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Development of Heliostat Field Calibration Methods

Theory and Experimental Test Results

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Abstract. In this work, three patent pending calibration methods for heliostat fields of central receiver systems (CRS) developed by the Solar-Institut Jülich (SIJ) of the FH Aachen University of Applied Sciences are presented. The calibration methods can either operate in a combined mode or in stand-alone mode. The first calibration method, method A, foresees that a camera matrix is placed into the receiver plane where it is subjected to concentrated solar irradiance during a measurement process. The second calibration method, method B, uses an unmanned aerial vehicle (UAV) such as a quadrocopter to automatically fly into the reflected solar irradiance cross-section of one or more heliostats (two variants of method B were tested). The third calibration method, method C, foresees a stereo central camera or multiple stereo cameras installed e.g. on the solar tower whereby the orientations of the heliostats are calculated from the location detection of spherical red markers attached to the heliostats. The most accurate method is method A which has a mean accuracy of 0.17 mrad. The mean accuracy of method B variant 1 is 1.36 mrad and of variant 2 is 1.73 mrad. Method C has a mean accuracy of 15.07 mrad. For method B there is great potential regarding improving the measurement accuracy. For method C the collected data was not sufficient for determining whether or not there is potential for improving the accuracy.

Keywords: Heliostat Field Calibration, Unmanned Aerial Vehicle, UAV, Quadrocopter, Camera System, Camera Matrix, Optical Filter System, Central Camera, Spherical Markers, CRS, Heliostat

1. Description of heliostat field calibration methods

A schematic of the three calibration methods is shown in Figure 1 (a) to (c). Shown in Figure 1 (a) is calibration method A with cameras in the receiver focus. Due to the extreme concentrated solar irradiance, the camera system includes an optical filter system and water cooling mechanism. Figure 1 (b) shows method B which uses a UAV for measuring the orientation of a heliostat whilst flying through the cross-section of the solar irradiance reflected by the heliostat towards the receiver/target. Finally, Figure 1 (c) illustrates method C which utilises central camera(s) pointed towards the heliostat field to measure the orientation of heliostats by determining the normal vectors from the positions of spherical red markers mounted on the edges of heliostats. All three calibration methods shall be applicable for any receiver or heliostat field.

In the publication of Sattler et al. (2020) [1], existing and proposed calibration methods were reviewed and, amongst others, classified in groups. In accordance with these groups, calibration method A falls into the group “Class C: Central solar focus position detection with cameras or sensors on tower", while methods B and C can be grouped into "A2: Camera(s) on tower or UAV(s)". More details on each of the calibration methods is given in the following subsections. As stated in Sattler et al. (2020) [1], the overall tracking accuracy of a heliostat should ideally be ≤1 mrad. Moreover, it is stated that due to other errors, for most calibration methods the measurement accuracy of the heliostat orientation must be around 5 to 10 times more accurate (i.e. 0.1 to 0.2 mrad) to achieve an overall tracking accuracy of ≤1 mrad. It is unrealistic to achieve a heliostat tracking accuracy of ≤1 mrad without a calibration system [1].

