Reply to report of reviewer #1 "Evaluating parallax and shadow correction methods for global horizontal irradiance retrievals from Meteosat SEVIRI by Wiltink et. al."

bold italic font = reviewer's comment
regular font = authors' reply
red regular font = original text in the manuscript
blue regular font = newly added or updated text in the manuscript

---

In this paper, the authors validate two corrections to satellite-based ground radiation retrievals using ground measurements: parallax correction and shadow correction. This is more involved than it looks at first glance and the paper contains some results that many might overlook. It presents some evidence that the parallax error and shadow error partially cancel out each other for geostationary-based radiation measurements, and that the combined error may therefore increase if only parallax correction is applied. The paper also shows that results improve when using a value smaller than the retrieved CTH, at least in some cloud regimes. These result should be stressed more clearly, including in the abstract. The science in this paper is good, but some conclusions should be presented more clearly. I have just one significant worry on the validation of the empirical collocation shift correction. Below is a list of suggestions before this paper can be accepted with minor revisions.

We thank the reviewer for the constructive feedback. Valid points were raised, which we addressed to further improve the quality of the manuscript. Please find our response below.

We tried to present the main findings more clearly in the manuscript and have made the following adjustments, starting with the conclusions Section:

Updates in conclusions:

We made the following adjustments to the conclusions Section:

- A paragraph has been added where the improvements of the different corrections w.r.t. the uncorrected retrieval are mentioned. Here, it is also more clearly stated that reducing H_c can further improve the accuracy of retrievals:
  Page 22, line 499: In general, GHI is retrieved most accurately when the time step optimal shift is performed, followed by the combined geometric shift. Compared to the uncorrected retrieval, the RMSE is reduced by 15.6 W m^{-2} (14.5 %) and 11.7 W m^{-2} (10.8 %) respectively. With the parallax-only or daily optimal shift correction a smaller improvement in accuracy is obtained because these correction methods do not account for diurnal variations in the cloud shadow position. Performing only a cloud shadow correction will in most cases even lead to an increase in RMSE as the correction is applied to the incorrect non-parallax-corrected cloud position.
  Depending on cloud regime and resolution, applying a parallax-only correction can also increase the RMSE of the retrieved GHI compared to applying no correction at all. On average, for the parallax-only correction, the best results are obtained if it is performed based on 40-50% of the originally retrieved cloud top height H_c. The reason is that by only performing a parallax correction, the cloud shadow position is not explicitly considered. However, in our study domain the cloud shadow displacement (away from the equator) is typically opposite to the parallax correction (toward the equator), so they partly cancel each other out. Thus, implicitly

the cloud shadow displacement is partly accounted for when the parallax correction is applied with reduced H_c. Overall, this underlines the need for a combined parallax and cloud shadow correction to achieve accurate GHI retrievals.
In addition, for the combined geometric correction, using a partial H_c of 70-90 % can also reduce the RMSE in the retrieval. This might be due to radiation scattered towards the satellite from altitudes lower than H_c, which would result in a smaller parallax and shadow displacement. However, the differences in RMSE with the full combined correction are not statistically significant.

- For readability we have rephrased and moved the statement about pixel- and area-based corrections:
  Page 23, line 536: [..] effect on GHI at the surface. Furthermore, the fully combined geometric correction shows a significant reduction in RMSE when the correction is performed with a median H_c around the region of interest rather than relying on the H_c of each pixel separately. The reductions are 2.4 and 1.5 W m^{-2} at HR and SR, respectively, indicating that the area-based correction better handles uncertainties related to the H_c retrieval. This study shows [..].
- We have condensed the paragraph on the effect of spatial resolution on correction accuracy.
- A new paragraph has been added where the findings are briefly put in a broader context as suggested by reviewer #2 (See our reply to that review).
- Finally some textual adjustments have been made to improve overall readability.

Updates in results Section:

The largest adjustments for clarity have been made in the abstract and conclusions section. In the results section, some small textual adjustments were included that should improve readability. We did not adjust the overall structure of the sections. The larger adjustments included in the results section are as follows:

Page 11, line 225: ~~If only a parallax correction is performed~~ → For the separate parallax correction, starting from a H_c of 0 %, [..].

Page 12, line 270: At both resolutions, applying a time step mean optimal shift results in the smallest RMSEs of the evaluated corrections~~.~~, 15.6 W m^{-2} (14.5 %) and 8.1 W m^{-2} (7.6 %) W m^{-2} lower than the respective uncorrected HR and SR retrievals.

