

24 May 2020

Responses to the comments from referees and open discussion comments

Dear editors, referees and commentator,

Thank you very much for useful comments. We have made a large effort to improve our manuscript following your comments as specified each by each as follows. We believe the manuscript has significantly improved and is informative to the science community.

Teruyuki Nakajima on behalf of the co-authors

### **1. Referee-1 comments**

C1-1. General comment: This paper presents in depth overview of SKYNET network of sun-photometers. It describes the hardware and many details of the network operation including calibration procedures, maintenance, atmospheric aerosol and gaseous property retrievals, as well as validation of the SKYNET products. The SKYNET has been founded about two decades ago and has been dynamically evolved since. In my opinion, the SKYNET together with AERONET is one of the bests established ground-based networks that provided extremely valuable information for validation of satellite observation and directly for aerosol science. It is difficult to overestimate the importance of this information provided by the ground-based networks for current understanding of properties of atmospheric aerosol and its impact on climate and environment. With no doubts this paper comprising many details of SKYNET operations is clearly interesting and important for the community and for the reader of Atmospheric and Measurement Techniques (AMT). Therefore, I think the paper should be published AMT and included AMT highlights. At the same time, the authors could try to clarify additionally certain aspects and improve the content of the paper even further. Below, I listed few suggestions for optional consideration by the authors.

A1-1. We added more information for improving the content of the paper as explained in answers to each comment.

Detailed comments;

C1-2. The abstract seems to be unusually short, probably it could be extended by adding some more essential information.

A1-2. We extended the abstract summarizing the results of the paper.

C1-3. In my opinion, the paper could be even more interesting if the authors put additional efforts in outlining even more the similarities and differences, as well advantages and

disadvantages of SKYNET observations and retrieval products with those from other networks, first of all compare to AERONET.

A1-3. We tried to put more comparisons in Sections 2 and 5 by adding measurement protocols, QC screening processes, and analysis algorithms with some comparison with those of AERONET to our knowledge. We have added new tables 3, 5, and 6 to quantify the discussion for calibration, AOT comparison, and SSA comparison.

C1-4. The paper seems to focus on the details of hardware description and acquisition of measurements. Probably, some more information about retrieval procedures could interest the readers.

A1-4. We added text in Section 5 to explain algorithms and performance of the analysis system with some comparison with those of AERONET.

C1-5. Some statements about accuracy of the retrieval, e.g. about size distribution and single scattering albedo are not justified in fully convincing way. The author just showed few figures and short explanations to them. The justification of retrieval products accuracy normally deserves more attention. For example, in AERONET activities many theoretical investigations and field campaigns are devoted to clarification of the retrieval accuracy of aerosol properties (SSA, etc.). I believe some more discussion and references to filed experiment and numerical tests could be beneficial for readers.

A1-5. The network is for research purpose without a centralized data analysis system and information is scattered in independent papers and documents, which makes SKYNET difficult to be understood by the science community. In this situation this paper intends to make an overview of key findings and issues of the SKYNET, providing better information for the community. We firstly stated this point in abstract and introduction. We also feel the original manuscript lacks some important details of the software system and data analysis protocols, so that we added more explanations in Section 2 and 5.

We eliminated 0.015 as the SSA accuracy, and instead added a statement that the difference is less than 0.03 if the improvements are introduced in the operational system, mentioning uses of AERONET knowledge. We also added discussion regarding AOT and SSA accuracies with new Tables 3, 5, and 6. We also added a new Table 2 to list information regarding the known SKYNET data archives.

## **2. Referee-2 comments**

C2-1. General Comments: A paper focused on the issues and algorithms of the SKYNET network is needed and could prove quite useful to the scientific community. The title and

Introduction section of this paper holds significant promise, however upon reading there was a strong emphasis on calibration methods within SKYNET (which is good), but then a lack of detail or even complete omission of some other important issues. On page 2 (lines 24-26) of the introduction you say: “Compared to the AERONET technology, SKYNET has several differences in measurement and analysis methods, which are useful to overview and assess for the world community to understand the system, which is the purpose of this paper.” This sentence outlines the basis for an interesting and useful manuscript, however the differences (between SKYNET and AERONET) in measurement sequences, cloud screening, data quality checking, and some algorithms were not adequately addressed in the current paper. However, revisions with additional in-depth discussion of these issues could make this paper a very valuable and important reference for SKYNET network data users and aerosol researchers worldwide.

A2-1. In section 5, we added text regarding the details of the analysis software with some comparison with those of AERONET. And we added new Tables 3, 5 and 6 to quantify the discussion for calibration, AOT comparison, and SSA comparison and mentioning uses of AERONET knowledge. We also added a new Table 2 to list information regarding the known SKYNET data archives.

Specific Comments:

C2-2. Abstract: This is likely the shortest abstract I have ever seen, and hardly informative. I recommend that a few specifics be mentioned as there is really nothing of substance in this abstract.

A2-2. We extended the abstract summarizing the results of the paper.

C2-3. Page 3, lines 4-5: Here you discuss the nations that contribute to SKYNET and that a committee was formed for collaboration. Please add information on the availability of data to the scientific community from these regions/sub-networks and include specific data access websites and data policies.

A2-3. We added a new Table 2 to list geophysical parameter products, versions of Skyrad.pack, and availability for sub-networks.

C2-4. Page 3, lines 4-5: It is necessary (here or elsewhere in the text) to include information on the temporal frequency of the direct sun and sky radiance measurements for SKYNET sun-sky radiometers. Also important are the types of sky scans made by SKYNET instruments. Are they all almucantar and/or some additional solar principal plane scans? How often are the sky scans made, and over what solar zenith angle (SZA) range? This

should be contrasted with the AERONET measurement protocols, almucantar and hybrid scans. Also over what SZA range are SKYNET almucantars identified as high quality retrievals. For AERONET the minimum SZA for Level 2 (high quality) almucantar retrievals is 50 degrees, corresponding to 100 degrees scattering angle range.

A2-4. We added more information about measurement protocols, theoretical basis, QC screening processes, and analysis algorithms with some comparison with those of AERONET to our knowledge in Section 5.

C2-5. Page 3, lines 4-5: It is surprising that the interference filters for the UV wavelengths would have such a wide band-pass of 10 nm. AERONET filters in the UV have 2 nm band-pass due to solar zenith angle dependent Rayleigh OD issues in measurement of AOD in the UV region.

A2-5. We are sorry that our original manuscript was inaccurate about the band-pass filter specifications. The POM 02 model uses 3 nm or less widths for 315, 340, and 380nm channels and 20nm for short IR channels. We added the numbers in Section 2.

C2-6. Page 4, lines 17-18: A short summary of the SKYNET cloud screening is warranted here in the text. It would be very useful to compare what aspects of the cloud screening are similar and which ones differ from the AERONET cloud screening (please refer to V3 cloud screening, discussed in Giles et al (2019)). For example, AERONET uses the angular steepness of the solar aureole as a cirrus filter, while I think that SKYNET does not.

A2-6. We added text to explain the cloud screening procedure and other QC protocols in Section 2 and 5 with text regarding the AERONET steepness test of the solar aureole referring to Giles et al. (2019).

