomes

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## ABSTRACT

Accurate characterization of individual heliostats and full heliostat fields is essential to improve the performance and reducing the operation and maintenance (O&M) costs of Concentrated Solar Power (CSP) Tower Plants. In this context, an international collaboration was initiated with the Analyze Heliostat Field project, funded by the International Energy Agency's Technology Collaboration Program on Solar Power and Chemical Energy Systems (IEA-TCP SolarPACES), to develop standardized methodologies for heliostat metrology, characterization, and calibration. This initiative has now evolved into Analyze Heliostat Field Phase II: "Beam Characterization System (BCS) as a Calibration Reference System". Given the growing importance of the BCS in real CSP Tower plants for quality control of heliostats during commissioning and start-up phases, as well as its widespread use as a verification system for heliostat aiming during operation, this work aims as a first step to consolidate the BCS as a reliable reference for heliostat pointing calibration (heliostat calibration). Through this collaboration, leading global research institutions and industry stakeholders have benchmarked metrology tools, identified technological gaps, and proposed guidelines to enhance optical quality, pointing accuracy and reliability in heliostat fields. The recent workshop "Solar Towers Performance Enhancement and Cost Reduction by the Development and Implementation of Innovative On-Site Measurement & Characterization Tools," organized at IMDEA Energy, further reinforced these efforts by fostering discussions between academia and industry on cutting-edge measurement techniques. Key outcomes include the evaluation of state-of-the-art metrology methods, the importance of standardization, and the need for cost-effective and scalable calibration solutions to improve heliostat field performance.

This work summarizes the key findings from both project phases, highlighting advancements in heliostat metrology tools and discussing the next steps toward implementing a unified calibration framework. The results of this collaboration will support the commercial deployment of more efficient and reliable solar tower technologies, ultimately strengthening the competitiveness of CSP Tower Plants.

**Keywords:** Heliostat metrology, Calibration, CSP Tower performance, BCS, CSP cost reduction, international collaboration.

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# 1. BACKGROUND

The BCS is an essential tool for evaluating beam quality and tracking accuracy of heliostats in CSP Tower systems. It typically employs image analysis of heliostat reflected light on a designated target to assess optical performance. Advances in image processing techniques and computational power have opened pathways toward highly accurate and autonomous evaluation, allowing plants to cycle automatically through each heliostat, correcting tracking errors (pointing error) to improve plant performance. Challenges such as the lack of standardized methodologies and the limited and ineffective integration of BCS into the diagnostic and control systems of commercial CSP plants continue to hinder the effectiveness of image-based BCS solutions. This project aims to develop standardized BCS configurations and procedures that ensure comparability of results across different setups, ultimately improving the effectiveness, reliability, transparency, and interoperability of the system.

# 2. INTRODUCTION

## a. Importance of heliostat field characterization

Many factors affect the efficiency of CSP plants. While manufacturing errors, such as the slope deviation of facets can be identified during production, many other factors can only be identified once the heliostat has been deployed. Tracking error is one of the most common causes of global heliostat field performance error. It can be caused by misalignment of the heliostat actuating mechanisms or drift of these drives over time, both of which can only be characterized after the mirrors were installed. To quantify these respective errors, in-field characterization needs to be performed. Image-based BCS is among the most commonly used methodologies [1].

## b. Overview of BCS in tower plants

The BCS hardware is usually composed of two parts: 1.A Lambertian target and 2. An image capturing device, such as a camera, to capture the reflection pattern (as illustrated in Figure 1. A BCS from literature

The image acquisition device captures the light pattern on the target, performs analysis, and then provides quantitative assessment of the heliostat aim point. Multiple analyses allow for the assessment of the drift behavior and empiric, kinematic or AI-driven correction models.