Page 14, line 297: First, [..] for all cloud regimes. Moreover, for CR1 to CR4, the mean HR RMSE of the parallax corrected retrieval is larger than for the uncorrected retrieval. For all cloud regimes besides CR7 and CR9 the shadow correction increases the HR RMSE with respect to the uncorrected retrieval. Second, [..].)

Find below our reply to the specific comments of the reviewer:

Abstract

1) ***This abstract undersells the paper. It should prominently mention that applying parallax correction alone can worsen validation results (as shown in Figure 4) and that using a height smaller than the retrieved CTH may be better than the full height.***

   The following adjustments were made to the abstract:

   - The first sentence of the abstract has been removed and replaced by the following sentence:
     Page 1 line 1: Satellite-derived GHI is an excellent data source for nowcasting solar power generation and validating weather and climate models.
   - The effect of cloud shadow displacement has been clarified (Also see our reply to point #2):
     Page 1, line 7: The geolocation of satellite retrievals is affected by parallax, a displacement between the actual and apparent position of a cloud, as well as by a displacement between the actual position of a shadow and the ~~cloud casting that shadow [..]~~ retrieved position of the shadow, which due to the 1-dimensional radiative transfer assumption, is directly below the cloud.

- We have reformulated the results mentioned in the abstract. For instance, it is now mentioned that the parallax and shadow-only corrections can worsen the accuracy while a reduced H_c might further improve the correction accuracy:
  Page 1, line 12: The time step averaged collocation shift correction generally yields the most accurate results, but a major drawback of this method is its reliance on ground measurements. The geometric correction, which does not have this disadvantage, achieves the most accurate results if a combined parallax and shadow correction is performed. It reduces the GHI root mean square error (RMSE) by 11.7 W m^{-2} (10.8%) compared to the uncorrected retrieval. Separate parallax or shadow corrections do not reach this level of accuracy. In fact, depending on the cloud regime, they may even increase the error compared to the uncorrected retrieval. In some cases, in particular when multilevel clouds are present, the retrieval accuracy improves if the geometric correction is based on a reduced H_c. Finally, it is demonstrated that GHI becomes increasingly sensitive to the applied correction at higher spatial resolutions, especially for variable cloud regimes. This has important implications for the retrieval accuracy of the current generation of geostationary satellites with spatial resolutions down to 500 m.

2) ***Page 1, line 7: This line is a bit confusing. The geolocation of the shadow (on the ground), as visible from the satellite, should not be affected by parallax. The 1-D assumption of "shadow is straight below the cloud" should be mentioned here, an assumption that is of course erroneous in most cases.***

We thank the reviewer for pointing out the unclarity when it comes to the cloud shadow position correction.

The CPP-SICCS retrieval for GHI assumes 1D radiative transfer. As a result, the retrieval places cloud shadows directly below the cloud. The radiances measured by SEVIRI and the pyranometer network are obviously governed by 3D radiative transfer and thus cloud shadows are normally displaced with respect to the below-cloud position.

Since the TOA radiance from cloud shaded pixels is low, the CPP-SICCS retrieval will (incorrectly) flag cloud-shaded pixels as clear sky. With the cloud shadow correction, we use the cloud top height and solar position to compute the distance between the position directly below the cloud (i.e. the assumed location of the cloud shadow in our 1D retrieval) and the actual location on the surface of this cloud's shadow.

In the end, with the cloud shadow correction, we can still take into account the effects of possible cloud shadow displacements, despite the 1D assumption in the GHI retrieval (See Figure 2 in the manuscript).

We agree with the reviewer that much of the confusion can be prevented if the 1D assumption in our retrieval is pointed out earlier, since this assumption is a crucial part in the correction.

The 1D assumption is now mentioned in the abstract. We also mention the 1D assumption in the introduction:

Page 3, line 63: [..] in addition. GHI retrievals almost exclusively assume 1D radiative transfer and as a result, in most cases, cloud shadows are incorrectly projected directly below the cloud. To correct the retrieved cloud shadow location [..] 2024-Preprint). With this correction the retrieved cloud shadow position can be shifted to the actual position of the cloud shadow at the surface.

Introduction

3) ***Page 3, line 64: same here, the shadow location would be retrieved accurately by just measuring the radiance from the shadowy pixel? But that's not what is done?***

Please see our response to comment #2.