C2-7. Page 5, line 16: Regarding the improved Langley (IL) method, please provide some estimated ranges of accuracy for different optical depth magnitudes. Also provide accuracy estimates of  $F_0$  determination for temporal variation in AOD over the Langley measurement sequence, as it would be expected that this would also be a factor.

A2-7. We added a new Table 3 to list mean values of  $n$  (number of observation points), AOT, and  $\sigma_{a,IL}$  (uncertainty in  $\ln F_0$ ) per 30 days (month) obtained from ILP operations carried out at Tokyo and Rome sites. For this explanation, we added a  $\gamma$ -value,  $\sqrt{(\epsilon_{\tau}/\langle\tau\rangle)^2+(\epsilon_{\omega}/\langle\omega\rangle)^2}$ , in new Eq. (10b). The  $\gamma$ -values for Tokyo and Rome are 7% and 15%, respectively, and close to 10% assumption for Eq. (10) in the original manuscript, but indication of 10% may cause a misleading idea to readers about the realistic accuracy,

so we omitted the text regarding 10% assumption.

As for temporal change during ILP, the method allows such temporal change, as already stated in the original manuscript with an example of a temporal variation in AOT and SSA  $\tau_1=0.2$  to  $\tau_2=0.4$ , and from  $\omega_1=0.85$  to  $\omega_2=0.95$  during ILP which is useful to increase the accuracy through Eqs. (7b) and (8a). It is also possible to have a change in the atmospheric conditions during a short time less than 5 min for one full angle scan for ILP to cause unexpected errors. Sub-networks, therefore, have their own screening protocols for ILP using stability of time sequence of variables to reject ill condition data for ILP. We added this point in the paragraph after Eq. (9).

C2-8. Page 6, line 13: Should be 'wasting' instead of 'waisting' here.

A2-8. Thanks. We corrected.

C2-9. Page 6, line 20: Since the AOD is much larger (and more variable) at 400 nm than 870 nm it seems that the error would be larger for the shorter wavelengths. Please explain why this would not be a factor or else include a statement that errors would be larger at shorter wavelengths unless the aerosol is coarse mode dominated (Angstrom Exponent of  $\leftarrow$ -zero).

A2-9. This is an important comment. It is true that ILP and AOT uncertainties increase with decreasing wavelength. The original intent was to state that the error relative to AOT is expected to be independent of wavelength by Eq. (10). But, this be misleading, so that we eliminate "regardless of wavelength" and instead we added new texts and new Tables 3 and 5 to give more observed numbers.

C2-10. Page 7-8 (last 2 sentences of P7 and first 2 sentences of P8): This data in Figure 4b should be discussed in more detail in the next section of Sky radiance calibration (Section 4). Section 4, starting on Page 9: Please provide some explanation of the causes of the temporal variance of the SVA as shown in the time series in Figure 4b. This data is from high altitude sites with stable very low AOD and therefore would be expected to be a best case scenario. Also discuss what the variability in SVA from sky scans would look like at a sea level site with moderate and variable turbidity, say  $AOD=0.5 \pm 0.3$  at 500 nm with  $\alpha=1.5$ .

A2-10. The analysis of Fig. 4 was made by the Skyrad pack software for data screened by a condition of RMSD of SVAs is below 0.20, while the median value of the long-term data is much as 0.05. The observations were taken from a wide range of AOT with minimum (instantaneous) 0.01 to maximum 0.22 with the yearly averaged AOT as  $0.0448 \pm 0.026$  at 500 nm during 2008 to 2018 at the two sites. Due to limiting cloudy conditions in the

afternoon hours, 35% of the disk scanning work are performed in between 8-9am. Since the disk scanning procedure takes around 20-25 minutes to complete the entire wavelengths, it is apparent that in some cases, some wavelengths may have been affected by thin (cirrus) clouds which carried by heavy wind (above 15 m/s) at both the sites.

We added this explanation in the related paragraph.

Uchiyama et al. (2018b) discussed that the SVA error by the disk scan can exceed 1% for large AOT condition like  $AOT_{550} > 0.5$  and proposed the subtraction method using sky radiance calculated from the size distribution retrieved from the relative radiance. This subtraction method can reduce the error to 0.5% for  $AOT_{550} < 2$  for sky radiance measurement with the minimum scattering angle  $\Theta = 3^\circ$ . So far, no sub-networks implement these methods in their operational analysis, but they reject large AOT cases from their disk scan data analysis by AOT value.

We added this explanation to the bottom paragraph of Section 4.

C2-11. Page 10, lines 13-15: It would be useful to provide the reader with an estimate of the magnitude of the error in sky radiance calibration as a result of this uncertainty in SVA from the disk scan. Or else state that the entire data base of SKYNET has been reprocessed with the correction method that was outlined by Uchiyama et al. (2018b).

A2-11. We added an error budget discussion for SSA retrieval by Pandithurai et al. (2008), Hashimoto et al. (2012), and Khartri et al. (2016) with new Table 6. According to these studies, the major error source of SSA retrievals by SKYNET is the underestimation of SVA by the disc scan method.

C2-12. Page 10, lines 20-24: Why are the retrievals within SKYNET made with two different versions of the Skyrad.pak code (Version 4.2 or version 5)? What are the effects of these different codes on the inverted parameters? Why is there no standardized inversion code for the entire network? Or if I have mis-interpreted this then please clarify in the text what the consistent data processing is for the data from all sites in the SKYNET network.

A2-12. SKYET is a research network without a unified operation system for analyzing all the data using a unified analysis software. We added this statement at the bottom of the introduction section.

Due to historical reasons, Skyrad.pak version 4.2 and 5 are used in parallel. Also the two versions adopt different cost functions as explained by new Eq. (21), so that we still have a benefit from version 4.2.

We added the information to describe the version differences in the two versions in Section

5 and added new Table 6 to quantify the version difference for SSA retrievals.

C2-13. Page 11, line 1: Please state here whether this Cimel instrument in Beijing is part of the AERONET network with their data processing algorithms or a part of CARSONET network with somewhat different algorithms (especially when compared to V3 of AERONET).

A2-13. We added a text: In Che et al.(2008), the AOTs were compared between POM-02 skyradiometer and Cimel sunphotometer at the top of Institute of Atmospheric Physics(IAP) in Beijing which belongs to SKYNET and AERONET, respectively. The POM-02 data were processed by Skyrad pack 4.2. The sunphotometer data is AERONET V2 Level 2 data.

C2-14. Page 11, lines 2-3: Please explain here why the error in AOD is smaller in the shorter wavelengths even though the AOD and its absolute temporal variance is larger at the shorter wavelengths. This seems to be counter-intuitive, and I would need some significant evidence presented in the paper in order to be convincing.

A2-14. We rechecked the statement and found that the numbers are not RMSD, but the relative bias errors defined as  $\langle \text{AOT}(\text{SKYNET}) - \text{AOT}(\text{AERONET}) \rangle / \text{AOT}(\text{AERONET})$ . That is why the errors are very small as 1% and relatively independent of wavelength. We added new Table 5 to show their RMSD numbers that increase with decreasing wavelength. We added this explanation to the paragraph for new Table 5.

