



1 Optimization of the SKYNET calibration with an iterative 2 Improved Langley method and its validation in the Mediterranean 3 area.

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14 **Abstract.**

15 The Improved Langley plot (ILP) method was developed for on-site calibration of PREDE-POM radiometers
16 within SKYNET. It eliminated the need to ship instruments to remote high-altitude sites as required by the
17 Standard Langley plot (SLP) method, reducing data gaps, transport-related risks, and operational costs while
18 maintaining field instrument uncertainty below 2.4 %. The study aims to update the ILP method by adopting the
19 latest Skyrad MRI v2 and introducing an iterative procedure. Testing with the data from the QUATRAM (QUALity
20 and TRaceability of Atmospheric aerosol Measurements) campaigns and the Burjassot site in Spain showed an
21 overall improvement of the ILP method. The median differences in direct aerosol optical depth (AOD) relative to
22 GAW-PFR (Precision Filter Radiometers) decreased to approximately -0.01 at the 500 and 870 nm channels.
23 AOD differences within the World Meteorological Organization (WMO) limits increased by 15-fold and 4-fold
24 at 500 and 870 nm channels, respectively. The PREDE-POM and AERONET Level 2 Version 3 direct AODs at
25 the Burjassot site showed good agreement, with median AOD differences within ± 0.01 across all wavelengths,
26 except at 340 nm. However, the fraction of points within WMO limits increases by over 10 % at wavelengths
27 below 500 nm, while remaining nearly unchanged (variations below 6 %) at longer wavelengths. These results
28 confirm the robustness of the ILP currently used in SKYNET and highlight the possibility of an improvement at
29 shorter wavelengths. This limitation is addressed in the present study through the proposed iterative ILP method
30 based on Skyrad MRI v2.

31 **1 Introduction**

32 Aerosols influence the Earth's radiative budget by both direct and indirect effects. In the direct effect, they absorb
33 and scatter the incoming Solar radiation back into space, thus modifying the amount of radiation that reaches the
34 Earth's surface. Indirectly, aerosols modify the cloud properties by acting as cloud condensation nuclei (CCN),
35 which affects the cloud radiative properties and their lifetime. In addition, they exhibit a strong spatial-temporal



36 variability, leading to a high uncertainty in the global effect calculations. As a result, the aerosol-related radiative
37 forcing remains one of the most uncertain components in the climate assessments, which has been reported in
38 various IPCC reports (IPCC, 2023; IPCC, 2007).

39 Surface-based Sun-sky radiometers are one of the most reliable instruments capable of providing a continuous
40 and high-quality aerosol measurement. These instruments measure direct Sun aerosol optical depth (AOD) and
41 other aerosols' optical properties, such as volume size distribution (VSD), real refractive index (RRI), imaginary
42 refractive index (IRI) and single scattering albedo (SSA) through inversions using sky radiance data. However, to
43 retrieve accurate aerosol optical properties with low uncertainties and to ensure the continuous long-term
44 monitoring, a robust radiometric calibration of the Sun-sky radiometers is always required. The standard Langley
45 Plot calibration technique, SLP (Ångström, 1970; Shaw, 1983; Shaw et al., 1973) is a commonly used technique
46 for calibrating solar radiometers. The fundamental idea is relatively simple: calibration is calculated from the
47 intercept of a least-squares fit of direct solar irradiance data measured at different air masses, performed during
48 clean and stable days. The Aerosol Robotic Network (AERONET) employs this technique (Toledano et al., 2018)
49 to calibrate its reference or master CIMEL CE318 sun-photometers. The clean skies require high and pristine sites
50 such as the Mauna Loa Observatory (Hawaii, USA) or Izaña Observatory (Tenerife, Spain). These conditions
51 allow a low uncertainty of the calibration values: 0.25 % for Mauna Loa and 0.4 % for Izaña (Toledano et al.,
52 2018). Afterwards, the master instruments are used to calibrate other secondary or field sun-photometers with the
53 calibration transfer technique, that requires lower altitude key sites easier to access. The calibration uncertainty
54 for the field instruments increases in the transfer process, sometimes doubling its value (Fargion et al., 2001;
55 Almansa et al., 2024). Despite a remarkable performance of the whole process, some limitations have been
56 identified: non-negligible economic cost, occasional instrumental damage during the frequent back and forth
57 transport. Not to mention data gaps occurring during the 2-3 months' calibration routine, if auxiliary instruments
58 are not available for swapping at the field site.

59 To overcome these limitations, (Campanelli et al., 2004) proposed an alternative method, known as the Improved
60 Langley plot (ILP). It is based on the previous work by (Tanaka et al., 1986) and (Nakajima et al., 1996) and it is
61 used in the operational calibration protocol of PREDE-POM sky radiometers in SKYNET (Sky Radiometer
62 Network, <https://www.skynet-isdc.org/>, last access; 15 May 2026). The ILP method uses the air mass multiplied
63 by the scattering AOD retrieved from diffuse sky radiance, rather than the air mass alone in the SLP, where the
64 scattering AOD are retrieved from aureole measurements using the retrieval algorithm. Thus, their approach
65 allows to calibrate the field radiometers on-site more accurately compared with the SLP under non-ideal
66 atmospheric conditions, such as near sea level sites with higher and more variable aerosol loads. The ILP method
67 provides sustainable calibration protocol over time with an uncertainty of 1.0-2.5 % across the instrument
68 wavelength range, 400-1020 nm (Campanelli et al., 2004). The comprehensive investigation performed by
69 (Uchiyama et al., 2018) showed that the ILP calibration, when compared to the transfer from reference instruments
70 calibrated using SLP at a high site, produced an RMSE of 0.6-2.5 %, very consistent with the results from
71 (Campanelli et al., 2004) and (Estellés et al., 2010). They also reported that the annual trend of the calibration
72 values was similar to SLP. (Nakajima et al., 2020) also reported monthly mean uncertainties between 0.5 % and
73 2.4 % at Tokyo and Rome sites, meanwhile the uncertainty decreased to 0.3-0.5 % at the higher altitude sites of
74 Mt. Saraswati, India, and Davos, Switzerland. (Kazadzis et al., 2018) also reported good agreement of the PREDE-
75 POM direct extinction AOD calculated using ILP calibrations with AERONET and PFR instruments. Later,



76 (Campanelli et al., 2024) conducted a more comprehensive analysis of the ILP performance, and compared the
77 ILP calibration values with those of high site SLP and transfer methods. The results showed excellent agreement,
78 with calibration values within ± 1 % of the SLP. This further assured the robustness of the ILP methodology over
79 time.

80 Despite the general excellent performance of the ILP, the recent analysis by (Campanelli et al., 2024) also reported
81 some discrepancies in the calculation of ILP calibration values when compared to different calibration transfers
82 from PFR and CIMEL instruments in the urban site of Rome. Some differences were as high as 4 % (340 nm)
83 which were attributed to molecular polarization (Momoi, 2022). Finally, (Karanikolas et al., 2024) reported a
84 slight underestimation of PREDE-POM direct extinction AOD in comparison to PFR during QUATRAM (Quality
85 and Traceability of Atmospheric Aerosol Measurements; <https://www.euroskyrad.net/quatram.html>, last access:
86 15 May 2026) campaigns, and attributed this to a systematic underestimation of the calibration obtained with the
87 ILP method as one of the potential reasons.

88 For many years, the ILP method in SKYNET relied on the estimation of scattering AOD from diffuse sky radiance
89 on the Skyrad v4.2 inversion algorithm, despite recent upgrades released by (Hashimoto et al., 2012) - Skyrad v5
90 -, and (Kudo et al., 2021) - Skyrad MRI v2. (Campanelli et al., 2024) already highlighted this issue, and suggested
91 to update the inversion algorithm used internally in the ILP method to retrieve the scattering AOD.

92 Thus, this study primary aims at updating the inversion algorithm in the ILP method according to the
93 recommendations of (Campanelli et al., 2024). We specifically implemented the Skyrad MRI v2 in the ILP method
94 to retrieve the scattering AOD, replacing Skyrad v4.2, to align with the operational aerosol inversion protocol in
95 the regional European SKYNET (ESR) and in one of the operational protocols in International SKYNET
96 (Nakajima et al., 2020). Additionally, we developed an iterative scheme in the ILP method based on the previous
97 study by (Tonna et al., 1995).