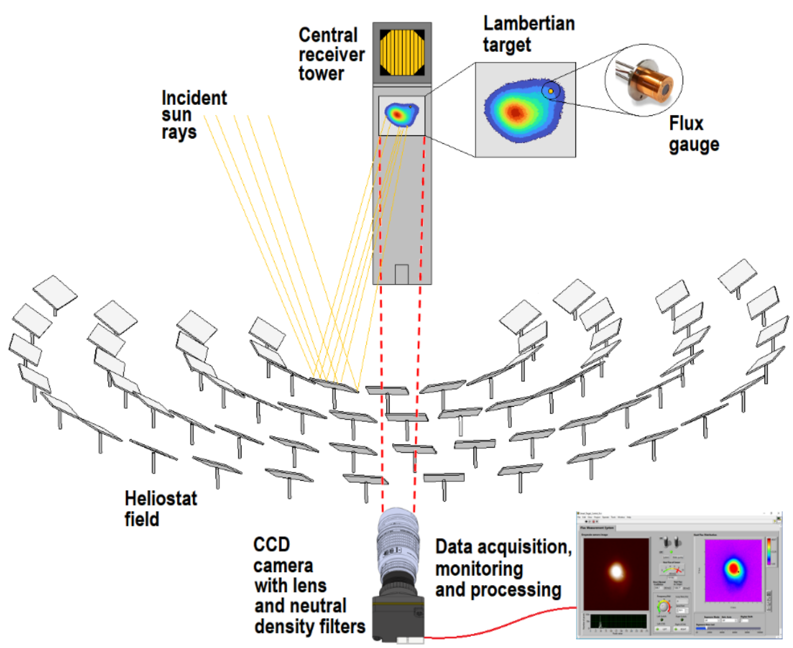


Figure 1. A BCS from literature

### c. Specific objectives of this work

While BCS is used by many operating plants and concentrated solar research institutions, each system has been developed independently and has used its own unique software, measurement definitions, conventions, and system hardware (targets, cameras, heliostats, etc.). This means that each new plant needs to design, select equipment, and develop custom software, which is incurring additional expenses. Besides, the diversity of conventions can also lead to measurement errors and make comparing BCS data difficult. Thus, this joint project ambitions to establish recommendations to perform BCS that allow for comparable and repeatable data collected from different plants. This would accelerate confident operations and the process in identifying potential problems, and benchmark remedy solutions to deal with various of the issues that currently burden the CSP Tower technology. More specifically, the goal is to set up a BCS standard for 1) general equipment selection, 2) general equipment setups, and 3) processing procedures of the collected data.

The selected equipment and procedures would ideally be easy to set-up and produce data with low uncertainty. Such procedures would ensure minimum influences of external factors, such as measurement noise and environmental conditions and produce comparable and sharable results.

## 3. INDUSTRY NEEDS FOR BCS IN COMMERCIAL TOWER PLANTS

The international collaboration under the Analyze Heliostat Field project has highlighted the indispensable role of BCS as a calibration reference tool. In this section, the industry needs for BCS, the immediate priorities and the major challenges that must be addressed to advance heliostat metrology, are discussed.

### a. Summary of workshop findings from IMDEA Energy

The recent workshop, held on October 3-4, 2024, at IMDEA Energy in Móstoles, Madrid, served as a dynamic platform for dialogue between industry stakeholders and research institutions. The event, which brought together 15 companies and 8 R&D centers from four continents, focused on collaboratively assessing Solar Tower Plant performance and identifying pathways to reduce O&M costs. The structure of the workshop consisted of an initial open debate to identify key challenges and assess the maturity of emerging technologies, followed by a strategic wrap-up session aimed at selecting high-impact innovations and developing a roadmap for their accelerated commercial deployment.
Key findings from the discussions included:

- **Enhanced Measurement Techniques:** Most participants recognized that current metrology tools require further refinement to capture the full spectrum of heliostat performance. Innovative on-site measurement methods and improved diagnostic protocols were identified as crucial for accurately assessing both individual heliostats and entire fields.
- **Standardization and Calibration Needs:** A common topic was the need for standardization in heliostat metrology. Stakeholders highlighted that establishing a unified calibration framework—based on the BCS—would ensure consistency and reliability across diverse systems. This is essential not only for quality assurance but also for enabling effective benchmarking and comparative analyses among different Solar Tower Plants.
- **Collaboration between Academia and Industry:** The workshop reinforced the benefits of cross-sector collaboration. Industry experts provided valuable insights into practical operational challenges, while academic partners showcased advances in measurement technologies and digital tools. This exchange has opened the door to joint roadmaps aimed at bridging the gap between research developments and commercial implementation.
- **Focus on Cost Reduction and Scalability:** Discussions emphasized the need for cost-effective, scalable solutions. The adoption of state-of-the-art metrology methods, when combined with digitalization strategies (e.g., the use of artificial intelligent (AI) and big data analytics), promises to streamline calibration processes and reduce long-term O&M expenses. These outcomes underscore the critical role of a robust BCS in driving the commercial competitiveness CSP Tower systems.

### b. Short-term priorities (0–3 years) for field characterization

In the near term, the industry's priorities for heliostat field characterization can be categorized into several key areas:

- **Implementation of Standardized Protocols:** There is a **crucial** need to develop and adopt standardized calibration protocols for heliostat metrology. Within the next three years, establishing an industry-wide framework that leverages the BCS as a primary reference is essential. This framework should encompass standardized measurement procedures, data processing guidelines, and quality assurance benchmarks.
- **Adoption of Advanced Digital Tools:** The integration of digital technologies is seen as a short-term priority. In particular, the application of AI for predictive analytics, big data methodologies for performance monitoring, and digital twins for simulation purposes are expected to play a crucial role in enhancing measurement accuracy and operational efficiency.
- **Rapid Deployment of Improved Metrology Systems:** Industrial stakeholders are keen to accelerate the commercialization of next-generation metrology systems. These latter systems should provide higher resolution and better real-time monitoring capabilities to quickly identify performance deviations and address them before they escalate into costly maintenance issues.
- **Enhanced Training and Knowledge Transfer:** To fully benefit from the new technologies, immediate efforts must be made by upskilling operational and maintenance personnel. Establishing collaborative training programs between research institutions and industry players will ensure that the latest measurement and diagnostic techniques are correctly implemented on the ground.
- **Pilot Projects and Validation Studies:** Short-term pilot projects are needed to validate the proposed calibration methods under real operating conditions. Such pilot studies will not only refine the measurement protocols but also build confidence among industry stakeholders regarding the reliability and cost-effectiveness of the BCS.

### c. Key challenges in heliostat field characterization

Despite the promising developments and clear industry needs, several challenges remain that could hinder the widespread adoption of enhanced heliostat metrology practices:

- **Measurement Accuracy and Resolution:** One of the primary technical challenges is achieving the high degree of accuracy and resolution required for effective heliostat calibration. Variations in heliostat design, coupled with environmental factors such as dust, temperature fluctuations, and atmospheric attenuation, complicate the measurement process. Continuous research is needed to refine sensor technologies and calibration algorithms to mitigate these effects.
- **Integration with Existing Plant Control Systems:** Another significant challenge is the seamless integration of advanced metrology tools with current plant control and monitoring systems. Many existing installations were not originally designed to incorporate high-resolution, real-time diagnostic data. Upgrading these systems requires substantial investment and may involve complex retrofitting procedures.

  **Data Processing and Standardization:** The volume of data generated by modern measurement systems poses its own challenges. Effective data processing, storage and analysis require robust algorithms and standardized formats. Furthermore, ensuring data interoperability across different systems and manufacturers remains an ongoing concern.
- **Cost Constraints and Economic Viability:** While the long-term benefits of enhanced metrology are evident, the costs associated with developing and deploying these advanced systems, though moderate, remain significant enough to warrant careful management. It is crucial to balance technological innovation with economic practicality, particularly for smaller-scale operators who may have more limited resources compared to larger players.
- **Environmental and Operational Variability:** Heliostat fields are subject to a wide range of environmental conditions that can affect measurement accuracy. Variability in weather patterns, seasonal changes, and site-

specific factors such as terrain and dust accumulation need to be carefully considered in the calibration process. Developing adaptable and robust measurement solutions is therefore a priority.