C2-15. Page 11, lines 10: This is a relatively large difference in Angstrom Exponent (0.5), but not if AOD is very low. Please state the AOD levels for these AE comparisons.

A2-15. Under low aerosol conditions, a small relative bias in the AOT determination at 500 and 865 nm can theoretically lead to large deviations in the calculated Ångström Exponents (AE). As an example, for AODs of about 0.05 and 0.02 at 500 and 865 nm, respectively, AOT differences of 0.01 and 0.005, respectively, can lead to AE differences up to ~1. We added this statement to the paragraph.

C2-16. Page 11, lines 13: It would be useful to also show or discuss comparison statistics of AOT for 380 nm (in addition to 870 nm in Figure 8) since all instrument types have larger uncertainties at this wavelength.

A2-16. The PFR used in the intercomparison campaigns did not have 380 nm channel available, therefore we cannot state the differences in channels below 400 nm. Instead, we compared, in the new Table 5, AOT retrievals from the POM-02 sky radiometer and the Cimel

sunphotometer in the the KORUS-AQ campaign. They found RMSD from 0.007 to 0.15 at wavelengths longer than 500nm, but values larger than 0.03 are found in UV channels, as the reviewer pointed out.

We added this discussion in the related paragraphs for Table 5 and Fig. 8. We replaced Fig.8(b) from Roman result to a Davos result, because the new corona virus lock-down in Rome made it difficult to retrieve detailed data from the university where the data are stored.

C2-17. Page 11, lines 17-18: When discussing differences in AOD it is much more useful to provide the differences in AOD rather than percentages.

A2-17. We presented absolute differences in AOT in new Tables 3 and 5 and those of SSA in new Table 6 and reorganized the text in the related paragraphs.

C2-18. Page 11, lines 19: Provide some quantification here of the SSA overestimate found by Che et al. (2008).

A2-18. Che et al.(2008) found RMSD of 0.025, 0.018, 0.018, 0.018 at  $\lambda= 440, 670, 870, 1020\text{nm}$ , respectively. We compared the numbers to others in new Table 6 and added some discussion using Hashimoto et al. (2012), Dubovik et al. (2000), and Khatri et al. (2016).

C2-19. Page 11, lines 23: There needs to be more discussion of the SKYNET cloud screening algorithms and comparison to co-located AERONET site data in order for users to understand the cloud contamination issue better.

A2-19. We added text to explain the cloud screening procedure and other QC protocols in Section 2 and 5.

C2-20. Page 11, lines 23-25: It is puzzling as to why all the data are not processed with Version 5. This suggests that data at some sites that process the data with V4.2 will have more cloud contamination than other sites that use V5. Please provide some clarification on which versions of SKYRAD.pak software/algorithms are used to process the data for what sites.

A2-20. As answered in A2-12, SKYET is a research network without a unified operation system for analyzing all the data using a unified analysis software. We added this text at the bottom of the introduction section. By this historical reason, Skyrad.pak version 4.2 and 5 are used in parallel. Also the two versions adopt different cost functions as explained by new Eq. (21), so that we still have a benefit from version 4.2. We added text to describe the



version differences in Section 5 and in new Table 6.

C2-21. Page 11, line 28: More details on the stricter cloud screening in V5 are needed here in the text, not just providing literature references.

A2-21. We eliminated the points (1)-(3), and instead we added text to explain the cloud screening and QC processes in ESR and CEReS in the second paragraph after Eq. (2c). And added discussion of the data screening protocols (C1)-(C3) to reject cloud contamination in the version 4.2 data analysis in Section 5.

C2-22. Page 12, lines 1-3: Your discussion of SSA differences (Fig 9) is misleading since the agreement was much poorer with standard SKYNET retrievals of SSA. The study of Mok et al. (2018) replaced the crude surface reflectance assumptions utilized by SKYNET with values derived from MODIS measurements (these were AERONET values). A discussion of the spectral surface reflectance used as input to the SKYNET retrievals is needed here.

A2-22. We added substantial text and a new Table 6 to compare reported SSA differences to show the SKYNET SSAs are larger by more than 0.06 and can be reduced to around 0.03, if we introduce the various improvements including the spectral reflectance by AERONET. The spectral reflectance effect is 0.004 to 0.008 in the short wavelengths compared to the fixed albedo case in SKYNET. The Skyrad pack assumes simplifications regarding the extinction model and the inversion process as compared to those of AERONET, which may need to be implemented after more investigation. We added this statement in the related paragraphs regarding Tables 5 and 6, and conclusion section.

C2-23. Page 12-13, last 2 lines of P12 & first 4 line of P13: Please note whether this is a SKYNET retrieval product for W (column water vapor) or just a possibility for future implementation. Also does SKYNET provide W retrieved from both methods shown in Fig 11 in the database for all sites?

A2-23. So far there are no sub-networks which produce an operational product of water vapor. We stated this point in Section 2 adding the new Table 2 to list what are the operational products. Figure 3 is also modified to show which are operational products. The method of Momoi et al. (2019) is just being applied to data in CEReS, but this point is too early to report in this paper. In this regard, we modified Eq. (26) (old Eq. (22)), which shows Momoi's new method, to the x-variable used in the classical methods.

C2-24. Page 13, line 11: It is very surprising that you use a 10 nm wide filter at 315 nm as stated on page 4 in this paper. This should cause significant SZA dependence in the signal and

result in SZA dependence of the retrieved columnar ozone.

A2-24. Our original manuscript was inaccurate about the band-pass filter specifications. The POM-02 model uses 3 nm or less for 315, 340, and 380nm and 20nm in 1600nm and 2200nm channels. We added the numbers in Section 2.

C2-25. Page 13, lines 26-28: With only 1% of the variance explained in this scatterplot (Fig 13b), it seems that there are likely other issues involved in the retrieval of CER from both the sky radiometers and also the satellite measurements. The result could not be any worse than this and therefore it seems like this could just be mentioned in the text without the need of a plot.

A2-25. We agree with the reviewer's suggestion and dropped Fig. 13(b) for CER and added a text to state Khatri et al. (2019) also did not find a good correlation between retrieved cloud effective particle radius between SKYNET and AHI observations. We also revised Fig. 13 and Figs. 14(a) and (b) adding regression lines.

C2-26. Page 14, line 2: This statement is confusing. The accuracy shown in the paper is better than 10% if the AOT is high. For example, if the AOD at a site averages 0.5 for a month then the accuracy of the IL calibration does not result in 0.05 uncertainty.

A2-26. This is for the accuracy of  $F_0$  for AOT condition in the ILP operation, in which AOTs are selected by a threshold smaller than the mean AOT at the site. For example, ESR rejects the data  $AOT_{500} > 0.4$ . So, the typical errors in retrieved  $F_0$  is less than 1%. We added new Table 3 to list the reported uncertainties in  $F_0$  and revised the text as above.