98 The article is structured as follows: Section 2 provides an overview on the instrumentation and datasets used in
99 this study. Section 3 outlines the ILP method and details the upgrade we introduce. Section 4 presents the
100 evaluation of the new implementation. We first assessed the performance of the upgraded ILP method by
101 comparing it with other calibration values obtained using SLP and transfer. Next, we present the comparison of
102 PREDE using the new calibration with the GAW-PFR and AERONET-CIMEL for a campaign and for a long-
103 term database in a fixed site. The conclusions are summarised in Sect. 5.

104 **2 Instrumentation and data**

105 **2.1. The PREDE-POM sun-sky radiometer**

106 The PREDE-POM radiometers are filter wheel radiometers manufactured by Prede Co., Ltd., Japan, since the 80s.
107 These sky-scanning radiometers are capable of measuring both direct irradiance (by looking directly at the Sun)
108 and scattered irradiance at the sky (in the almucantar and principal planes geometries). PREDE-POM radiometers
109 are the standard instruments used in the SKYNET international network. The instrument has two main models,
110 namely POM-01 and POM-02. POM-01 is a first-generation instrument capable of measuring at seven nominal
111 wavelengths: 315, 400, 500, 675, 870, 940 and 1020 nm. The channel at 940 nm is used for the retrieval of
112 columnar water vapour content, but not for aerosol retrievals. The field of view (FOV) of the instrument is ~ 1
113 degree. POM-02 is the extended version of POM-01, capable of measuring at 10 aerosol wavelengths: 315, 340,



114 380, 400, 500, 675, 870, 1020, 1627 and 2200 nm. The FWHM values for the various channels of the PREDE-
115 POM radiometer are 3 nm for the UV (315-380 nm), 10 nm for the visible and near infrared channel (400-1020
116 nm) and 20 nm for the shortwave infrared channels (1225-2200 nm). Direct sun data is typically measured at 1-
117 minute intervals, whereas the almucantar radiance data is typically recorded every 10 minutes. POM-01 is
118 thermostatically controlled at 30 degrees Celsius, whereas POM-02 is thermostated at 20 degrees Celsius for the
119 Si photodiode for the VIS wavelengths. The InGaAs photodiode used for NIR wavelengths operates between 0
120 and -25 degrees Celsius. In contrast, the measurement ranges from 0 to -25 degrees Celsius in longer wavelengths
121 for InGaAs photodiode for the NIR wavelengths.

122 2.2. The CIMEL CE318 sun photometer

123 The CE318-type sun photometers are manufactured by CIMEL Électronique (<http://www.cimel.fr>, last access: 15
124 May 2026). These are the standard radiometers used in AERONET (Giles et al., 2019; Holben et al., 1998). It is
125 also a filter wheel type radiometer operating at several sets of wavelengths, with 340 nm being the shortest and
126 1640 nm being the longest. The instrument has a FOV of 1.2 degrees, whereas the FWHM is 2, 4 and 25 nm for
127 340, 380 and 1640 nm channels, and for the rest of the wavelengths it is nominally 10 nm. The CIMEL instruments
128 typically record direct irradiance data in a triplet every 15 minutes, and measure almucantar radiance data in 30-
129 minute intervals (Toledano et al., 2018). These instruments are not thermostatically controlled, but the Si
130 photodiode temperature is measured along with the raw radiometric data, and a temperature compensation is
131 performed later during data processing (Giles et al., 2019).

132 2.3. The Precision Filter Radiometer (PFR)

133 The Precision Filter Radiometer, PFR (Wehrli, 2000) is also a filter type radiometer, used as standard the Global
134 Atmosphere Watch network (GAW). However, instead of using a rotating filter wheel to change the measurement
135 channel, it uses four fixed-wavelength filters centred at 368, 412, 501, and 862 nm. PFR instruments have a
136 FWHM of 3 to 5 nm with a FOV of 2 degrees. For every wavelength, a sequence of 10 measurements is done
137 with a temporal resolution of one minute. These instruments implement an active Peltier system to maintain a
138 temperature of 20 degrees Celsius (Karanikolas et al., 2024). Another difference with PREDE and CIMEL is that
139 the PFR only measures direct sun irradiance, not sky radiance.

140 2.3. Datasets

141 The QUATRAM campaigns addressed the homogeneity and compatibility of instruments across different
142 international networks. One of the primary objectives of the campaigns was to evaluate the accuracy of the on-
143 site calibration procedure employed in the PREDE-POM instruments. The campaigns were conducted in three
144 phases, from 2017 to 2021, at the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Centre
145 (PMOD/WRC) and the University of Rome, Sapienza, Italy. Two PREDE-POM instruments from the University
146 of Valencia (POM-UV) and the Institute of Atmospheric Sciences and Climate (ISAC-CNR) (POM-CNR)
147 participated in the campaigns. In addition, PFR and CE318 instruments also participated. In the present study, we
148 used the data from QUATRAM II and III campaigns held in Rome from May 2019 to September 2019, and
149 September 2021, respectively. The details of the PFR and CE318 data obtained during QUATRAM II and III can
150 be found in (Karanikolas et al., 2024). The details for the calibration data, obtained using traditional ILP and
151 calibration transfer during QUATRAM III, were described by (Campanelli et al., 2024).



152 Additionally, we utilized a 1-year dataset from January to December 2023 of a POM-02 radiometer from the
153 Burjassot Atmospheric Station (BASS) located near Valencia city (Spain) with a population of more than 1.5
154 million people in city and the metropolitan area. The Burjassot site includes remote sensing and in-situ
155 instrumentation within a coastal, near sea-level urban environment. More details about the site and long term
156 columnar and surface aerosol characteristics can be found elsewhere (Valdelomar et al., 2021; Garcia-Suñer et
157 al., 2024; Matos et al., 2025; Valdelomar et al., 2026). In this study, we also used simultaneous AERONET version
158 3 level 2 data from a collocated CE318 at this site, downloaded from the AERONET website
159 (https://aeronet.gsfc.nasa.gov/new_web/webtool_inv_v3.html, last access: 15 May 2026). The calibration and
160 technical testing of the CE318 instruments used at Burjassot site is routinely done by Red Ibérica de Medida de
161 Aerosoles (RIMA) at their Valladolid (Spain) premises.

162 3. Calibration method

163 Radiometric calibration is the fundamental requirement to convert the raw signal from the Sun photometer into a
164 meaningful parameter such as AOD. The SLP (Ångström, 1970; Shaw, 1983; Shaw et al., 1973) is the simplest
165 yet the most accurate calibration method used for Sun photometers. Besides, other calibration methods such as
166 calibration transfer, lamp calibration and the ILP method have been developed. ILP is the primary method used
167 for calibrating PREDE-POM instruments in SKYNET. In this section, we overview the ILP method, and present
168 the upgrades we implemented.

169 3.1 The Improved Langley Plot, ILP

170 The ILP calibration and inversion methods were first proposed by (Tanaka et al., 1986) and (Nakajima et al.,
171 1996) to establish an on-site calibration routine for ground-based radiometers, such as PREDE-POM instruments.
172 Later, it was formalised, and a standard procedure was developed by (Campanelli et al., 2004). An overview of
173 the ILP workflow is provided in Fig. 1.

174 Similar to the SLP method, in the ILP alternative we express the observed signal using the Beer-Lambert law in
175 Eq. (1):

$$176 \quad F = F_0 e^{-m(\tau_{ext}^{dir} + \tau_{o3} + \tau_g + \tau_{H2O} + \tau_{ray})} \quad (1)$$

$$177 \quad \ln F = \ln F_0 - m(\tau_{ext}^{dir} + \tau_{o3} + \tau_{ray} + \tau_{H2O}) \quad (2)$$

178 where F is the direct solar signal measured by the PREDE-POM instrument, m is the optical airmass defined by
179 $m = \frac{1}{\cos \theta}$ (where θ is the solar zenith angle), τ_{ext}^{dir} is the extinction AOD calculated using the direct sun data, τ_{o3}
180 is the ozone optical depth, τ_{ray} is the Rayleigh scattering optical depth due to molecular scattering, and τ_{H2O} is
181 the optical depth due to water vapour.

182 In the case of SLP, we write Eq. (2) in the form of a linear equation as shown in Eq. (3):

$$183 \quad y = a_{SL} + b_{SL}x \quad (3)$$

184 Where, $x=m$

$$185 \quad y = \ln F - m(\tau_{o3} + \tau_{ray} + \tau_{H2O}) \quad (4)$$



186 a_{SL} and b_{SL} are calculated as the intercept and the slope of the linear fit of Eq. (3). Finally, we calculate the
187 calibration value as the exponential of a_{SL} .