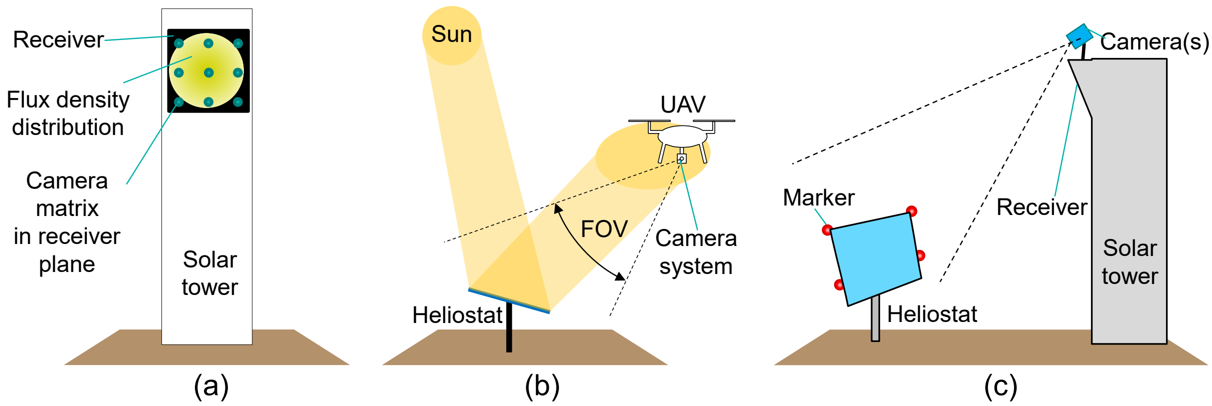


Figure 1. Schematic of the three calibration methods: (a) method A with cameras in the receiver focus, (b) method B using a UAV, and (c) method C with spherical markers on the heliostats and central camera(s). Schematic by SIJ.

There are several examples of research work on class C calibration methods. Kribus et al. (2004) [2] fitted four cameras around the receiver, Goldberg et al. (2015) [3] fitted a pinhole camera into the receiver and Collins et al. (2017) [4] used a camera array that sweeps along the receiver. Regarding class A2, using UAV for calibrating heliostats is described, for example, by Qianjun et al. (2018) [5] and Jessen et al. (2022) [6]. Calibration methods with camera(s) on the tower are, for example, Röger et al. (2010) [7] and Sauerborn et al. (2013) [8].

2. Experimental results of heliostat field calibration methods A, B and C

Through the course of the research project H2Loop, a series of laboratory and functional tests were carried out in order to investigate the calibration methods A, B and C and their accuracies. Towards the end of the project, experimental results were obtained from tests at the Solar Tower Jülich and Multi Focus Tower from the German Aerospace Center (DLR) in Jülich, Germany. As three calibration methods were explored which can operate independently from one another, the field tests were consequently carried out independently from one another. As there was limited time available for testing, the focus was set onto obtaining as much data as possible. Due to the completely different setups and needed time for preparing and carrying out the measurement campaigns, the number of measurements presented in this work varies.

2.1 Method A

Calibration method A foresees that a camera matrix is fitted e.g. into the receiver, in gaps between multiple receivers or temporarily moved to a fixed position into the concentrated solar irradiance impinging on the receiver. The complexity of the method A calibration system was to design the optical filter and cooling mechanism in such a way that it can withstand high-intensity irradiance. To test the camera system's physical limits, a test with high concentrated irradiance was carried out at the German Aerospace Center's (DLR) artificial sun research facility Synlight in Jülich. The camera system was subjected to various irradiance intensities up to 1.5 MW/m^2 for different durations between about 1 to 5 minutes. Only after 5 minutes of irradiation at 1.5 MW/m^2 it could be observed that the optical filter started becoming curvy but it had neither failed in its function nor cracked. From this test result, it became evident that the camera system with optical filter was, in principle, highly effective. It was also shown that in a real-life environment of a CRS, it is essential to protect the camera system from extreme solar irradiance concentrations in such a way that the camera system is only temporarily exposed to concentrated solar irradiance, e.g. 10 seconds, when measuring the orientation of the heliostats. In other separate tests, the camera system was exposed to an artificial sun (near-infrared emitter) at SIJ with 530 kW/m^2 irradiance in dozens of trials for durations of about 1 minute, whereby the camera system remained in mint condition. For reasons of protecting the filter from soiling and allowing easy cleaning, a transparent glass cover is fitted at the entrance of the camera system. Furthermore, it should be noted that in a real-life application, it is foreseen that the camera system is protected from the concentrated irradiance during times when the calibration system is not measuring the orientation of the heliostats e.g. by use of a mechanical shutter. A positive side effect of a mechanical shutter is that it blocks dust and rain such that neither reach the transparent glass cover during the times when the system is not measuring.