C2-27. Page 14, lines 2-3: This 'conclusion' is also misleading since the 'accuracy' of SSA is very hard to define as there is no gold standard for SSA measurement to use as a benchmark. Additionally, as discussed before this value of 0.015 (difference with AERONET and Pandora) is not based on standard SKYNET retrievals but on retrievals made with much more accurate inputs of surface reflectance (AERONET values were used). Also, Mok et al. (2018) applied additional improved quality checks to SKYNET retrievals, not the standard SKYNET product. The way it is currently written would give most readers a false sense of the consistency of the SKYNET retrievals of SSA versus AERONET.

A2-27. We revised the text that Mok et al. used spectrally varying AERONET ground albedo and stated that they also found that a prefixed ground albedo  $A_g$  at 0.1 by SKYNET increased RMSD by 0.004 to 0.008 in the short wavelengths.

In order to avoid readers' misunderstanding, we also stated in the abstract, introduction, and conclusion sections that some of these improvements are still in research phase and not involved in the operational system.

C2-28. Page 14, line 8: This is the first time the size of the financial budget for SKYNET has been mentioned in the entire paper. It is therefore a bit strange and confusing to include budget considerations in the Conclusions section.

A2-28. We eliminated the budget consideration from the text.

C2-29. Page 14, lines 10-13: It is odd to put these alternate calibration methods in bullet form in the Conclusions section. Please format into a typical sentence structure.

A2-29. We modified the statement in a running form.

### **3. Open discussion comments by Dr. A. Smirnov**

C3-1. The statement in the Introduction “Combined analyses of sun and sky radiation data were not attained until the 1980s . . .” is not exact. Aureole measurements combined with the direct sun measurements to study atmospheric optical properties and stability were made by Abbot (I do not have a reference though), Kalitin (1930), Fesenkov (1933), Pyaskovskaya-Fesenkova (1957), Bullrich (1964), Lifshits (1965), and Murai (1967). B.N.Holben et al. (2001, Table 1) provided an exhausted history of the long- term optical depth measurements by various researchers over different parts of the world. A nice chronological essay regarding history of the direct sun measurements was presented by G.E.Shaw (2006).

A3-1. Thank you for an important comment regarding the early-day activities of sun and sky observation. We revised the texts for dating and added description of milestones by Abbot (1911), Abbot and Aldrich (1916), de Bary (1964), Bullrich (1964), Bullrich et al. (1967, 1968), Fesenkov (1933), Gorodetskiy et al. (1976), Holben et al. (2001), Kalitin (1930), Murai (1967), Phillips (1962), Pyaskovskaya-Fesenkova (1957), Roosen et al. (1973), Shaw (2006), Shifrin et al. (1972, 1974), Terez and Terez (2003), Turchin and Nozik (1969), Twitty et al. (1976), Yamamoto and Tanaka (1969).

We also added the name of Dr. Smirnov to the acknowledgments section.

### **4. Other revisions/corrections**

The following revisions/corrections were applied other than comments by reviewers.

4-1. We added two authors, Akihiro Yamazaki and Sujung Go, because we needed their data

and discussion for producing answers to some of reviewers' comments.

- 4-2. We added Ministry of Ocean and Fisheries, Korea in Acknowledgments.
- 4-3. Accuracy of precipitable water vapor was 0.2 cm instead of typo 2 cm in the original manuscript.
- 4-4. Table numbering changed because of insertion of new Table 3; accordingly Table 3 became Table 4. We also added new Tables 5 and 6. Equation numbering also changed due to insertion of new Eq. (21)-(24).
- 4-5. We replaced Fig.8(b) from Roman result to Davos result, because, in the new corona virus lock-down in Rome, we had a difficulty to retrieve detailed data from the Italian university where the data are stored.

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## An overview and issues of the sky radiometer technology and SKYNET

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## 15 Abstract

This paper overviews the progress in the sky radiometer technology and development of the network called SKYNET. It is found that the technology has produced useful on-site calibration methods, retrieval algorithms, and data analyses from the sky radiometer observation of aerosol, cloud, water vapor and ozone.

20 [A formula was proposed for estimating the accuracy of the sky radiometer calibration constant  \$F\_0\$  using the improved Langley \(IL\) method, which was found to be a good approximation to observed monthly mean uncertainty in  \$F\_0\$  around 0.5% to 2.4 % at Tokyo and Rome sites and smaller values around 0.3% to 0.5% at the mountain sites of IOA and Davos. A new XIL method was also developed to correct an underestimation by the IL method in case of](#)

25 [large aerosol retrieval errors.](#)

30 [The RMSD in AOT comparisons with other networks took values less than 0.02 for  \$\lambda \geq 500\text{nm}\$  and a larger value about 0.03 for shorter wavelengths in city areas, and smaller values less than 0.01 in mountain comparisons. Accuracies of Single Scattering Albedo \(SSA\) and size distribution retrievals are affected by propagation of errors in measurement. calibrations for direct solar and diffuse sky radiation, ground albedo, cloud screening, and version of analysis software called Skyrad pack. SSA values from SKYNET were up to 0.07 larger than those from AERONET, and major error sources were identified as underestimation of SVA and cloud contamination. Correction of these known error factors reduced the SSA difference to less than 0.03.](#)

Retrievals of other atmospheric constituents by the sky radiometer were also reviewed. Retrieval accuracies were found to be about 0.2 cm for precipitable water vapor amount and 13 Dobson Unit for column ozone amount. Retrieved cloud optical properties still showed large deviations from validation data, suggesting need to study causes of differences.

It is important that these recent studies on improvements presented in the present paper are introduced in the existing operational systems and future system of the International Skynet Data Center.

### 1. Introduction

A sun-sky radiometer is a narrow band filter photometer able to perform measurements of direct solar and diffuse sky radiation at selected wavelengths and at several scattering angles. Observed data have large information contents for aerosol, cloud, and gaseous constituents, but are difficult to retrieve because of the need for full radiative transfer computation to quantify single and multiple scattered radiation.

The origin of the idea of the technology dates back to the beginning of the last century, (Shaw, 2006). Long-term direct solar and diffuse sky measurements were carried out during 1923-1957 by the Smithsonian Astronomical Observatory by monitoring the solar constant with a pyrheliometer at Montezuma (Chile) and Table Mountain (California) (Abbot, 1911; Ångström, 1961, 1974; Roosen et al., 1973; Hoyt, 1979a, b). Diffuse sky irradiance in the circumsolar or solar aureole region was measured by the pyranometer to correct for the atmospheric effects in the measured solar constant (Abbot and Aldrich, 1916). This method was also used by Kalitin et al. (1930), Fesenkov (1933), and Pyaskovskaya-Fesenkova (1957) (Terez and Terez, 2003). By 1970s, spectral measurements of the direct solar radiation became popular for air pollution monitoring by introduction of a low cost compact narrow band radiometer called a sunphotometer with a silicon photodiode and cutoff or interference optical filters (Volz, 1959, 1974). In parallel, pioneering measurements of the spectral diffuse sky radiance started from ground and aircraft (Bullrich, 1964; Bullrich et al., 1967, 1968; Murai, 1967; Eiden, 1968; Green et al., 1971; Gorodetskiy et al., 1976; Twitty et al., 1976). They were attracted by the characteristic radiance distributions including bright circumsolar region and neutral points of the degree of polarization in the sky dome. Theoretical and inversion schemes for the involved ill-conditional problems were studied for data analysis (Deirmendjian, D., 1957, 1959; Phillips, 1962; Twomey 1963; de Bary, 1964; Turchin and Nozik, 1969; Yamamoto and Tanaka, 1969; Dave, 1971; Shifrin et al., 1972; Shifrin and Gashko, 1974).