188 However, in the case of ILP, we rewrite Eq. (2) as follows;

$$189 \quad y = a_{IL} + b_{IL}x \quad (5)$$

190 Here, y remains the same as in SLP. However, unlike SLP, $x = m\tau_{sca}^{dif}$, and $b_{IL} = \frac{-1}{\omega}$, where ω is the SSA (defined

191 as $\frac{\tau_{sca}^{dif}}{\tau_{ext}^{dif}}$), τ_{ext}^{dif} and τ_{sca}^{dif} are aerosol extinction and scattering optical depth retrieved using the diffuse sky radiance

192 data. We obtain a_{IL} and b_{IL} as the intercept and slope by linear fitting of Eq. (5).

193 τ_{sca}^{dif} required in ILP method are obtained from the diffuse sky measurements via inversion procedure. First of all,
194 the diffuse sky measurements are normalized by the direct solar irradiance as:

$$195 \quad R(\theta) = \frac{E(\theta)}{F_m \Delta\Omega} = \omega \tau P(\theta) + q(\theta) \quad (6)$$

$$196 \quad R(\theta) = \beta(\theta) + q(\theta) \quad (7)$$

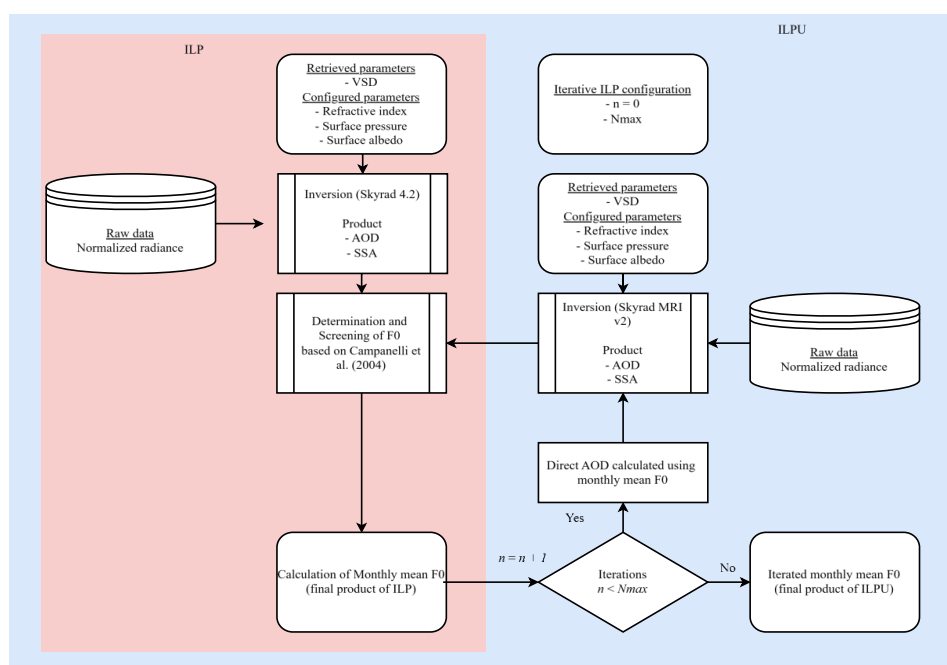
197 where R is the normalized radiance; P is the atmospheric phase function; q is the multiple scattering term. Notably
198 this normalization cancels the calibration constants out from the measurement due to the use of same sensor for
199 both measurements. However, we still need a calibration value for the solid viewing angle (SVA) $\Delta\Omega$, which we
200 obtain using the Solar Disk method proposed by (Boi et al., 1999) and described in (Campanelli et al., 2024). The
201 angular distribution of normalized radiance described in Eq. (6), thus contains information about aerosol
202 properties, such as volume size distribution, complex refractive index, and particle shape in addition to
203 atmospheric/surface conditions (i.e., atmospheric pressure, surface albedo, gas amount, etc). Within the inversion
204 process, aerosol characteristics are retrieved to reconstruct the measured quantities using the radiative transfer
205 model (forward model). For the ILP protocol, the aerosol volume size distribution is retrieved from diffuse sky
206 radiances measured at scattering angles up to 30 degrees. This is because in this angular range of the aureole
207 regions (up to 40 degrees), radiances are mainly sensitive to aerosol particle dispersion rather than to the complex
208 refractive index or the particle shape (Nakajima et al., 1996; Tanaka et al., 1986; Kaufman et al., 1994). Finally,
209 τ_{sca}^{dif} is calculated from the retrieved volume size distribution using precomputed scattering kernels.

210 This study used the latest Skyrad MRI v2 (Kudo et al., 2021) for the inversion procedure, replacing the Skyrad
211 v4.2 which has been used in the operational processing in the international SKYNET network for a long time
212 (Campanelli et al., 2024; Nakajima et al., 2020). Moreover, diffuse sky radiance measurements with a scattering
213 angle ranging from 4.5 degrees to 35 degrees is used in this study.

214 After the successful retrieval of the τ_{ext}^{dif} and τ_{sca}^{dif} , the retrieved data is filtered following the protocol described in
215 (Campanelli et al., 2004). Retrievals corresponding to the τ_{ext}^{dif} greater than 0.4, airmass (m) greater than 3, and
216 root mean square error between the simulated and observed sky radiance greater than 0.07 are rejected. Using the
217 remaining data, we do a least square fit following Eq. (5) to calculate the intercept a_{IL} . Thus, we calculate the
218 daily calibration value (F_0) using the intercept as $e^{a_{IL}}$. The daily calibration values are screened further using the
219 Chauvenet criterion and three-point moving average. In the end, if the number of calibration values left after
220 screening is greater than 3 and their coefficient of variation is less than 3 %, then the monthly mean calibration
221 value (F_{0_mean}) is obtained.



222



223

224 *Figure 1: Flowchart illustrating the inversion procedure and the calculation of ILP and ILPU calibration values.*
 225 *The left-hand side section (in pink) shows the ILP calibration procedure, whereas the right-hand side section (in*
 226 *blue) shows the ILPU calibration procedure.*

227 3.2 The iterative ILP method proposed in this study

228 Although the ILP method described in the previous section has been operatively used by the international
 229 SKYNET network for years, limitations still remain in the achievable accuracy from the reference calibration
 230 technique (i.e., SLP method at high altitude and calibration transfer). This study therefore explores refinements to
 231 the on-site calibration protocol through iterative application of the ILP method using the latest inversion code
 232 Skyrad MRI v2 (Kudo et al., 2021). The idea of using an iterative technique is based on the proposal already made
 233 by (Tonna et al., 1995). In their study, they first calculated the calibration value using the τ_{sca}^{dif} obtained from the
 234 inversion of only radiance data. Next, this calibration value is used to derive the τ_{ext}^{dir} from the direct irradiance
 235 data, which will serve as input for the second inversion. They reported that the results improved, but the suggestion
 236 was not implemented in their study. The main reason is that the improvement was not very significant compared
 237 to the required increase in computation time (i.e. the calibration value obtained was already within 1% compared
 238 to the calibration values obtained using SLP, a value considered good at that time). However, in the present study,
 239 the iterative approach works better thanks to the algorithm update. As explained by (Kudo et al., 2021), the
 240 retrieval of the aerosol optical parameters is optimised to the transmittance data rather than to the input direct
 241 extinction AOD. This allows the retrieved extinction and scattering AOD to adjust freely during the iteration



process. In contrast, in Skyrad v4.2 and earlier algorithms, the retrieved extinction and scattering AOD were closer to the input extinction AOD, and thus the iterations did not provide a significant improvement. In this study, we implemented an iterative method (from now on ILPU) that uses direct extinction AOD as input for the inversion, and updated the ILP inversion algorithm from Skyrad v4.2 to Skyrad MRI v2. The schematic flowchart of the new iterative technique is presented on the right-hand side of Fig. 1. The process begins by setting the Iteration index (n) to 0, for which the monthly mean calibration value is calculated using only the radiance data. The monthly mean calibration value obtained in this step as called as $F_{0_ILPU}^{(0)}$ works as an initial guess for next iteration, n=1. In the second step when n=1, the $F_{0_ILPU}^{(0)}$ is used to compute the direct AOD (τ_{ext}^{dir}), which is further used during the inversion in Skyrad MRI v2. After determining the scattering AOD using the Skyrad MRI v2, we repeat the process from the step 1 to compute the monthly mean calibration value. The process of iteration can be performed for multiple times, and the monthly mean calibration value obtained after every iteration is termed as $F_{0_ILPU}^{(n)}$. However, in this study, we performed only one iteration ($N_{max}=1$) because one iteration was found sufficient for and accurate calibration, as discussed in Sect. 4.1.