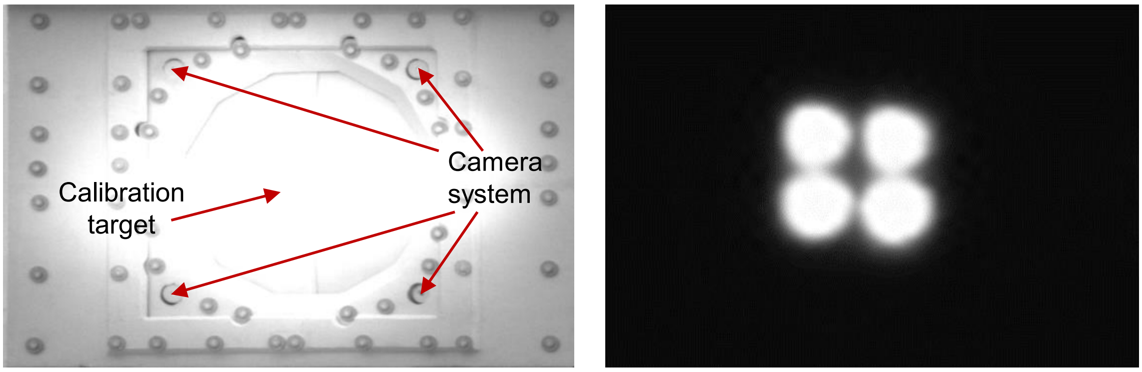
A difficulty of the method A calibration system is that the software must be able to distinguish between the reflected solar irradiance from the individual heliostats at all times. This can be complicated when parts of a heliostat's mirror surface(s) are not visible in the camera image, which occurs if a heliostat in front of it causes blocking. Therefore, the image processing algorithm of the calibration software was developed in such a way that it pre-calculates the positions of the visible heliostat mirror contours by considering blocking by other heliostats depending on the time of the measurement during a day. Also, a possibility is to test the accuracy of the heliostat orientation measurement if only the central mirror area is used for evaluating the brightness distribution. This way, blocking of another heliostat is no longer an issue and this reduces the complexity of the heliostat detection. Therefore, with this second proposed brightness evaluation, only e.g. 70 % of the mirror area is used for determining the orientation of a heliostat. The region of interest (ROI) can be defined e.g. around the pivot point of the heliostat whereby the ROI can be any shape such as rectangular, circular or any other desired shape.

Theoretical results of the accuracy of method A were obtained by simulating flux distributions on a receiver and overlaying them with the positions of the cameras that are located within the flux distribution. The result of the simulation was that an accuracy between 0.1 and 1 mrad is theoretically possible, however, it should be noted that the flux distribution was idealised.

Method A was validated at the Multi Focus Tower on the premises of the Solar Tower Jülich using a matrix of four camera systems which surrounded a temporary calibration target as shown in Figure 2 (a). In a pre-test, a single heliostat was aimed at the calibration target and the aim point measured by the calibration system was monitored through live measurement updates every few seconds. When moving the aim point from the centre of the calibration target to various corners where the cameras are positioned or centrally between two cameras, the live measurement showed that the measured aim point coincided with the different positions of the sun spot. The accuracy of method A was validated via the state-of-the-art camera-target method (for more details on the camera-target method see publication by Sattler et al. [1]). The brightness distribution and resulting mean aim vectors of single heliostats were measured with the camera-target method and compared with the aim vector that was computed with method A. For method A, the result of the accuracy was determined to be 0.17 mrad (mean) from 14 calibration measurements (more details of the results are shown in Table 1). This calibration method has enormous potential. It should be noted that the camera system needs to still be further optimised as there was an overexposure in the images. The overexposure, however, did not appear to compromise the measurement accuracy, probably because the overexposure affected the heliostat's mirror facets equally. For this test, altogether two heliostats were used (one heliostat at a distance of 106 m and the other 66 m from the solar tower) and individually pointed on the calibration target. The centroid of the sun shape on the calibration target was evaluated using the camera-target method. The measured overall orientation of the two heliostats was compared with the position of the sun shape centroid on the calibration target at the specific times of the measurements. Figure 2 (b) shows a photograph of one of the heliostats with four mirror facets during a calibration measurement. The data processing of the image data of the heliostat field from the four cameras takes around ≤ 8 ms which means that method A is fast enough to be used as an online calibration system, i.e. a fully closed-loop control can be realised. If the tracking accuracy of the heliostats of a heliostat field is generally good then it may be sufficient to have calibration intervals of method A in the order of e.g. several minutes.

Table 1. Measurement accuracy of calibration method A determined from 14 measurements.