Addressing the short-term priorities and overcoming the outlined challenges will be key to ensuring that the BCS becomes a central pillar in the drive toward more efficient and reliable Solar Tower Plants. The industry needs and challenges identified should shape the roadmap for immediate improvements but also define the strategic direction for future research and development in the CSP sector.

## 4. CAPABILITIES OF CURRENT BCS SYSTEMS

As mentioned in the introduction, BCS system is a key tool capable of evaluating the performance of heliostat fields, providing essential information for both beam shape assessment and heliostat tracking accuracy.

Referring to the conclusions obtained in IMDEA Energy workshop, several R&D centers are validating the potential of BCS systems in operational conditions, aiming to bridge the gap between research and field implementation in commercial tower plants. Within this context, this international collaboration has proven essential to promote standardization, benchmarking and broader development.

### a. BCS methodologies in R&D infrastructures

Multiple BCS methodologies have been developed by R&D institutions worldwide. These methodologies differ in hardware configurations, image capture procedures, and data processing workflows. Table 1 summarizes the main characteristics of BCS implementations at leading institutions.

Table 1. Main characteristics of different BCS systems

| BCS System | Camera Hardware | Capture Steps |
|---|---|---|
| **CSIRO** | Camera manufacturer: Basler<br>Bit depth: 10 or 12 bits<br>Resolution: [1296x966]<br>Exposure time: 10-100 ms | Autoexposure based on peak brightness<br>Capture non-saturated image of calibration target with or without heliostat on target |
| **Sandia NSTTF** | Camera manufacturer: Basler<br>Bit depth: 12 bits (camera), 8 bits (software)<br>Resolution: [1626x1236]<br>Exposure time: embedded in software | Choose neutral density filters, then set aperture and after, set gain<br>Capture non-saturated image of calibration target with or without heliostat on target |
| **CYI** | Camera manufacturer: Basler<br>Bit depth: 10 or 12 bits<br>Resolution: [2448x2048]<br>Exposure time: embedded in software | Manual/Auto exposure based on grey level histogram within Lambertian target area<br>Capture non-saturated image of calibration target with or without heliostat on target |
| **CIEMAT-PSA** | Camera manufacturer: Hamamatsu<br>Bit depth: 16, 12 and 8 bits<br>Resolution: [2048x2048]<br>Exposure time: 10 – 100 ms | Manual/Auto exposure based on grey level histogram within Lambertian target area<br>Capture non-saturated image of calibration target with or without heliostat on target |
| **CENER** | Camera manufacturer: Retiga<br>Bit depth: 14 bits<br>Resolution: [1360x1024]<br>Exposure time: 0.025 ms – 60 min | Perform a manual or automatic exposure adjustment, aligning with the peak intensity of the spot reflected on the Lambertian target to prevent pixel saturation at the spot's centroid<br>Capture non-saturated image of calibration target with or without heliostat on target |
| **NREL** | Camera manufacturer: Basler<br>Bit depth: 8, 10 or 12 bits<br>Resolution: [3840x2160] | Manual exposure adjustment<br>Capture non-saturated image of calibration target with or without heliostat on target |

| | | |
|---|---|---|
| | Exposure time: embedded in software | Secondary BCS setup with consumer camera (Sony a6400 or Sony a7rV) and tripod. |
| **IMDEA Energy** | Camera: Prosilica GT 1920<br>Bit depth: 12-bit or 14-bit<br>Resolution: 1936 x 1456<br>Exposure time: 0-26 s | Automatic exposure algorithm captures unsaturated flux maps at the Lambertian target |
| **DLR (Julich solar towers)** | Camera manufacturer: Axis<br>Bit depth: 8bit<br>Resolution: up to [3072 x 1728]<br>Exposure time: automatic camera settings | Automatic exposure by camera settings<br>Capture non-saturated image of calibration target with heliostat on target |

These BCS operational variations reflect how each institution adapts to specific test environments, calibration targets, and field deployment strategies. Despite the technical differences, a convergence is emerging around the importance of:

- Capturing high dynamic range images to ensure accurate measurement of beam shape and intensity.
- Avoiding image saturation, especially when operating under full solar irradiance.
- Using Lambertian reference targets to evaluate beam uniformity and focus.