4. Results

This section describes the results using the calibration values from ILPU methodology. We begin by analysing the stability of the calculated calibration value across different iterations. Next, we discuss the differences in τ_{ext}^{dif} when using ILPU compared to the full inversion using Skyrad MRI v2 with the calibration values obtained earlier, in other words their consistency. We then compare the PREDE-POM's inversion extinction AOD with level 2 AERONET inversion extinction AOD (τ_{ext}^{dif}). Finally, we will present several comparisons of the PREDE-POM's direct extinction AOD (τ_{ext}^{dir}) with AERONET direct AOD and PFR direct AOD for data from the QUATRAM III campaign and the fixed site in Burjassot.

4.1 Stability and convergence of the calibration values

We conducted a simple experiment to check the convergence of the calibration values across different iterations. In this experiment, we utilised the data from QUATRAM III campaign, which covered the period 1-20 September 2021. The experiment included two rounds, namely round A and round B. ILPU calibration values ($F_{0A}^{(0)} = F_{0_ILPU}^{(0)}$) were first calculated at iteration index n=0, representing the lower baseline calibration values without iteration for round A. The upper baseline calibration values for round B were calculated by increasing the lower baseline calibration value by 3%, that is, $F_{0B}^{(0)} = 1.03 * F_{0A}^{(0)}$. The 3% perturbation is chosen arbitrarily, as it should not affect the final results in the convergence conditions. The ILPU calibration values were then calculated independently in both rounds in subsequent iterations until n = 6. The resulting calibration values across the six iterations were analysed to determine the convergence. Figure 2 and Table 1 represent the convergence of the calibration values after six iterations using ILPU. Blue solid line (F_{0A}) in Fig. 2 and the first seven rows of Table 1 show the calibration values from the round A. The red solid line (F_{0B}) in Fig. 2 and rows 7–13 of Table 1 corresponds to the round B. The dotted blue line ($F_{0_ILPU}^{(0)}$ or $F_{0A}^{(0)}$) represents the starting calibration value from the round A, whereas the dotted red line ($F_{0B}^{(0)}$) represents that from the round B. The black dotted line (F_{0_ILP}) is the calibration value calculated with older ILP using Skyrad v4.2.



We confirm that regardless of the starting point, the calibration values for all wavelengths (red and blue solid lines in the six panels of Fig. 2) ultimately converge to the same point or within a small range. For wavelengths above 400 nm, the discrepancy of 3 % in the starting calibration values in both the rounds reduced to less than 0.4 % in single iteration, whereas, the discrepancy reduced to below 1.4 % in single iteration for 400 nm. Subsequent iterations caused refinement thereafter reducing the discrepancy to 0 or below 0.25 % for wavelengths above 340 nm. The convergence of the 340 nm channel is relatively slow compared to the other channels. It can be observed that the rate of change in the calibration value decreases when the iteration number increases, and the discrepancy at every iteration reduced, with final discrepancy at the end of sixth iteration remained below 0.62 %. Concurrently, both calibration (F_{0A} and F_{0B}) values are progressing in the identical direction. This convergence test suggests that the calibration values across successive iterations are stable. Therefore, the final calibration value can be determined in one iteration for wavelengths greater than 500 nm. Wavelengths shorter than 500 nm require 2 to 3 iterations, irrespective of the starting point. It is worth noting that obtaining the monthly calibration values for each iteration requires several hours of computing time on a standard desktop computer so only one iteration will be used for the rest of the study. We consider the substantial improvement in the calibration values obtained for all wavelengths outweighs the slightly smaller improvement observed for 340 nm.

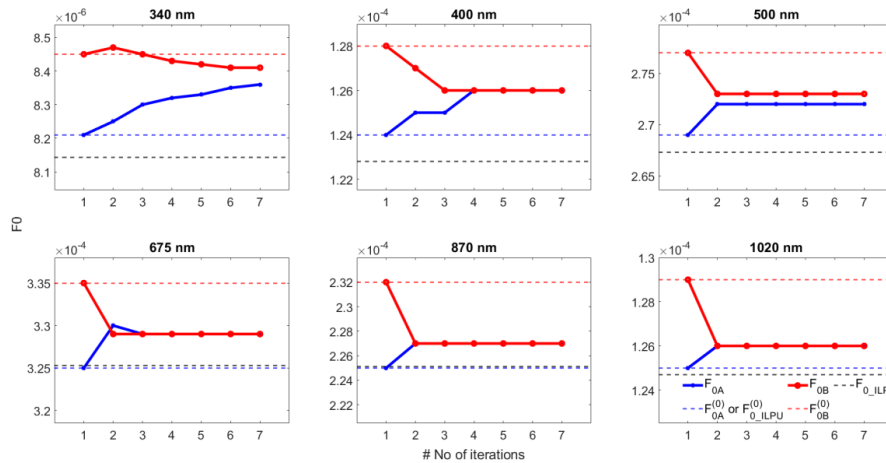


Figure 2: Convergence of ILPU calibration values across six iterations across six wavelengths. Y axis indicates the calibration value. X axis indicates the number of iterations.

Table 1: - Calibration values obtained from six different iterations during two rounds of ILPU.

Iterations index (n)	340 nm	400 nm	500 nm	675 nm	870 nm	1020 nm
(Round A)						
0 ($F_{0A}^{(0)}$)	8.207E-06	1.244E-04	2.690E-04	3.250E-04	2.252E-04	1.251E-04
1 ($F_{0A}^{(1)}$)	8.248E-06	1.251E-04	2.721E-04	3.295E-04	2.272E-04	1.258E-04
2 ($F_{0A}^{(2)}$)	8.297E-06	1.253E-04	2.718E-04	3.290E-04	2.272E-04	1.258E-04
3 ($F_{0A}^{(3)}$)	8.320E-06	1.255E-04	2.721E-04	3.291E-04	2.272E-04	1.258E-04



4 ($F_{0A}^{(4)}$)	8.334E-06	1.257E-04	2.722E-04	3.291E-04	2.272E-04	1.258E-04
5 ($F_{0A}^{(5)}$)	8.349E-06	1.258E-04	2.723E-04	3.291E-04	2.272E-04	1.258E-04
6 ($F_{0A}^{(6)}$)	8.358E-06	1.258E-04	2.723E-04	3.291E-04	2.271E-04	1.258E-04
(Round B)						
0 ($F_{0B}^{(0)}$)	8.453E-06	1.281E-04	2.771E-04	3.348E-04	2.320E-04	1.289E-04
1 ($F_{0A}^{(1)}$)	8.473E-06	1.268E-04	2.731E-04	3.291E-04	2.268E-04	1.256E-04
2 ($F_{0A}^{(2)}$)	8.452E-06	1.264E-04	2.727E-04	3.292E-04	2.268E-04	1.258E-04
3 ($F_{0A}^{(3)}$)	8.434E-06	1.263E-04	2.727E-04	3.291E-04	2.267E-04	1.258E-04
4 ($F_{0A}^{(4)}$)	8.424E-06	1.262E-04	2.726E-04	3.291E-04	2.267E-04	1.258E-04
5 ($F_{0A}^{(5)}$)	8.414E-06	1.262E-04	2.725E-04	3.291E-04	2.267E-04	1.258E-04
6 ($F_{0A}^{(6)}$)	8.410E-06	1.261E-04	2.725E-04	3.291E-04	2.271E-04	1.258E-04

Figure 2 also highlights the differences in the $F_{0,ILP}$, ILPU with $n=1$ ($F_{0,ILPU}^{(1)}$) and ILPU for $n=0$ ($F_{0,ILPU}^{(0)}$). The relative differences among the calibration values, $F_{0,ILP}$, $F_{0,ILPU}^{(1)}$ and $F_{0,ILPU}^{(0)}$ are summarized in Table 2. The first row of Table 2 presents the differences between $F_{0,ILP}$ and $F_{0,ILPU}^{(0)}$, which ranges from -0.6% to -0.8% for wavelengths below 675 nm, and remaining below 0.35% for wavelengths above 500 nm. The second row shows the differences between $F_{0,ILPU}^{(0)}$ and $F_{0,ILPU}^{(1)}$. The behaviour is notably different across wavelengths: for 500–870 nm, the differences are significantly larger, ranging from -0.88% to -1.38% , whereas for the remaining three wavelengths they are confined to a narrower range of -0.50% to -0.56% . The third row of the Table 2 presents the difference between $F_{0,ILP}$ and $F_{0,ILPU}^{(1)}$. In this case, the differences are consistently larger across all wavelengths, reflecting the cumulative effect of the differences observed in the first and the second rows, since $F_{0,ILP}$ is lower than $F_{0,ILPU}^{(0)}$ and $F_{0,ILPU}^{(1)}$ is greater than $F_{0,ILPU}^{(0)}$. Overall, the results show that the application of ILPU leads to systematic and cumulative differences compared to ILP, especially when iterations are included. Although the differences may seem small, they help us reduce the direct extinction AOD underestimation typically shown by the ILP technique leading to more precise results.