By 1980s, analyses of combined sun and sky radiation data became comprehensive (e.g., O'Neill and Miller, 1984a, b; Tanaka et al., 1986; Tanré et al., 1988) after the full yet fast

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radiative transfer computation became possible, allowing quantification of the multiple scattering component of sky radiance and retrieval of the column-averaged size distribution and the complex refractive index of polydispersed aerosol (Twitty, 1975; Weinman et al., 1975; Box and Deepak, 1978, 1979; Nakajima et al., 1983; O'Neill and Miller, 1984b; Tanré et al., 1988; Tonna et al., 1995; Dubovik and King, 2000; Dubovik et al., 2000, 2002). Networks of the radiometer have been developed to utilize sun and sky measurement data for various applications such as satellite remote sensing validation, air pollution monitoring and study of climate effects of atmospheric constituents, as overviewed by Holben et al. (2001). The largest network is the NASA AERONET (Holben et al., 1998) developed in the early 1990s and currently with more than 500 radiometers named the sun-sky photometer. Later in around the 2000s, SKYNET was formed with the sky radiometer (Nakajima et al., 2007). Compared to the AERONET technology, SKYNET has several differences in measurement and analysis methods.

The SKYNET is for research purposes without a centralized data analysis system and information is scattered in independent papers and documents, which makes SKYNET difficult to understood by the science community. In this situation this paper intends to make an overview of key findings and issues of the SKYNET providing better information for the community.

## 2. Sun and sky measurements by the sky radiometer

The SKYNET is a research group of users of the sky radiometer initiated around the time of the East Asian Regional Experiment (EAREX) 2005 (Nakajima et al., 2007), one of the regional experiments under the UNEP Atmospheric Brown Cloud (ABC) project (Ramanathan et al., 2007). A number of sky radiometers were deployed in the East Asian region for measuring the aerosol optical properties in order to estimate the aerosol impact on the earth's radiation budget (Takamura et al., 2004; Khatri et al., 2010). Since then, users of the sky radiometer have kept growing globally and the number of sky radiometers now exceeds 100 units. Table 1 and Fig. 1 show the sky radiometer sites as recognized by the International Skynet Committee (ISC). Users established regional sub-network groups in China, Europe, India, Japan, Korea, Mongolia, and South East Asia for data analysis and formed the ISC to discuss international collaboration issues (Fig.2). Historically two major groups were grown for regional data collection and analysis: the SR-Center for Environmental Remote Sensing (SR-CEReS) of Chiba University (Takamura et al., 2004, 2009, 2013) and the European Skynet Radiometers network (ESR) (Campanelli et al, 2004, 2007, 2012). Analysis systems were developed by the sub-networks independently, so that analysis methods and data archive

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systems have not been unified. Table 2 lists the archived geophysical parameters, versions of the retrieval software called Skyrad pack, and data availability in the known data archives. The table indicates the features of archives are different from each other and difficult for use by the science community.

5 In 2017, the SKYNET has become a contributing network of the WMO Global Atmospheric Watch (GAW) (<https://community.wmo.int/activity-areas/gaw>). In this expanding situation of SKYNET with more burden and responsibility, the ISC decided to establish the International SKYNET Data Center (ISDC) at the National Institutes for Environmental Studies (NIES) in Japan to start a shared data collection and analysis based on the MOU between users and the  
10 ISDC. Among the sites in Table 1, the ISDC started receiving data from 25 sites in the world. The ISDC is going to provide standard products from the SKYNET network, whereas the regional sub-networks will develop new research products and test new methodologies.

The main instrument of the SKYNET is the sky radiometer manufactured by PREDE Co. Ltd. Several versions of the radiometer have been made by users' requests. POM-01 is the  
15 standard version with seven wavelengths of  $\lambda=315, 400, 500, 675, 870, 940$  and  $1020$  nm and POM-02 is an extended version with UV wavelengths of  $340$ nm and  $380$ nm, and shortwave infrared wavelengths of  $1600$ nm and  $2200$ nm. Channels of  $315$ nm and  $940$ nm are installed for ozone and water vapor amount retrievals. Full-widths at half-maximum of band-pass filters are  
20 3nm or less for channels shorter than 380nm, 10nm between 400nm and 940nm, and 20nm for longer wavelengths. There is a modified version of POM-02 for lunar photometry (Uchiyama et al., 2019). Shipborne versions have been also built (Kobayashi and Shiobara, 2015).

Sky radiometer readings of direct solar and diffuse sky measurements,  $V_d$  and  $V_s$ , are related to the direct solar irradiance  $F_d$  and sky radiance  $\bar{L}_s$  at the mean earth's orbit as,

$$F_d = C_R R_{es}^2 V_d, \quad \bar{L}_s = \frac{F_s}{\Delta\Omega} = C_R \frac{R_{es}^2 V_s}{\Delta\Omega}, \quad (1)$$

25 where  $C_R$  is the radiometric sensitivity or calibration coefficient of the radiometer to translate the radiometer reading to irradiance unit, say  $\text{Wm}^{-2} \text{nm}^{-1}$ ;  $\Delta\Omega$  is the Solid Viewing Angle (SVA) of the radiometer;  $R_{es}$  is the sun-earth distance in the astronomical unit. SKYNET remote sensing uses the beam transmittance  $T_d$  of the atmosphere and relative sky radiance  $R$  (Nakajima et al., 1986) defined as,

$$30 \quad T_d \equiv \frac{F_d}{F_0} = \exp(-m_0 \tau), \quad (2a)$$

$$\tau = \tau_a + \tau_m, \quad \omega\tau = \omega_a \tau_a + \omega_m \tau_m, \quad (2b)$$

$$R(\theta, \phi; \theta_0, \phi_0) \equiv \frac{\bar{L}_s(\theta, \phi; \theta_0, \phi_0) / m}{F_d} = \frac{1}{m \Delta\Omega} \frac{V_s}{V_d}, \quad (2c)$$

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where  $\tau$  is the Optical Thickness (OT) of the atmosphere consisting of molecular optical thickness  $\tau_m$  and Single Scattering Albedo (SSA)  $\omega_m$ , and Aerosol Optical Thickness (AOT)  $\tau_a$  and SSA  $\omega_a$  in the clear sky condition;  $F_0$  is the Extraterrestrial Solar Irradiance (ESI);  $(\theta, \phi)$  and  $(\theta, \phi)$  are zenith and azimuthal angles of the sun and the line of sight of the sky radiometer, respectively;  $m_0$  and  $m$  are optical airmasses for solar insolation and line of sight of the radiometer, which are approximated as  $1/\cos(\theta_0)$  and  $1/\cos(\theta)$  for plane-parallel geometry of the atmosphere. SKYNET adopts on-site calibration routines to determine the two radiometric constants,  $F_0$  and  $\Delta\Omega$ , by the Improved Langley plot method (hereafter, IL or ILP) and the disk scan method (Nakajima et al, 1996; Boi et al., 1999; Uchiyama et al., 2019a, b) as discussed in Sections 3 and 4. Under the condition that  $C_R$  and  $F_0$  do not change between time of measurement and time of  $F_0$  determination,  $T_d$  and  $R$  do not depend on the calibration coefficient  $C_R$ , so that we can select the radiometer reading for  $F_0$ , i.e.  $C_R=1$ , without the absolute radiometric calibration. On this assumption,  $F_0$  in the radiometer reading is sometimes called a calibration constant. In order to meet this condition, therefore, the on-site calibration is required to be performed as frequent as possible to monitor change of  $C_R$  due to machine condition change and  $F_0$  change due to solar luminosity change.