	Accuracy in mrad (azimuth component)	**Accuracy in mrad (elevation component)**	**Accuracy in mrad (radial component)**
Min	0.061	0.002	0.061
Max	0.226	0.220	0.315
Mean	0.152	0.078	0.171



(a) (b)

Figure 2. (a) Photograph of a sun spot on the calibration target and surrounding camera system matrix, (b) Example of a photograph showing one heliostat with four mirror facets as seen by one of the four cameras (image zoomed in). The mirror facets appear circular as the sun shape of the light reflected by the heliostat is circular as well. Photographs by SIJ.

In a next step, the camera matrix was exposed to 7 heliostats but due to a lack of time the tracking accuracy of all of these heliostats could not measured. Finally, in a stress test, the camera systems were subjected to a flux density of about 600 kW/m^2 from around 400 heliostats without water cooling for several hours whereby none of the components got damaged.

Generally, for a more accurate calibration result, the number of camera systems of the camera matrix would need to be increased. Whether or not this is necessary depends on the individual receiver type and the requirements of the flux distribution as well as the heliostat and receiver size. If the sun spot were to differ strongly from a Gaussian shape, then a camera matrix with cameras in the centre of the receiver may be necessary. For best results, it is important that the distance between the cameras is (slightly) smaller than the smallest sun shape produced by a heliostat. However, the method will also give results if, for example, only one or two cameras detect the sun spot of a heliostat.

2.2 Method B

Two distinguishing characteristics of method B with UAV are that the calibration occurs in real-time without the need of post-processing and that heliostats can remain in tracking mode during the calibration procedure. However, because the calibration of a single heliostat is comparatively slow, an online calibration of all heliostats of a heliostat field is not possible. Method B can be used for three or more modes of operation, including: (1) calibration of heliostats during the operation of the CRS alongside method A (e.g. in between the calibration intervals of method A), (2) during the installation phase of a heliostat field even when the solar tower has not been constructed yet, or (3) as a replacement of the camera-target method. Moreover, it is foreseen that in a real-life application, multiple UAVs are used to carry out the calibration measurements in vector or matrix flight formation. This will increase the measurement speed and accuracy of this method. The authors estimate that with a flight in vector formation with around 5 UAVs, a single calibration measurement of a heliostat can be carried out in around 5 seconds. Two versions of method B were tested and are described below.

Version 1 foresees that a UAV flies through the cross-section of direct solar irradiance reflected by a heliostat and an attached camera measures the brightness during the flight. The mean orientation vector of the heliostat can then be determined by calculating the weighted brightness across the cross-sectional area of the beam from dozens of images taken during the flight and by combining the images with the corresponding UAV positions. A selection of images taken during a flight is shown in Figure 3. It can be observed that there is an overexposure in the images. The overexposure is likely to not have affected the measurement accuracy as the overexposure equally affects all mirror facets. However, in future tests, the overexposure shall be eliminated by a technical adjustment. The calibration measurement was carried out in real-time with a live result of the test heliostat's orientation. A test of the live feedback to the heliostat field control computer for correcting the orientation was not yet realised though. The results of the accuracy of calibration method B – version 1 based on 13 measurement flights are shown in Table 2. With a mean accuracy of 1.36 mrad (radial component), the method is accurate enough for carrying out a coarse calibration. Generally, the result of calibration method B – version 1 can be improved by increasing the horizontal distance between the heliostat and the UAV such that the beam cross-section increases and the position error of the UAV has a lower impact. Version 1 of method B has the potential of measuring the orientation of multiple heliostats (ideally at least around 5 heliostats). Whether or not this is achievable depends on the thermal stability of the UAV when subjected to low concentrated irradiance, but this has not been evaluated or tested yet and requires a thorough safety assessment. However, it should be noted that when multiple heliostats are calibrated simultaneously, then the heliostats must be aimed at a common focal point and cannot be used for receiver operation.

Table 2. Measurement accuracy of calibration method B – version 1 determined from 13 measurement flights.