Table 2: Percentage difference in the ILP ($F_{0,ILP}$) and ILPU calibration values with $n=0$ ($F_{0,ILPU}^{(0)}$) and $n=1$ ($F_{0,ILPU}^{(1)}$).

Difference (in %)	340 nm	400 nm	500 nm	675 nm	870 nm	1020 nm	
$(F_{0,ILP} - F_{0,ILPU}^{(0)})/F_{0,ILP} * 100$	-0.8	-1.3	-0.64	0.09	-0.04	-0.32	POM-CNR
$(F_{0,ILPU}^{(0)} - F_{0,ILPU}^{(1)})/F_{0,ILPU}^{(0)} * 100$	-0.5	-0.56	-1.15	-1.38	-0.88	-0.56	
$(F_{0,ILP} - F_{0,ILPU}^{(1)})/F_{0,ILP} * 100$	-1.28	-1.87	-1.79	-1.29	-0.93	-0.88	



313

314 4.2 Consistency of the extinction AOD using the almucantar radiance data (τ_{ext}^{dif}) in the ILPU method

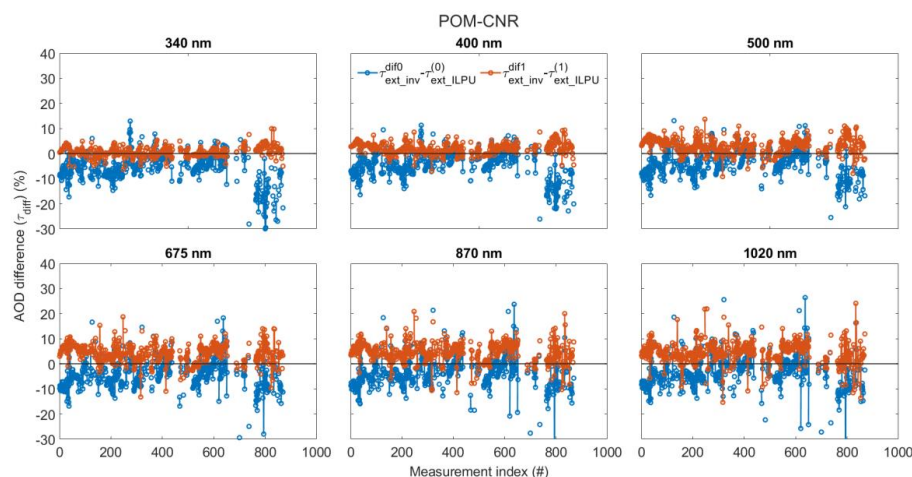
315 After successfully demonstrating the stability of the ILPU calibration values at multiple iteration, we decided to
 316 check the consistency of the τ_{ext}^{dif} retrieved during the ILPU method. In this case, the consistency is defined as the
 317 difference between the τ_{ext}^{dif} retrieved during the inversion while performing ILPU and the τ_{ext}^{dif} retrieved with the
 318 full inversion using the ILPU calibration values. The inversion algorithm yields slightly different values of τ_{ext}^{dif}
 319 when run with ILPU compared to the full retrieval process. The reason is that ILPU uses data at scattering angles
 320 from 4.5 to 35 degrees, whereas the full retrieval angles range from 2.5 to 180 degrees. Moreover, ILPU uses
 321 fixed refractive indexes, while the full retrieval inversion uses dynamic ones. However, since both the inversions
 322 are performed in the identical environment, the difference between the two AODs must be minimum. The
 323 objective of this exercise is to demonstrate the advantage of using the iteration in calculating the calibration value,
 324 ultimately leading to the improved retrieval of the inversion AOD, and hence achieving a better consistency.
 325 The exercise is performed in two rounds using the data from POM-CNR and POM-UV during the QUATRAM
 326 III campaign. In the first round, we run the ILPU method and obtain the calibration values, $F_{0,ILPU}^{(0)}$, using only the
 327 almucantar radiance without any iteration ($n=0$). We termed the extinction AOD obtained in this process $\tau_{ext,ILPU}^{dif0}$.
 328 Later, the $F_{0,ILPU}^{(0)}$ from the previous process are used to calculate the extinction AOD (τ_{ext}^{dir}) from direct Sun data
 329 and serve as input in Skyrad MRI v2 to retrieve extinction AOD from almucantar radiance data in full inversion,
 330 termed $\tau_{ext,inv}^{dif0}$. In a second round, we repeat the same steps, but applying the ILPU technique with one iteration
 331 ($n=1$), as shown on the right-hand side of Fig. 1. We will refer to the extinction AOD obtained during ILPU and
 332 full inversion as $\tau_{ext,ILPU}^{dif1}$ and $\tau_{ext,inv}^{dif1}$, respectively. Finally, we calculated the difference between the two AOD
 333 ($\tau_{ext,inv}^{dif0} - \tau_{ext,ILPU}^{dif0}$ and $\tau_{ext,inv}^{dif1} - \tau_{ext,ILPU}^{dif1}$), and the percentage difference as follows.

$$334 \quad \tau_{diff} = \frac{\text{Extinction AOD after full inversion} - \text{Extinction AOD used during ILPU}}{\text{Extinction AOD after full inversion}} \times 100 \quad (8)$$

335 The comparison of the τ_{diff} is shown in Fig. 3 and 4. The corresponding standard deviations of the differences
 336 are presented in Table 3:

337 *Table 3: Standard deviations of the τ_{diff} in the two rounds of ILPU and full inversion during QUATRAM III*
 338 *campaign for UV and CNR instruments.*

	340 nm	400 nm	500 nm	675 nm	870 nm	1020 nm	
Std (in %) – Round one	6.1	5.5	5.3	5.6	6.3	6.8	POM-
Std (in %) – Round two	1.8	2.1	2.9	3.6	3.8	4.3	CNR
Std (in %) – Round one	7.2	6.8	6.1	6.5	7.7	8.7	POM-
Std (in %) – Round two	1.8	1.9	2.6	3.5	4.1	4.7	UV

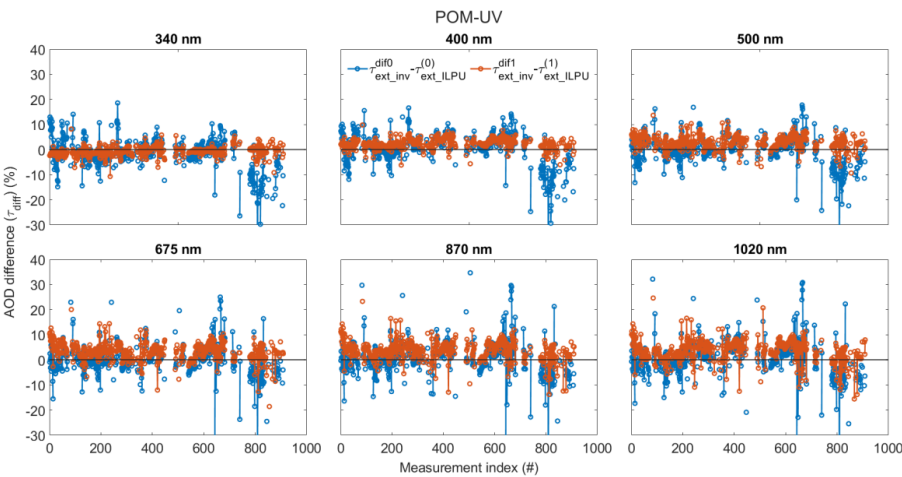


339

340 *Figure 3: Comparison of τ_{diff} in the two rounds of ILPU and full inversion during QUATRAM III campaign for*
341 *CNR instrument.*

342 Figures 3 and 4 represent the consistency of τ_{ext}^{dif} for both instruments, CNR and UV. The y-axis shows the
343 difference between the two AOD τ_{diff} (in %). The x-axis indicates the measurement index. Blue and red lines
344 show τ_{diff} during the first and second rounds of ILPU and full inversion, and the black line represents 0 %
345 difference. We observe that the differences are more pronounced with the CNR instrument compared to the UV,
346 but this could be due to instrument-specific effects.