Standard measurement protocols of SKYNET are as follows. Direct solar irradiance is measured every 1 minute. Diffuse sky radiance is measured by full almucantar scan at scattering angles from set of  $\Theta = \{2^\circ (1^\circ) 5^\circ, 7^\circ, 10^\circ (5^\circ) 30^\circ (10^\circ) 160^\circ\}$  for  $\theta_0 < 78^\circ$ , whereas the forward almucantar scan is made in  $\Theta < 30^\circ$  for  $\theta_0 > 78^\circ$ . The sky radiometer has several angle scan modes, i.e. almucantar scan, principal plane scan, cloud scan, and solar disk scan. There are two temporal sampling modes of regular time interval of 10 minutes (mode-1) and regular solar airmass interval of 0.25 (mode-2). Most of the sites in Table 1 adopt the mode-1 measurement with one-side almucantar scan. The disk scan mode is scheduled once a week at 10:00am local time, though the scan time can be changed by the user's plan. A cloud scan mode at nadir is taken every 10 minutes at POM-02 sites and some POM-01 sites.

Once the radiometric constants are determined, the direct solar irradiance  $F$  and relative sky radiance  $R$  are used for the Level-2 (L2) analysis, i.e., retrievals of the geophysical parameters of aerosol, cloud, water vapor and ozone as discussed later in Section 5. The flow of sky radiometer measurements and data analysis are schematically depicted in Fig. 3. As overviewed in the following sections,  $F_0$  and SVA are obtained on site through various Langley plot methods and solar disk scan method using data from direct solar and forward scan measurements. Cloud screening is also performed differently by sub-networks. The ESR performs a cloud screening for a direct solar measurement at 1 min frequency by a procedure based on the methodology developed by Smirnov et al. (2000), (Estellés et al., 2012a; Song et al.,

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2014), Cloud screening for sky measurements uses the downward shortwave radiative flux measured by a co-located pyranometer (Khatri and Takamura, 2009), otherwise they do not perform cloud screening for sky data. CEReS conducts the cloud screening with the method of Khatri and Takamura (2009), but without using global irradiance data from a pyranometer (Irie et al., 2019). It corresponds to the combination of a spectral variability test (Kaufman et al., 2006) and statistical analysis test of Smirnov et al. (2000) including checking the number of data, a diurnal stability check, smoothness criteria, and three standard deviation criteria, but without triplet stability criteria test. We do not use several QC tests such as the angular steepness of the solar aureole, for a stricter cloud filter as in AERONET (Giles et al., 2019).

To obtain data for L2 data analysis for retrieval of geophysical parameters for atmospheric constituents, an analysis software called Skyrad pack has been developed (Nakajima et al., 1996; Hashimoto et al., 2012) and publicly opened on the OpenCLASTR shareware site ([http://157.82.240.167/~clastr/data\\_policy.html](http://157.82.240.167/~clastr/data_policy.html)) for the research community. Various L2 products are retrieved by the Skyrad pack such as spectra of AOT, its slope called Ångström exponent (AE), Size Distribution Function (SDF), SSA, Complex Refractive Index (CRI), asphericity, cloud optical thickness (COT), cloud effective particle radius (CER), and water/ice phase from data in the non-gas absorbing channels, Precipitable Water Vapor (PWV) and column ozone amount (O<sub>3</sub>) from the gas absorbing channels, as explained in the following sections. Common operational products by the sub-networks are AOT, AE, SDF, SSA, and CRI assuming Mie particles. Other products have been retrieved by research studies. The current operating versions are version 4.2 and 5, and a version of Meteorological Research Institute of Japan Meteorological Agency (MRI version) developed by Kobayashi et al. (2006, 2010).

### 3. Radiometric calibration of the direct solar irradiance measurements

In the case of non-gas absorption channels, the Standard Langley plot method (SL or SL plot method) can be used to obtain  $F_0$  by plotting the logarithm of the Lambert-Beer's law Eq. (2a) versus  $m_0$ ,

$$\ln F_d = \ln F_0 - m_0 \tau, \quad (3)$$

to extrapolate the linear regression line to  $m_0=0$ . It is known, however, that an airmass dependence or a quadratic time dependence of AOT introduces a serious error in the SL as claimed by Shaw (1976). Correction methods to this problem were proposed by O'Neill and Miller (1984a, b) and Tanaka et al. (1986) with use of a time dependence of the circumsolar radiance of which the major part is approximated by the single scattered radiance proportional to the OT along the solar almucantar circle ( $\theta = \theta_0$ ), given as,

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$$R(\theta, \phi; \theta_0, \phi_0) = \omega\tau P(\Theta) + R_{mult}(\theta, \phi; \theta_0, \phi_0), \quad (4)$$

where  $P$  is the normalized scattering phase function at the scattering angle of  $\Theta$  and  $R_{mult}$  is the multiple scattered radiation. Tanaka et al. (1986) used a forward scattering around  $\Theta = 20^\circ$  at which the phase function is relatively independent of the SDF of the atmospheric particulate matter. Extending this principle, SKYNET adopts the IL method to extrapolate Eq. (3) regarding the total scattering optical path,

$$x = m_0 \omega \tau, \quad (5a)$$

or its aerosol part,

$$x_a = m_0 \omega_a \tau_a, \quad (5b)$$

which can be retrieved from the forward scattering part,  $\Theta < 30^\circ$ , of the relative sky radiance  $R$ , Eq.(4). The formulae in Eqs. (4) and (5) indicate that  $x_a$  is relatively accurately retrieved from the inversion of the forward scattering part of the sky radiance. We use Eq. (5b) in most of ILP by sub-networks.