	Accuracy in mrad (azimuth component)	**Accuracy in mrad (elevation component)**	**Accuracy in mrad (radial component)**
Min	0.32	0.03	0.32
Max	2.71	1.34	3.02
Mean	1.23	0.58	1.36

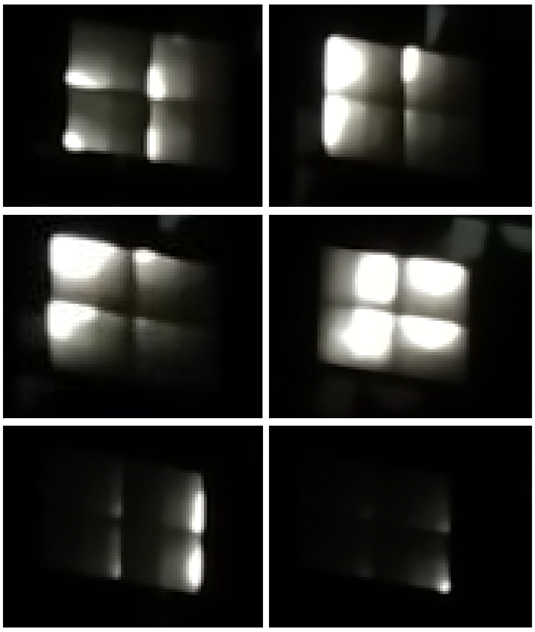


Figure 3. Selection of images taken during flight (version 1 of method B). Images by SIJ.

Version 2 of method B foresees that a UAV flies through the cross-section of a beam whereby the solar irradiance is reflected (diffuse) by the UAV's surface towards two (or more) cameras on the ground. The cameras are positioned at different angles from one another and simultaneously capture photographs of the UAV illuminated by the solar irradiance. The position of the UAV can either calculated from two images in real-time or real-time UAV position data is used. By evaluating the images with the brightness of the UAV during the passage through the cross-section of the beam, a brightness map is obtained from which the weighted mean orientation of the heliostat can be determined when combining it with the UAV positions. Only one heliostat's orientation can be evaluated at a time.

In an experiment at the Solar Tower Jülich, version 2 could only partly be tested. The UAV's position was obtained from the UAV itself in real-time and not, as preferred, from two cameras. For capturing images of the illuminated UAV during a calibration flight, one camera on the ground was used. The results (based on 13 measurement flights) of the accuracy of calibration method B – version 2 are shown in Table 3. With a mean accuracy of 1.73 mrad (radial component), the method is accurate enough for carrying out a coarse calibration. It should be noted though that version 2 was tested in unfavourable conditions (during some flights there was a white sky due to clouds) and the camera's frame rate was only around 1 frame per second (a white background reduces the accuracy of method B version 2). Moreover, as the UAV's position data also has an error and as the timing of the frame capture was not synchronised, this led to further inaccuracy. The authors are confident that evaluating the real-time UAV position via two images from the two cameras on the ground with a frame rate of a few frames per second will lead to the most accurate result. However, this would require the calibration flights to take place during clear-sky days with blue-whitish sky. When testing version 2 with a complete setup in the future, it is expected that the accuracy of version 2 will be greater than that of version 1 in a clear-sky environment.

Table 3. Measurement accuracy of calibration method B – version 2 determined from 13 measurement flights.

	Accuracy in mrad (azimuth component)	**Accuracy in mrad (elevation component)**	**Accuracy in mrad (radial component)**
Min	0.27	0.16	0.31
Max	2.29	2.31	3.25
Mean	1.37	1.06	1.73

2.3 Method C

For calibration method C, the focus of this work is to be able to measure the orientation of heliostats that are installed at a distance up to around 100 m from the central cameras. Distances greater than 100 m are also possible but then the marker size must be increased. To maximise the accuracy of method C, spherical red balls should be attached to heliostats, rather than taking two-dimensional markers. The method also foresees two cameras (stereo photography) to be used which simultaneously capture images of the heliostat field. For method C the data processing of the image data of the heliostat field from the two cameras takes around ≤ 2000 ms (10 heliostats per image → 200 ms for 1 heliostat) which means that method C is fast enough to be used as an online calibration system, i.e. a fully closed-loop control can be realised. An experiment was carried out at the Multi Focus Tower on the premises of the Solar Tower Jülich.

The overall result from 43 measurements is shown in Table 4 below showing that method C is very inaccurate. The collected data was not sufficient for determining whether or not there is potential for improving the accuracy.

Table 4. Overall measurement accuracy of calibration method C (based on 43 measurements).