3.2 Shadow correction

4) ***Page 6, line 160: this 1-D assumption should be pointed out earlier (introduction and perhaps abstract) as otherwise the reader may be confused why there is an error in the shadow location, as a simple radiance retrieval without any assumptions will have the correct geolocation for the shadowed pixel (if the shadow is on the ground and not on a lower cloud).***

Please see our response to comment #2.

3.4 Empirical collocation shift correction

5) ***Page 8, line 195: variations in CTH are also not accounted for.***

The reviewer is correct in pointing out that another shortcoming for the daily mean optimal shift is that variations in CTH remain unaccounted for. Also the time step mean optimal shift does not account for the diurnal variation in CTH. This is because the shift computed for each time step is based on all corresponding times during the entire length of the field campaign. Only the geometric correction accounts for variations in cloud top height. The consequences of not accounting for cloud top height are also discussed in more detail in Section 4.2.3 about high clouds. We have decided to already provide a comment on this in the methodology:

Page 8, line 195: The mean optimal shift method does have some drawbacks. For instance, variations in H_c are not considered in the correction. ~~A~~ Another shortcoming of the daily mean optimal shift [..] unaccounted for.

6) ***Page 9, Figure 3, latitude shift: why is there no latitude shift (south/north) around 12 noon? Shouldn't there be a shadow in the north?***

In Figure 3, the diurnal variation in optimal longitude shift is more apparent than the latitudinal variation. For the longitudinal shift, the optimal shift location changes with shadow position from west to east and becomes zero around noon when the sun is directly south, meaning that there is no cloud shadow displacement in the east west direction at that moment.

We attribute the flatter diurnal curve for the latitude shift mainly to compensating effects of the cloud shadow position and parallax. In our domain (i.e. midlatitude northern hemisphere) around noon the cloud shadow will indeed be positioned north of the cloud as the sun is located in the south. Accounting for the cloud shadow position in our retrieval will result in a northward shift, while the parallax correction will result in a southward shift towards the subsatellite point at the equator. (We also discuss this in section 4.1.1 about the separate parallax and shadow corrections). Therefore, the effect of cloud shadow position and parallax partly cancel each other out. As this opposing effect is largest around noon, the curve for diurnal variations in optimal latitude shift is flattened. However, around noon, the mean optimal shift is not zero but ± 3.0 km south for both the time step and daily mean optimal shift.

7) ***Page 10/11, Figures 3 (both panels) and 4(right panel): please add a thin grid line at 0, like you have in figures 5, 7, 8.***

Grid lines at y=0 have been added.

4.1.3 Pixel-based and area-based corrections

8) ***Page 12, line 258: I think "uncertainties" here should be "errors", shouldn't it?***

We agree with the reviewer and have replaced "uncertainties" with "errors" in this sentence.

4.1.5 Resolution sensitivity

9) ***Page 12, line 283: You have derived the emipirical collocation shift correction using pyranometer measurements and now you are using comparisons with pyranometer measurements to validate them. It would seem your validation is not independent of your reference.***

The reviewer makes a valid point by noting that the HOPE pyranometer network is used both for the derivation of the empirical collocation shift as well as for the validation making the validation data not fully independent of the reference.

Normally one would use data from prior years to establish these optimal shifts but, these are not available here. Yet, we would argue that the influence on the results remains limited.

To compute the daily mean optimal shift, we use 96 days of pyranometer observations from the HOPE field campaign. Here, all timeslots between 06:15 and 16:45 UTC are used, which means that with the (averaged) 5 minute temporal resolution, each day 127 observations are made. In total 12192 observations are used to derive a single daily mean optimal shift.

Non-independence of the collocation shift from the reference data might be a larger concern for the time step optimal shift as the time step optimal shift is computed for each of the 127 timeslots separately. However, in this case each collocation shift is still based on 96 observations of the various days. These 96 days represent a large range of weather conditions and cloud types. Therefore, we expect the mean time step optimal shift to remain largely insensitive to the time-to-time variability in GHI measured by the pyranometers.

This now mentioned in the main text as well:
Page 10, line 215: Note that the same pyranometer data is used for computation of the optimal shift and evaluation of the accuarcy of the emperical collocation shift method, which makes the data not fully independent. Ideally, data from previous years would be used to establish the optimal shifts, but these are not available for the field campaign. Yet, to derive each optimal shift, large volumes of data are used, representing a wide range of weather conditions and cloud types. Therefore, we expect the optimal shifts to remain largely insensitive to time-to-time variability in GHI measured by the pyranometers.