347 The analysis of the standard deviations (std) of τ_{diff} for UV and CNR instruments during the two rounds (Table
348 3) clearly shows that the extinction AOD produced with ILPU is much more consistent with the full inversion
349 when ILPU is used with an iteration ($n=1$), especially for smaller wavelengths. At the same time, the differences
350 between the two AOD types are strikingly similar for both instruments. The std ranges from 5.3 to 6.8 % (6.1 to
351 8.7 %) for CNR (UV) instruments in the first round. But for the second round these values lower, so the std now
352 ranges from 1.8 % to 4.3 % (1.8 % to 4.7 %) for CNR (UV)



353
354 *Figure 4: Comparison of τ_{diff} in the two rounds of ILPU and full inversion during QUATRAM III campaign*
355 *for UV instrument.*

356 **4.3 Comparison of different calibration values during QUATRAM III campaign**

357 To evaluate the performance of the ILPU method, we compared its calibration values with the ILP and transfer
358 calibration values obtained from CIMEL_1270 and PFR during the QUATRAM III campaign. Tables 4 and 5
359 summarize the results for the POM-CNR and POM-UV instruments. The ILP and transfer calibration values are
360 taken from (Campanelli et al., 2024), whereas the ILPU values were calculated in this study

361 *Table 4: - Percentage differences between ILP, CIMEL_1270 transfer, and PFR transfer calibration values with*
362 *ILP as reference for the POM-CNR and POM-UV instruments during the QUATRAM III campaign.*

Method	340 nm	400 nm	500 nm	675 nm	870 nm	1020 nm
POM-CNR						
PFR (transfer)	-	-	-2.53	-	-2.31	-
CE #1270 (transfer)	-3.91	-	-3.13	-1.29	-1.33	0.80
POM-UV						
PFR (transfer)	-	-	-3.16	-	-2.07	-
CE #1270 (transfer)	-5.08	-	-3.16	-1.21	-1.94	2.39



Table 5: - Percentage differences between ILPU, CIMEL_1270 transfer, and PFR transfer calibration values with ILPU as reference for the POM-CNR and POM-UV instruments during the QUATRAM III campaign.

Method	340 nm	400 nm	500 nm	675 nm	870 nm	1020 nm
POM-CNR						
PFR (transfer)	-	-	-1.21	-	-1.32	-
CE #1270 (transfer)	-2.96	-	-1.77	-0.45	-0.35	1.45
POM-UV						
PFR (transfer)	-	-	-1.87	-	-1.58	-
CE #1270 (transfer)	-3.94	-	-1.87	-0.55	-1.45	2.94

The results in Table 4 and Table 5 show that the ILPU calibration systematically reduces the differences with respect to the transfer calibrations obtained from CIMEL and PFR compared with the standard ILP method. The largest improvements are observed at shorter wavelengths, particularly at 340 and 500 nm, whereas smaller changes are found at longer wavelengths. The ILPU calibration reduces discrepancies by up to ~1.3 % for both POM-UV and CNR instruments for all the wavelengths except 1020 nm. The discrepancy increases in the case of 1020 nm for both POM-UV and CNR instruments, which could be associated to temperature effects. Since the temperature sensitivity is unique to every instrument (Uchiyama et al., 2018), the larger differences shown here could be due to the temperature effect of one or both the instruments. Nevertheless, a more detailed study is required to identify the exact source of this discrepancy, as the temperature effect cannot be corrected for these specific units.

So far, we demonstrated that the proposed ILPU technique produces a stable calibration value using an iterative approach. Next, we presented the consistency between the extinction AOD obtained during the ILPU process and the extinction AOD obtained in the full inversion retrieval using the almucantar radiance data. The results also indicate an improvement in the calibration values obtained by the new method by comparing with calibrations transferred from PFR and CIMEL sun-photometers during the QUATRAM III campaign.

Our next step will be to assess the improvement in the extinction AOD values when compared to PFR-GAW and AERONET networks. For this, we will present the comparison for direct and retrieved AOD from PREDE-POM, AERONET, and PFR during the QUATRAM II and III campaigns. Finally, we will compare the direct extinction AOD from PREDE-POM and AERONET at the permanent site of Burjassot in Valencia, Spain.

4.4 Comparison of inversion AOD with AERONET during QUATRAM III campaign

We used both ILP and ILPU calibration values to process the QUATRAM III radiance data using Skyrad MRI v2 to retrieve extinction AOD τ_{ext}^{dir} for both POM-CNR and POM-UV. We then compared it with the level 2



inversion extinction AOD from AERONET. We only selected simultaneous data, defined as data points from PREDE and AERONET within a 10-minute time interval. Table 6 summarizes the statistical comparison between the ILP and ILPU calibration methods. The RMSD values remain within the nominal combined uncertainty of 0.02 at all wavelengths. Table 6 also shows a consistent reduction in both RMSD and MBD when the ILPU calibration is applied to the POM-CNR and POM-UV instruments, although the improvements are relatively small. In all cases, R^2 remains very high (0.98–0.99), indicating excellent agreement between AERONET and PREDE retrievals. Overall, these results suggest that the effect of the calibration method on inversion-derived AOD is limited. The impact becomes more evident for direct extinction AOD, as discussed in the next section.

Table 6. Root mean standard deviation (RMSD), mean bias deviation (MBD) and coefficient of determination (R^2) at the three common wavelengths of 675, 870 and 1020 nm for POM-CNR and POM-UV instruments for ILP and ILPU calibration methods

Instrument	RMSD			MBD (AERONET- PREDE)			R^2			
	675 nm	870 nm	1020 nm	675 nm	870 nm	1020 nm	675 nm	870 nm	1020 nm	
POM-CNR	0.0054	0.0037	0.0031	0.0042	0.0029	0.0025	0.99	0.99	0.99	ILP
POM-CNR	0.0035	0.0024	0.0019	-0.0002	0.0000	0.0003	0.99	0.99	0.99	ILPU
POM-UV	0.0045	0.0033	0.0029	0.0015	0.0009	0.0008	0.99	0.98	0.98	ILP
POM-UV	0.0044	0.0033	0.0028	-0.0007	-0.0006	-0.0003	0.99	0.98	0.98	ILPU

4.5 Comparison of POM-CNR direct AOD with PFR direct AOD during QUATRAM II and III campaign

After comparing the inversion extinction AOD in the previous section, we will now show the comparison of the POM-CNR direct extinction AOD using ILPU and ILP method with PFR direct extinction AOD during the QUATRAM II and III campaigns. This comparison is of particular interest because Karanikolas et al., (2024) reported that underestimation of the PREDE's direct extinction AOD. ILP calibration values were pointed out as one of the factors of the underestimation. To ensure consistency in the data and minimise any potential errors, the direct AOD products from both PFR and POM-CNR radiometers were obtained from Karanikolas et al., (2024). Simultaneously, we reprocessed the POM-CNR data using the SUNRAD (Estellés et al., 2012) to calculate direct extinction AOD τ_{ext}^{dir} from the direct sun measurements for POM-CNR instruments during the QUATRAM II and III campaigns, using ILPU calibrations.



To assess the improvement in direct AOD when using the ILPU method, we repeated the comparison done by (Karanikolas et al., 2024). Fig 5 shows the box plots of the direct extinction AOD differences between POM-CNR and PFR during the QUATRAM II and III campaigns using ILP and ILPU calibration values. Table 7 summarizes the percentage of points fulfilling the WMO acceptance criteria, defined as $\pm 0.005 + 0.01/m$, where m is the air mass. The WMO limits define the acceptable differences between field and reference instruments, ensuring inter-instrument consistency of AOD measurements.

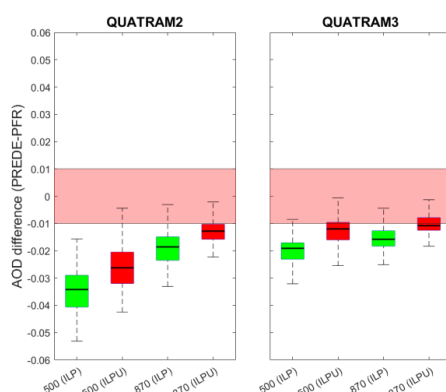


Figure 5: Box plot of the direct extinction AOD differences for POM CNR and PFR in QUATRAM II and III campaigns at 500 and 870 nm. The WMO acceptance criteria is shown in pink; the thick black line represents the median.