	Accuracy in mrad (azimuth component)	**Accuracy in mrad (elevation component)**	**Accuracy in mrad (radial component)**
Min	0.14	0.85	0.86
Max	32.89	20.91	38.97
Mean	12.08	9.02	15.08

3. Advantages and disadvantages of heliostat field calibration methods A, B and C

The tested heliostat field calibration methods are very different from one another. For each of the methods, some of the most important advantages and disadvantages are listed below:

Advantages method A: online calibration in short time intervals; heliostats can be kept in tracking mode during calibration; highly compact, robust, water-cooled design; high quality image of heliostat field (each heliostat can be seen on dozens of pixels); high optical quality feasible with optimised camera and objective lens; FOV can be increased when optimising camera system; the cost of the calibration system is relatively low (estimation for a matrix of 20 camera systems <150,000 €); flux density can also be measured via brightness; camera system withstands high-intensity solar irradiance; brightness data from varying flux distribution is used for calculating a brightness-weighted heliostat normal vector;

Disadvantages method A: access to camera systems in the event that maintenance and cleaning is necessary must be carefully planned; possibly difficult to integrate into existing receiver systems; it is necessary to keep the distance between camera systems relatively small to maximise the calibration accuracy (ideally, the sunspot of a heliostat should cover four cameras at all times); difficult to install camera matrix inside a receiver that does not have some form of gaps; if camera matrix is installed within receiver which does not by default design have gaps, then there is a loss of energy as no solar light is used by the receiver in these gaps; if the sun shape of the light reflected by a heliostat does not have a Gaussian shape, then the accuracy of the measurement will be less accurate; if the sun spot is generally distorted, then the accuracy of the measurement may also be lower.

Advantages method B: real-time calibration is possible; possibly more than 1 heliostat could be calibrated e.g. during heliostat field installation phase if beams overlap (version 1 only); when the calibration method is optimised, the accuracy can probably be (well) below 1 mrad; heliostats can be kept in tracking mode during calibration with a UAV; it is estimated that with a flight in vector formation with around 5 UAVs, a single calibration measurement of a heliostat can be carried out in around 5 seconds; automation of flight possible (flight supervision by UAV pilot(s) obligatory as well as adhering to all flight safety regulations and rules); the cost for the calibration system is relatively low if 5 UAV are used (estimation <50,000 €); brightness data from varying flux distribution is used for calculating a brightness-weighted heliostat normal vector; flux density can also be measured via brightness (for version 1 with higher accuracy than for version 2).

Disadvantages method B: the rechargeable battery of a UAV usually allows flight time of around 30 minutes to 1 hour (depending on UAV model); during receiver operation and if keeping all heliostats in tracking mode then only 1 heliostat can be calibrated at a time.

Advantages method C: online calibration is possible; suitable cameras and objective lenses as well as spherical markers are relatively cheap (a multiple stereo camera system consisting of 40 cameras and lenses and 40,000 markers for equipping 10,000 heliostats will cost around 50.000 € (ca. 5 € per heliostat)); cameras and objective lenses can be housed (safe from rain) and heated in winter.

Disadvantages method C: multiple stereo cameras are necessary to cover the FOV of the heliostat field; only distances of heliostats below around 100 m can be measured (for higher distances the spherical marker must have a diameter bigger than 10 cm); the markers may need to be cleaned from time to time; heliostat normal is just based on plane from four spherical markers (variable flux distribution cannot be detected); the calibration method is currently too inaccurate (more tests are necessary).

4. Outlook for heliostat field calibration methods A, B and C

One more research project is necessary to advance all three calibration methods for market entry. This includes optimising the components (e.g. different cameras, different objective lenses, larger UAV, different size spherical markers along the distance). Methods A shall be developed further to additionally become a heliostat field characterisation method (2-in-1 feature) for measuring the flux density.

Data availability statement

The detailed and extensive amount of data supporting the results of this paper is only (and even only in parts) accessible to the consortium members of project H2Loop within legal restrictions bound by a cooperation agreement. For reasons of maintaining intellectual property, the information and data presented in this paper is limited.

Author contributions

J. C. Sattler: Conceptualisation, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualisation, Writing – original draft, Writing – review & editing;

I. P. Schneider: Conceptualisation, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Validation, Visualisation, Writing – review & editing;

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V. Atti: Formal Analysis, Writing – review & editing;

C. Teixeira Boura: Funding acquisition, Project administration, Supervision, Writing – review & editing;

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Competing interests

The authors declare no competing interests.

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