In addition to the camera setup and exposure strategy, other factors such as mounting systems, image analysis software, and environmental compensation methods differ across institutions and influence system performance.

### b. Parameters Measured and Data Provided

The BCS developed by different institutions vary significantly in terms of the type and number of parameters measured, the depth of data processing, and the format and usability of the output data.

Despite these differences, most systems provide at least the essential outputs required to evaluate heliostat optical performance, including:

1. **Flux distribution analysis on the target** – assessment of the beam image formed on the target surface and the measurement of irradiance peak values.
2. **Tracking error estimation** – determination of heliostat aiming accuracy by interpreting the actual aiming vector based on the flux distribution.
3. **Total reflected power measurement** – calculation of the total reflected energy under controlled conditions by integrating the image flux and applying appropriate calibration.

These variations are often driven by the specific technical goals, operational strategies, and resource constraints of each institution. However, they also highlight a fragmented landscape that could benefit from increased standardization and coordination—particularly as heliostat fields become more complex and performance requirements continue to rise.

## 5. LIMITATIONS AND GAPS IN CURRENT BCS SYSTEMS

The accuracy of BCS in CSP Tower plants is subject to significant variability due to heliostat design differences, environmental conditions, and the diversity of measurement methodologies. While solar tracking accuracies close to 0.1 mrad would be achievable but under controlled laboratory conditions, real-world heliostat tracking implementations often experience errors of several milliradians—an unacceptable range for optimal plant performance.

### a. Key Sources of Error

Measurement Errors:
Multiple factors affect the determination of a heliostat normal vector

- Surface imperfections and alignment issues, especially for heliostats near the tower, distort the flux pattern on the target.

- Shading and blocking from adjacent heliostats introduce centroid biases, affecting nearly 30% of calibration images.

- Astigmatism and sun-position-dependent shifts influence spot shape and intensity.

- Camera-related problems such as overexposure or background light can obscure or distort the focal spot.

- Timing mismatches between heliostat updates and image acquisition can introduce drift-induced errors.

- In some cases, total image failures (e.g., missing or multiple focal spots) occur and must be filtered out.

<u>Dataset Sampling Challenges:</u>
Non-uniform sampling of solar positions (e.g., poor representation at sunrise/sunset or seasonal extremes) introduces model bias. Uniform sampling, using clustering methods like k-means or k-NN, is recommended. The lack of standardized dataset structures across facilities further contributes to variability in model performance.

<u>Model Limitations:</u>
A range of heliostat models—analytical, hybrid, and data-driven—have been proposed. While data-driven models offer advantages in capturing complex physical behaviors, the presence of measurement errors limits their overall accuracy. Current evidence suggests [1] [2] [3] that improvements in measurement quality may yield greater benefits than refinements in modeling techniques alone.

### b. Data Processing Issues

Initial cross-institutional comparisons of BCS image analysis have revealed discrepancies due to inconsistent processing criteria. Key unresolved issues include:

- Whether and how to apply background subtraction.

- How to define the energy threshold for determining the beam centroid.

- Methods to reduce noise and correct for artifacts.

These inconsistencies highlight the need for shared guidelines to ensure processing repeatability and cross-comparability.

### c. Integration Limitations

Most current BCS systems are designed for post-process analysis and are not integrated into real-time control systems. The main limitations include:

- High computational demands for real-time image processing.

- Limited scalability to monitor all heliostats in large fields simultaneously.

- Lack of closed-loop integration with heliostat control systems.

- Incompatibility with industrial SCADA/PLC systems

### d. Conclusion

To fully exploit the potential of BCS, improvements are needed in measurement accuracy, dataset standardization, image processing protocols, and plant-level integration. Addressing these limitations will be critical for enabling real-time diagnostics, reducing O&M costs, and enhancing the overall efficiency and automation of CSP Tower plants.