Figure 5 displays box plots of the direct extinction AOD differences between POM-CNR and PFR during the QUATRAM II and III campaigns. The green boxes represent the differences computed using the dataset published by (Karanikolas et al., 2024), processed using ILP calibration values, whereas the red boxes represent AOD obtained using the ILPU calibration values. The pink band represents the median difference at ± 0.01 , and the thick black line within each box represents the median difference. The Y-axis denotes the AOD differences from the ILP and ILPU calibration values. At 500 nm, the ILP results for QUATRAM II show a median difference well below -0.01, with most values lying outside the ± 0.01 range. A similar pattern is observed in QUATRAM III, although a small number of points fall within the ± 0.01 band. Overall, the median differences remain below -0.01, confirming the underestimation of ILP calibration reported by (Karanikolas et al., 2024). The agreement at 870 nm is slightly better, but the differences are still larger than desirable. In both campaigns, only a few points fall within the ± 0.01 range, and the median difference remains below -0.01.

When comparing the ILPU calibration method with ILP, we notice an increase in the number of points within the WMO limits, for both 500 and 870 nm. Table 7 summarizes these results, with the left column showing ILP percentages, and the right column showing ILPU results. Under ILP, a small fraction of points falls within the WMO limits at 500 nm, while only 11.7 % are within the limits at 870 nm during QUATRAM II. Slightly higher values are observed in QUATRAM III, reaching 2.3 % and 14.7 %, respectively. With ILPU, the agreement improves substantially, particularly at 870 nm, where the fraction of points within the limits increases by a factor



of about 3.5, while at 500 nm it rises from nearly zero to 2.5 %. Overall, QUATRAM III shows the larger improvement, with increases of more than 15-fold at 500 nm and almost fourfold at 870 nm. In terms of central tendency, the median difference remains outside the ± 0.01 band but shifts closer to -0.01 with ILPU. The improvement is more evident at 870 nm where the median difference approaches -0.01 in QUATRAM II and nearly reaches it in QUATRAM III.

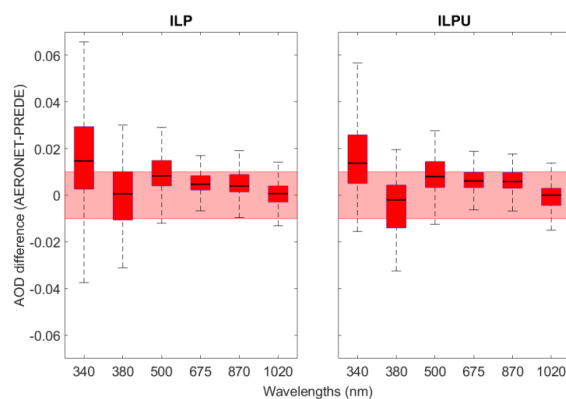
Table 7: - The percentage of AOD differences between POM-CNR and PFR within the WMO limits for both QUATRAM campaigns.

Campaign	Year		No of data points	Points within WMO limit (%) (ILP)		Points within WMO limit (%) (ILPU)	
				500 nm	870 nm	500 nm	870 nm
QUATRAM II	2019	5 months	3806	0	11.7	2.5	41
QUATRAM III	2021	1 month	1221	2.3	14.7	43.5	58.5

4.6 Comparison of PREDE direct AOD with AERONET direct AOD at Burjassot site

In the previous section, we presented the results comparing direct extinction AOD between PFR and POM-CNR during the QUATRAM II and III campaigns. Although the results showed improvements, the limited duration of the comparison motivated the analysis of a longer-term dataset from a permanent site in Burjassot (València) operating within both AERONET and SKYNET networks, and maintained by our research group. The database consists of one year of direct sunlight data from January to December 2023. Both ILP and ILPU calibrations were used in the SUNRAD algorithm (Estellés et al., 2012) to get the direct AOD, with cloud-screening and at the common PREDE and CIMEL wavelengths. A maximum time difference of 10 seconds was allowed to minimise temporal variability in direct extinction AOD.

The analysis of the extended dataset reveals a somewhat different behaviour compared with the campaign results (Figure 6 vs. Figure 5). Now, the median difference for all channels except 340 nm already fall within the ± 0.01 band (in pink), and the improvement between ILP and ILPU is less marked. However, a notable improvement is still observed at shorter wavelengths, particularly at 340 and 380 nm, where the fraction of points within the WMO limits increases by more than 10 % (14 % and 13 %, respectively). For the remaining channels, the number of points within the WMO limits remains largely unchanged, with variations below 6 %.



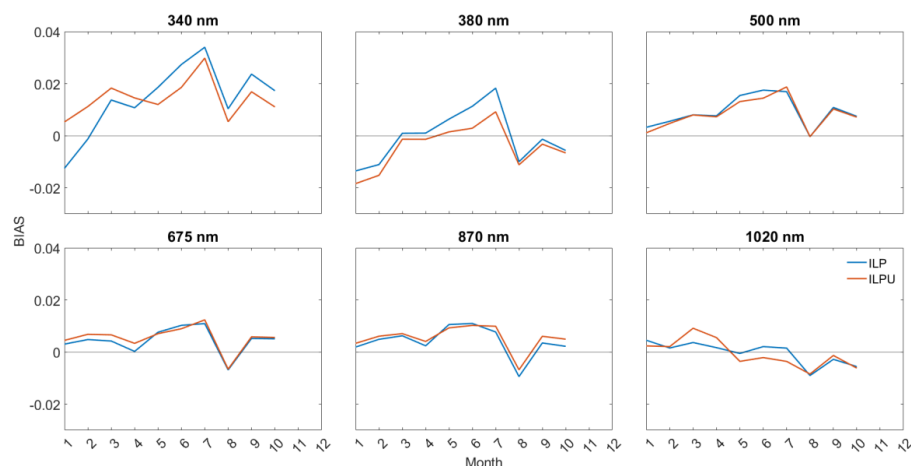
459

460 *Figure 6 Box plot of the direct extinction AOD differences for PREDE-POM and AERONET in the Burjassot site*
 461 *(València) for ILP (left) and ILPU (right). The WMO acceptance criteria is shown in pink; the thick black line*
 462 *represents the median.*

463 *Table 8: - The percentage of AOD differences within the WMO limits at common POM and CIMEL wavelengths*

Wavelength	No of data points	Points within WMO limit (%) (ILP)	Points within WMO limit (%) (ILPU)
340	788	26	40
380	788	51	64
500	788	64	66
675	788	88	82
870	788	91	89
1020	787	90	89

464

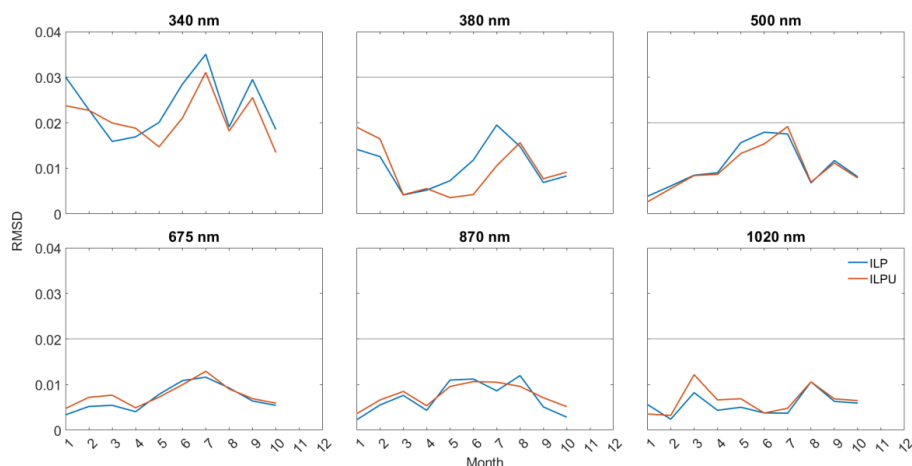


465

466 *Figure 7 Monthly mean bias deviation (MBD) in Burjassot site (Valencia) at six common channels: 340, 380,*
 467 *500, 675, 870 and 1020 nm. The blue line corresponds to ILP and the red line to ILPU calibration. The black line*
 468 *shows zero bias and the reported uncertainty in each channel. X axis indicates the months in 2023; Y axis indicates*
 469 *the monthly RMSD.*

470 To examine the results in greater details, we plotted the monthly RMSD (Fig. 7) and MBD (Fig. 8) and observed
 471 a similar behaviour. The longer wavelengths (500 nm and above) display almost identical patterns and values,
 472 with minimal bias in both cases. For shorter wavelengths, some differences appear, with bias being slightly less
 473 systematic at 340 and 380 nm. The monthly RMSD remains below the combined nominal uncertainty for
 474 wavelengths greater than 380 nm across all months. Below 500 nm, the RMSD stays under the combined nominal
 475 uncertainty in all months except July, where it exceeds 0.03 in both calibration methods. Although smaller, the
 476 improvement also exists, as the RMSD decreases from 0.034 to 0.031.