The accuracy of  $F_0$  estimation by the IL method depends on the turbidity condition of the site. The theory of a linear regression model is formulated with a normal random observation error  $u$  as,

$$y_i = a + bx_i + u_i, \quad i = 1, \dots, n, \quad (6a)$$

$$a = \ln F_0, \quad x = m_0 \omega \tau, \quad y = \ln(F), \quad (6b)$$

where  $n$  is the number of observations. Here, we omit subscript "a" from  $\tau_a$  and  $\omega_a$  for the sake of compact notation unless otherwise specified. Equation (6) gives estimates of regression coefficients and their dispersion as,

$$b = \frac{\langle (x - \bar{x})(y - \bar{y}) \rangle}{\sigma_x^2}, \quad a = \bar{y} - b\bar{x}, \quad (7a)$$

$$\sigma_b^2 = \frac{\varepsilon_u^2}{n\sigma_x^2}, \quad \sigma_a^2 = \frac{\varepsilon_u^2}{n} \left(1 + \frac{\bar{x}^2}{\sigma_x^2}\right), \quad (7b)$$

where upper bar and  $\langle \rangle$  stand for averaging operation and  $\varepsilon_u$  is the root mean square error (RMSE) for  $u$ . The standard linear regression theory assumes  $x$  is an independent variable to be related to a dependent variable  $y$  which includes random residual of the fitting  $u$ . Based on this assumption, the dispersion of  $x$  is given as,

$$\left(\frac{\sigma_x}{\bar{x}}\right)^2 \sim \frac{\sigma_{m_0}^2}{\bar{m}_0^2} + \frac{\sigma_\tau^2}{\bar{\tau}^2} + \frac{\sigma_\omega^2}{\bar{\omega}^2}, \quad (8a)$$

where  $\sigma_{m_0}^2$ ,  $\sigma_\tau^2$  and  $\sigma_\omega^2$  are dispersions of sampling airmasses  $\{m_{0i}\}$ , natural variations in  $\{\tau\}$  and  $\{\omega\}$  during the ILP, respectively. The dispersion of residual  $\{u_i\}$  is approximated by the

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sum of mean square errors of  $\tau$  and  $\omega$ , i.e.  $\varepsilon_\tau^2$  and  $\varepsilon_\omega^2$ , caused by the inversion process of Eq.

(4) as,

$$\varepsilon_u^2 = b^2 \bar{m}_0^2 [(\bar{\omega} \varepsilon_\tau)^2 + (\bar{\tau} \varepsilon_\omega)^2] + \varepsilon_r^2, \quad (8b)$$

where  $\varepsilon_r^2$  is the mean square error of  $\{y_i\}$  caused by observation by the radiometer, which is usually small and neglected from the formula. The budget of dispersions Eq. (8a) leads to the following estimate for a typical air mass sampling from  $m_1=1.3$  to  $m_2=3.5$  and atmospheric conditions of large optical parameter change from  $\tau_1=0.2$  to  $\tau_2=0.4$ , and from  $\omega_1=0.85$  to  $\omega_2=0.95$  during the ILP, as,

$$\left(\frac{\sigma_x}{\bar{x}}\right)^2 \approx \frac{1}{3} \left(\frac{m_2 - m_1}{m_2 + m_1}\right)^2 + \frac{1}{3} \left(\frac{\tau_2 - \tau_1}{\tau_2 + \tau_1}\right)^2 + \frac{1}{3} \left(\frac{\omega_2 - \omega_1}{\omega_2 + \omega_1}\right)^2 = 0.070 + 0.037 + 0.001, \quad (9)$$

if we assume a regular sampling of linear change models for  $m$ ,  $\tau$ , and  $\omega$ . This budget indicates that the wide sampling of air mass is the main contributor to decrease  $\sigma_a^2$ . The IL method allows selection of the atmospheric condition in which  $\tau$  and  $\omega$  undergo natural variations that help to increase  $\sigma_x$  and thus decrease  $\sigma_a$ . But such selection of unstable atmospheric conditions may increase inversion errors,  $\varepsilon_\tau$  and  $\varepsilon_\omega$ , wasting the benefit of natural changes in  $\omega$  and  $\tau$ . It is also possible to have a change in the atmospheric conditions during a short time of less than 5 min in one full angle scan, causing unexpected errors. Sub-networks, therefore, have their own screening protocols for ILP using stability of time sequence of variables to reject ill condition data for ILP. They also reject large AOT cases to secure the calibration accuracy, e.g. AOT > 0.4 by ESR (Campanelli et al., 2004).

Combining Eqs. (7) and (8), we have the following estimate for  $\sigma_a$  assuming  $b$  and  $\omega$  are close to 1,

$$\sigma_{a,IL} = \frac{3.5}{\sqrt{n}} \frac{\bar{m}_0^2}{|m_2 - m_1|} \gamma \bar{\tau} \sim \frac{9.2}{\sqrt{n}} \gamma \bar{\tau} \sim \frac{1.3}{\sqrt{n}} \bar{\tau} \quad (10a)$$

$$\gamma \equiv \sqrt{\left(\frac{\varepsilon_\tau}{\bar{\tau}}\right)^2 + \left(\frac{\varepsilon_\omega}{\bar{\omega}}\right)^2}. \quad (10b)$$

The third expression of rhs Eq. (10a) is an estimate for  $m_1=1.3$  and  $m_2=3.5$  and the rightmost one is an approximation with 10% relative errors in inversion of  $\tau$  and  $\omega$  as a typical example of ILP. This estimate indicates the accuracy of  $\ln(F_0)$  from the IL method is proportional to the OT during ILP operation at the site. Table 3 lists mean values of  $n$ ,  $\tau_a$  and  $\sigma_{a,IL}$  per 30 days (month) obtained by ILP operation carried out at Tokyo University of Science (TUS) and Rome sites.

The table shows the monthly value of  $\sigma_{a,IL}$  ranges from 0.5% to 2.4% with a tendency to increase with decreasing wavelength. We also estimated  $\sigma_{a,IL}$  by Eq. (10) with optimum

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$\gamma$ -values of 7% and 15% for Tokyo and Rome, respectively. These estimates correspond to 5% and 11% for relative retrieval errors  $\varepsilon_r / \langle \tau \rangle$  and  $\varepsilon_{\theta} / \langle \theta \rangle$  during ILP operation.

The monitoring ability of  $F_0$  by IL on site has merits such as low cost, frequent calibration to detect the changing constants and a short-term ESI change, and minimizes the radiometer environmental change avoiding shipping for calibration. The error in  $F_0$  is propagated to cause an error in OT from Eq. (3) as,

$$\varepsilon_{direct, \tau} \sim \frac{\sigma_a}{m_0}. \quad (11)$$

A rough estimate of  $\Delta$ OT error by the IL calibration is expected to be the order of 0.003 to 0.01 for  $m_0 = 2$ , in the case of Table 3, though real errors depend on detailed setup and observation sequence at each site. It is important to compare this accuracy of IL with that of SL. In the SL case, we assume  $x = m$  in Eq. (6a), so that the error estimate Eq. (7b) is reduced to the following expression as,

$$\sigma_{a,SL}^2 = \frac{\tau'^2}{n} \left( 1 + \frac{\bar{m}^2}{\sigma_m^2} \right), \quad (12a)$$

where we assume the error in  $a$  is caused by a part of OT change during the SL plot which tends to the inverse of the optical airmass as,

$$\tau = \bar{\tau} + \frac{\tau'}{m}. \quad (12b)$$

A measure of OT change during airmass change from  $m_1$  to  $m_2$  can be defined as

$$\delta_\tau \equiv \frac{\tau_1 - \tau_2}{2} = \frac{1}{2} \left( \frac{1}{m_2} - \frac{1}{m_1} \right) \tau' = 0.24 \tau'. \quad (12c)$$