4.2 Separation into cloud regimes

10) ***Page 13, figure 13: bit surprised by seeing the clear sky regime here, as there will be no parallax or shadow error. But that actually provides a baseline for improved analysis of the rest of the results. If you have ca. 50 W/m² RMSE just from other sources, couldn't you subtract that error estimate from all the other figures so you get an estimate that covers only parallax and shadow effects? Or at least indicate this in the other figures for context.***

It is correct that in the clear sky regime no parallax or cloud shadow errors should be present, although, minor errors might arise from the imperfect classification of clear sky scenes. However, the current errors for CR9 are considerably larger than can be attributed to this effect. In this article, the error within the clear sky regime is not treated as a baseline error due to the following reasons:

1) Firstly, the RMSE of around 48 W m^{-2} for CR9 mainly represents a bias between what is measured by the pyranometers and the SEVIRI retrieval. The GHI measured with the pyranometer network underestimates what is retrieved by the CPP-SICCS retrieval as well as by the McClear model (Gschwind et al., 2019). This is what has also been observed in our previous publication: Wiltink et al. (2024), for instance in Figure 7a. In Section 4.3 of that article we mention imperfect calibration and tilt of sensor as possible reasons for this deviation.
2) Secondly, our retrieval for clear-sky pixels deviates from the cloudy pixel retrieval. In fact for clear-sky pixels, the CPP-SICCS retrieval does not rely on SEVIRI reflectance but computes GHI directly from the NWP input. For cloudy pixels, a Nakajima and King (Nakajima and King, 1990) bispectral retrieval is performed to derive cloud optical depth and effective radius which can then be used to compute (broadband) GHI. As a consequence, the error in cloudy pixels has entirely different characteristics than in clear-sky pixels.
3) Finally, the errors for cloudy pixels are largely due to uncertainties in the retrieval, for example related to cloud inhomogeneity. These uncertainties vary per cloud regime and explain the largest part of the additional error compared to clear sky. Parallax and shadow displacement errors form a relatively minor contribution, as can be infered from the difference between corrected and uncorrected retrievals.

The comment made us realize that it is useful to mention that the clear sky bias of 48 W m^{-2} is not due to parallax or shadow effects. Therefore, we have added the following sentence to the manuscript:

Page 14, line 295: The best agreement [..] clear-sky situations (CR9). The errors observed in this regime are not the result of parallax or cloud shadow displacement, but originate in a bias between the SEVIRI retrieval and the HOPE pyranometer network. Possible causes of this bias are imperfect calibration and sensor tilt as identified in Madhavan et al. (2016) and Wiltink et al. (2024).

11) ***Page 13, figure 13 caption: Note that the "natural color RGB" is known as the "day land cloud RGB" in the USA and perhaps some other communities. Adding this name (in addition to "natural colour" common in europe") 5may help some readers.***

We have adopted the term "natural color RGB" from the Satpy Python Library. The naming for this RGB-composite is in line with how it is used by EUMETSAT. For clarity, we have added the term "Day land cloud RGB" as well:

Page 13, Figure 5, caption: Satpy natural color RGBs of SEVIRI → Satpy natural color RGBs (also referred to as "Day land cloud RGB") of SEVIRI.

4.3 Diurnal Cycle

12) ***Page 19, line 398: "growing importance at increasing spatial resolutions", here one could mention FCI.***

This paragraph provides a good opportunity to mention the current generation of geostationary satellites that have spatial resolutions that go down to scales of 500 m. We do make a statement about this, however, this is only in the conclusions/ outlook. We have added the following sentence to the manuscript:

Page 19, line 398: Overall this illustrates [..] spatial resolutions. This also makes it increasingly relevant for the current generation of geostationary satellites like the GOES Advanced Baseline Imager (GOES ABI; Schmit et al., 2017) and the Meteosat Third Generation Flexible Combined Imager (MTG-FCI; Holmlund et al., 2021) which enable retrievals of GHI down to scales of 500 m.

And have slightly adjusted the part in the conclusions/outlook where this is mentioned.

Page 23, line 538: The current generation of geostationary satellites like the GOES Advanced Baseline Imager (GOES ABI; Schmit et al., 2017) and the Meteosat Third Generation Flexible Combined Imager (MTG-FCI; Holmlund et al., 2021) enables retrievals of GHI down to scales of 500 m. → The current generation of geostationary satellites like the GOES ABI and the MTG-FCI enables retrievals of GHI down to scales of 500 m.