477 A seasonal pattern also emerges in both Fig. 7 and 8, with MBD and RMSD increasing from winter to summer
 478 (January to July-August). This trend is more pronounced at shorter wavelengths, particularly below 675 nm. In
 479 contrast, the pattern becomes weak or absent at longer wavelength. This trend correlates well with frequent long-
 480 range dust transport in the Valencia region from spring to summer (Estellés et al., 2007; Garcia-Suñer et al., 2024).
 481 However, further research is required to better understand site and seasonal effects on the relative improvement
 482 of the proposed method.



483

484 *Figure 8 Monthly RMSD in Burjassot. Same convention as Fig. 7*

485 5. Summary and conclusions

486 We evaluated an updated and improved version of the ILP calibration method adopted by the international network
 487 SKYNET with official instruments (PREDE-POM sky radiometers). The improved version, called ILPU, adopts
 488 the latest inversion algorithm (Skyrad MRI v2) instead of the legacy algorithm Skyrad 4.2, and an iterative method
 489 to calculate the calibration value at six wavelengths namely, 340, 380, 400, 500, 675, 870 and 1020 nm.

490 Using the ILPU method, we first demonstrated the stability of the calibration values by performing a convergence
 491 test over six iterations. The calibration values were computed using two different initialization strategies. In the
 492 first strategy (round A), the initial calibration values were obtained using radiance data only. In the second strategy
 493 (round B), the initial values were defined by applying a 3 % increment to the round A starting calibration value.
 494 The results show that the calibration values converged either to the same points or within a narrow range,
 495 regardless of the starting point. They converged rapidly for wavelengths above 400 nm. the discrepancy of 3 % in
 496 the initial calibration values reduced to less than 0.4 % in single iteration, whereas it reduced to either 0 or less
 497 than 0.25 % in later 5 iterations. At 400 nm, the single iterations reduced the discrepancy to less than 1.4 %, while
 498 reducing it to less than 0.25 % in rest of the iterations. The convergence was relatively slow at 340 nm, however,
 499 the discrepancy at every iteration reduced and the final discrepancy at the end of sixth iteration remained below
 500 0.62 %. This convergence test showed that the calibration values obtained through the ILPU method were stable
 501 and consistent. However, since a single iteration requires several hours of computation and further iterations have
 502 little to negligible impact on the results, the remaining analysis was limited to one iteration.

503 After the convergence test, we evaluated the consistency between two extinction AOD datasets: one obtained
 504 from full inversion and another from the ILPU inversion using restricted scattering angles. This analysis was
 505 performed in two rounds to assess the effect of iteration. In the first round, ILPU was applied without iteration,
 506 whereas in the second round one iteration was included.

507 The results show that, in the first round, the standard deviation of the differences between both AOD products
 508 ranged from 5.3 % to 6.8 % for the POM-CNR instrument and from 6.1 % to 8.7 % for the POM-UV instrument.



509 In contrast, after one iteration these values decreased to 1.8–4.3 % and 1.8–4.7 %, respectively. This indicates that
510 the ILPU retrieval becomes significantly more consistent with the full-inversion AOD when one iteration is
511 applied, particularly at shorter wavelengths.

512 We then compared the ILP, ILPU and transfer calibration from PFR and CIMEL (instrument no. 1270) for both
513 POM-UV and CNR during QUATRAM III campaign. The ILP and transfer calibration values were obtained
514 from (Campanelli et al., 2024). The discrepancies between the ILPU and transfer calibration were by up to 1.3 %
515 lower as compared to the discrepancy between ILP and transfer calibration.

516 In the next step, the PREDE inversion extinction AOD was compared to the level 2 AERONET inversion
517 extinction AOD during the QUATRAM III campaign for both POM-UV and CNR instruments. The PREDE-
518 POM radiance data was processed using both ILP and ILPU calibration values, to check the effect of calibration
519 value difference in the inversion extinction AOD. The root mean standard deviation (RMSD), and mean bias
520 deviation (MBD) were calculated for the analysis. The results showed that although the RMSD decreased for the
521 ILPU calibration value, it remained below 0.0055 for both POM-UV and CNR instruments at 675, 870, and 1020
522 nm, regardless of the calibration method. MBD shows a reduction when using ILPU for both instruments. For the
523 POM-UV instrument, values range from 0.0008 to 0.0015 (ILP) and from –0.0003 to 0.0 (ILPU). For POM-CNR,
524 values range from 0.0025 to 0.0042 (ILP) and from –0.0007 to 0.0003 (ILPU), across the 675–1020 nm range.

525 Finally, the coefficient of determination (R^2) was found to be 0.98–0.99 for both ILP and ILPU across all three
526 wavelengths. Overall, this indicates a very good agreement between PREDE and AERONET data, and suggests
527 that the effect of the calibration method on the retrieved extinction AOD is minimal.

528 The effect of the calibration method is more evident in the direct AOD comparisons, as shown in the POM-CNR
529 and PFR analysis during the QUATRAM III campaign and in the PREDE–AERONET comparison at Burjassot.

530 During QUATRAM II and III campaigns, the analysis of (Karanikolas et al., 2024) was repeated using ILPU
531 calibration values. The result revealed reduction in median differences in direct AOD indicating the improvement
532 in calculation of the direct AOD. This is accompanied by a significant increase in the number of points within the
533 WMO limits. In QUATRAM II, the fraction of points within the limits increases from nearly 0 % and 11.7 %
534 (ILP) to 2.5 % and 41 % (ILPU), at 500 and 870 nm respectively. In QUATRAM III, it increases from 2.3 % and
535 14.7 % (ILP) to 43.5 % and 58.5 % (ILPU) at the same wavelengths.

536 A long-term comparison was conducted in the case of Burjassot between PREDE-POM direct AOD and
537 AERONET Level 2 direct AOD for the year 2023. The mean direct extinction AOD difference remained within
538 the 0.01 limit at all wavelengths from 380 to 1020 nm, except at 340 nm. Monthly MBD and monthly RMSD
539 were also analysed, showing a similar pattern for both calibrations. RMSD was already within the reported
540 uncertainty at all wavelengths except for 340 nm in July. In this case, a slight improvement was observed, with
541 RMSD decreasing from 0.034 to 0.031 after applying the ILPU method. The number of points within the WMO
542 limits was also evaluated, showing a substantial increase at shorter wavelengths. In particular, the fraction of
543 points increased by more than 10 % at both 340 and 380 nm, whereas changes at the remaining wavelengths were
544 negligible. Therefore, at the Burjassot site, the median ILP differences were already close to the combined
545 uncertainty, and the improvement obtained with ILPU was consequently limited but still present.

546 In conclusion, this study demonstrates that updating the ILP to ILPU, by using the latest Skyrad MRI v2 algorithm
547 and introducing an iterative procedure, improves the calibration values. Although the improvement is observed at
548 all wavelengths, it is more pronounced at shorter wavelengths, particularly below 500 nm.



In future work, an alternative retrieval algorithm such as GRASP will be used to determine the calibration values using the new proposed ILPU method. This will help improve the calibration robustness, and identify and remove potential algorithm-based biases. Additionally, this method will also be tested at different sites, including both urban and rural environments, in order to evaluate its performance under a range of atmospheric conditions.

Code availability

The FORTRAN and Python code for calculating the calibration value is available from the corresponding author upon reasonable request. The SKYRAD and SUNRAD packages used for processing the data are maintained and developed by its respective authors. They are available upon a request to the developers.

Data availability

AERONET processed data are available at AERONET's website (<https://aeronet.gsfc.nasa.gov>, last access: 15 May 2026). The raw data of PREDE, CIMEL and PFR from QUATRAM campaigns and Burjassot will be made available on request.

Author contributions

GK: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **MM:** Data curation, Formal analysis, Methodology, Software, Writing – review & editing. **MC:** Formal analysis, Software, Writing – review. **MGS:** Formal analysis, Software. **RK:** Conceptualization, Formal analysis, Software, Writing – review. **NK:** Data curation, Writing-review. **RP:** Funding acquisition, Writing – review & editing. **VE:** Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Competing interests

The authors have no competing interests to declare.

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