## 6. TOWARDS STANDARDIZATION AND OPERATION INTEGRATION

Analysis of the BCS implementations of the partnering R&D centres reveals a clear potential to improve the performance of BCS technologies. The different BCS strategies and developments of the different R&D centres reveals a clear potential to enhance the role of BCS technologies beyond experimental characterization, advancing towards operational integration and cross-institutional standardization.

Several key aspects can guide this transition:

- Definition of key performance indicators: Establishing a common set of optical parameters (eg. Root mean square tracking error, effective beam spread, canting error distribution) would enable meaningful comparisons between system and sites.
- Common protocols and test conditions: Harmonizing procedures for system calibration, image acquisition, and data interpretation would improve repeatability and reduce uncertainty.
- Standardized output formats: Facilitating data sharing and integration with plant-level digital tools (SCADA systems, digital twins, etc.) can unlock new value for O&M and performance prediction.
- Benchmarking and validation frameworks: Developing shared test cases or synthetic scenes could help validate BCS tools across institutions, fostering trust and accelerating adoption.
- Role of collaborative platforms: Initiatives such as SolarPACES Task III, EU Solaris or international projects could serve as vehicles to coordinate such efforts and define practical guidelines.

In this context, the diversity of current practices is not a limitation but rather an opportunity. By learning from each other's experience, the community can progress toward more robust, interoperable and impactful BCS solution that serve both research and industrial needs.

## 7. CONCLUSIONS

The accurate and consistent characterization of heliostat fields is increasingly recognized as a cornerstone for optimizing the performance, reliability, and economic viability of CSP Tower plants. In this context, BCS have persisted as essential diagnostic tools, capable of providing detailed information on heliostat pointing accuracy and optical quality.

One of the most significant insights from the Analyze Heliostat Field international collaboration is the urgent need to standardize BCS methodologies, equipment setups, and data processing protocols. The current diversity in BCS implementations—driven by institutional preferences, hardware configurations, and software workflows—results in non-comparable outputs and hampers cross-plant benchmarking. Establishing standardized procedures will not only ensure that data from different systems is interoperable and comparable but also foster confidence in the reliability and repeatability of BCS-derived metrics.

A strong international consensus has emerged among R&D centers, industry stakeholders, and CSP operators regarding the importance of standardized, field-deployable heliostat metrology. Workshops such as the one held at IMDEA Energy have underscored this consensus, highlighting the necessity of a common calibration framework based on BCS, and a collective willingness to align on technical definitions, performance indicators, and best practices.

Furthermore, the collaboration revealed the strategic value of international cooperation in leveraging complementary strengths across institutions. Sharing methodologies, calibration datasets, and validation results enables the consolidation of a robust knowledge base. Such collaboration is key to developing practical and scalable diagnostic tools that address both research and industry needs. By integrating diverse methods and learning from the strengths and limitations of each approach, the community can collectively deliver BCS systems that are not only effective but also adaptable to different plant conditions and operational constraints.

When effectively integrated into plant control and monitoring systems, standardized BCS tools could drastically improve solar field diagnostics. This includes enabling automated heliostat assessments, early detection of tracking or optical failures, and providing inputs for predictive maintenance routines. As highlighted in the report, this integration has the potential to:

- Enhance overall plant efficiency by continuously correcting heliostat pointing errors.
- Reduce O&M costs through early fault detection and reduced manual inspections.
- Increase automation levels, thus decreasing human intervention and related operational risks.

- Improve long-term reliability and durability of heliostat components by enabling more precise and responsive maintenance strategies.

Despite the clear benefits, challenges remain particularly related to measurement accuracy under real-world conditions, seamless integration with existing SCADA systems, and managing large volumes of high-resolution image data. Nevertheless, recent advances in digital technologies, such as AI, digital twins, and big data analytics, present promising pathways to overcome these barriers.

In conclusion, this initiative marks a critical step toward bridging the gap between academic research and industrial application in heliostat metrology. The collaborative effort has laid the groundwork for a unified, reliable, and cost-effective approach to heliostat field characterization, which will be instrumental in enhancing the competitiveness and scalability of CSP technologies in the renewable energy landscape.

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