5.1 Generalizability of results

13) ***Page 19, line 414: this could be tested with IODC. Not suggesting you need to do it for this study, but you could mention it at least.***

Comparing retrievals from the prime and/or rapid scan service of Meteosat with the IODC service would indeed be a good way to test the relative importance of east-west versus north-south parallax. However, for the period of the HOPE campaign which we use in this study, direct comparison with IODC is not possible since the IODC service only became operational in 2016 and the campaign took place in 2013. We do agree with the reviewer that it is worth mentioning that there is a possibility for such a comparison at later periods, and have added the following sentence to the manuscript:

Page 12, line 283: For regions [..] more impact on the retrieval accuracy. The relative importance of the north-south and east-west parallax could be studied in more detail by comparing retrievals from the MSG Prime or RSS service, for which the satellite is positioned at 0/9.5 °E, to the MSG Indian Ocean Data Coverage (IODC) service, for which the satellite is positioned further east at 41.5/45.5 °E. However, this comparison is not possible for the dates of the HOPE field campaign as the MSG-IODC service became operational in 2016.

5.2 Remaining mismatch errors

14) ***Page 21, line 473: this could be tested with LEO, such as Sentinel data or even Landsat (if calibration is good enough).***

It would be interesting to test the magnitude of the spatial mismatch with LEO satellites. These higher resolution retrievals would become more sensitive to temporal misalignment and 3D radiative effects. Therefore, it would also be interesting to study the effect of these higher resolutions on the cloud shadow displacement and parallax corrections. This is beyond the scope of the current study.

15) ***Page 21, line 479: the comment on 3D is a bit oddly formulated.***

We have rephrased this sentence as follows:

Page 21, line 479: Furthermore, these 3D effects might limit the accuracy of geometric parallax and shadow corrections, for instance, when it comes to cloud-side illumination → For instance, 3D effects like cloud-side illumination might limit the accuracy of geometric parallax and shadow corrections.

Typos:

16) ***page 19, line 391, missing space in "theassymmetric".***

The reviewer's comment has been modified accordingly.

17) ***page 24, line 563: Github → GitHub***

The reviewer's comment has been modified accordingly.

References

Gschwind, B., Wald, L., Blanc, P., Lefèvre, M., Schroedter-Homscheidt, M., and Arola, A.: Improving the McClear model estimating the downwelling solar radiation at ground level in cloud-free conditions – McClear-v3, Meteorologische Zeitschrift, 28, 147–163, https://doi.org/10.1127/METZ/2019/0946, (data available at: `https://ads.atmosphere.copernicus.eu/datasets/cams-solar-radiation-timeseries`, last access: 7 March 2024)., 2019.

Holmlund, K., Grandell, J., Schmetz, J., Stuhlmann, R., Bojkov, B., Munro, R., Lekouara, M., Coppens, D., Viticchie, B., August, T., Theodore, B., Watts, P., Dobber, M., Fowler, G., Bojinski, S., Schmid, A., Salonen, K., Tjemkes, S., Aminou, D., and Blythe, P.: Meteosat Third Generation (MTG): Continuation and Innovation of Observations from Geostationary Orbit, Bulletin of the American Meteorological Society, 102, E990–E1015, https://doi.org/10.1175/BAMS-D-19-0304.1, 2021.

Madhavan, B. L., Kalisch, J., and Macke, A.: Shortwave surface radiation network for observing small-scale cloud inhomogeneity fields, Atmospheric Measurement Techniques, 9, 1153–1166, https://doi.org/10.5194/amt-9-1153-2016, 2016.

Nakajima, T. and King, M. D.: Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part I: Theory, Journal of Atmospheric Sciences, 47, 1878 – 1893, https://doi.org/10.1175/1520-0469(1990)047⟨1878:DOTOTA⟩2.0.CO;2, 1990.

Schmit, T. J., Griffith, P., Gunshor, M. M., Daniels, J. M., Goodman, S. J., and Lebair, W. J.: A Closer Look at the ABI on the GOES-R Series, Bulletin of the American Meteorological Society, 98, 681–698, https://doi.org/10.1175/BAMS-D-15-00230.1, 2017.

Wiltink, J. I., Deneke, H., Saint-Drenan, Y.-M., Heerwaarden, C. C. V., and Meirink, J. F.: Validating global horizontal irradiance retrievals from Meteosat SEVIRI at increased spatial resolution against a dense network of ground-based observations, Atmos. Meas. Tech., 17, 6003–6024, https://doi.org/https://doi.org/10.5194/amt-17-6003-2024, 2024.