The rightmost estimate is given for  $m_1 = 1.3$  and  $m_2 = 2.5$  as an example. If we assume  $\delta_\tau / \bar{\tau} = 0.1$  as same as inversion error in the estimate of IL accuracy, the following estimate is given as,

$$\sigma_{a,SL} = \frac{1.6}{\sqrt{n}} \bar{\tau}. \quad (13)$$

This estimate of the SL error is similar to that of IL given in Eq. (10), suggesting the SL performance is similar to or slightly larger than that of IL under conditions of 10% change in OT during the SL plot. Selection of the calibration methods, therefore, depends on the character of the turbidity conditions at the site. There are reports from city-area sites, such as Rome, Beijing and Chiba city, that the accuracy of SL method exceeds 1 to 2% worse than that of IL method, suggesting  $\varepsilon_r / \bar{\tau} > 0.1$  commonly happens at these sites, so that we recommend comparison of  $F_0$  values from both SL and IL methods to diagnose the calibration quality of the SL and IL methods. At the same time, we recommend high mountain calibration and/or transfer

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This error estimate is comparable to the RMSD of

1 to 2% regardless of wavelength in the  $F_0$ -time series obtained by the ESR data analysis with 30 to 60 days calibration period with the IL method (Campanelli et al., 2004, 2007). [1](#)

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of calibration constants from a well-calibrated standard radiometer to keep the on-site IL calibration healthy.

The SKYNET community performed high mountain calibrations at Mauna Loa (USA, 3397mMSL) and two similar pristine aged-background sites (AOT<sub>500</sub>~0.05, AOT at  $\lambda=$  500nm), Indian Astronomical Observatory (IAO), Hanle (Mt. Saraswati, 32°47'N, 78°58'E, 4500m MSL) and Merak (33°48'N, 78°37'E, 4310m MSL), located in the high-altitude Ladakh region in the north-western Himalaya. Figure 4 shows retrieved values of  $F_0$  and SVA from the observation taken by a single instrument (POM-01) from IAO-Hanle during January 2008-December 2010 and June 2015-December 2018 and Merak during January 2011-May 2015.

They used the Skyrad pack software for data screening with a condition of RMSD of SVAs below 0.20, while the median value of the long-term data as much as 0.05. The observation were taken from a wide range of AOTs with minimum (instantaneous) 0.01 to maximum 0.22 with the annual averaged AOT as  $0.045 \pm 0.026$  at 500 nm during 2008 to 2018 at the two sites. Due to limiting cloudy conditions in the afternoon, 35% of the disk scanning work is performed in between 8-9am at this site. Since the disk scanning procedure takes around 20-25 minutes to complete the entire wavelengths, it is apparent that in some cases, some wavelengths may have been affected by thin (cirrus) clouds which carried by strong winds (above 15 m/s) at both the sites. The figure indicates the RMSD of  $\ln(F_0)$  from SL and IL methods agree within about 0.5%. This  $F_0$  uncertainty is smaller than the minimum value of  $\sigma(a,IL)$  about 0.5% at Tokyo and Rome shown in Table 3 and corresponds to an estimate Eqs. (10) and (13) assuming the mean AOT at the site of order of 0.03 at  $\lambda=500\text{nm}$  and  $n=100$ . The figure shows that the disk scan method, discussed in the next section, was obtained with monthly mean SVA within 1.5% for all the spectral channels. The disk scan was performed from observations taken under full clear sky conditions with minimum 3-5 days data in every month (Ningombam et al., 2014). Therefore, there are 12 values of SVA in all the spectral channels in a year. The vertical bar indicates a representative RMSD of monthly means in each year.

The first Quality and Traceability of Atmospheric aerosol Measurements (QUATRAM, <http://www.euroskyrad.net/quatram.html>) Campaign compared the  $F_0$ -value from IL method with that of the standard Precision Filter Radiometer (PFR) (Kazadzis et al., 2018b) of the World optical depth Research and Calibration Center (PMOD/WRC). A preliminary analysis showed the difference is 0.3% at Davos (1590m MSL) where the mean AOT<sub>500</sub> is 0.15 and AOT<sub>500</sub> in clean aerosol conditions is 0.05. This  $F_0$  uncertainty is similar to those of the IOA sites and again smaller than the minimum value in Table 3, indicating the importance of the careful constant calibration effort at high mountains.

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Another important point to note is that comparison of Eqs. (3) and (6) lead to the following relation,

$$b = -\frac{1}{\omega}. \quad (14)$$

The forward scattering analysis of the IL method prescribes the refractive index, so that it is highly possible for  $x$  in Eq. (5a) to include a factor type systematic error like,

$$x = Cx_0. \quad (15a)$$

In this case, Eq. (6) results in the following relation between fitted and true values of  $a$  and  $b$ ,  $a_0$  and  $b_0$ , as

$$b = \frac{1}{C}b_0, \quad a = \bar{y} - \frac{1}{C}b_0C\bar{x}_0 = \bar{y} - b_0\bar{x}_0. \quad (15b)$$

This result shows that the formula of  $a$  in Eq. (7a) is invariant to the factor type error indicating the robustness of the IL calibration. On the other hand, the  $b$ -value changes depending on the value of  $C$  and takes a value  $-1/\omega$  according to Eq. (14). Boi et al. (1999) utilized this point and proposed an iterative IL method to improve the  $F_0$ -value and find the optimum CRI by trying several refractive indices. They reported the method can improve the precision of  $F_0$  by 30%, e.g. 2% to 1.5%.

There is another caution regarding use of the formulae Eq. (7a). In the real observation, it is difficult to separate natural variations and inversion errors of  $\tau$  and  $\omega$ , so that the dispersion  $\sigma_x$  tends to include undesired inversion errors, that lead the IL method to underestimation of  $a$  and  $b$  as understood by Eq. (7b). We are testing a new solution to this problem, named the cross IL method (XIL), which exchanges the role of  $x$  and  $y$  in the regression analysis, i.e.,

$$x_i = \alpha + \beta y_i + v_i, \quad i = 1, \dots, n, \quad (16a)$$

$$b = \frac{1}{\beta}, \quad a = -\frac{\alpha}{\beta}. \quad (16b)$$

Figure 5 presents retrieved values of  $a$  ( $=\ln F_0$ ) from IL and XIL methods with ten ensemble runs of an idealized experiment with  $F_0=1$ ,  $\omega=1$ ,  $\tau=0.1$ ;  $n=20$  and  $m=1.3$  to 3.5 as a function of normal random errors  $\varepsilon_x$  in  $x$ . The figure shows that the IL method underestimates the  $a$ -value, while the XIL stays accurate within RMSE less than 0.03 up to  $\varepsilon_x=0.01$  (10% of  $\tau=0.1$ ) and 0.05 at  $\varepsilon_x=0.025$  (25% of  $\tau=0.1$ ), as consistent with Eq. (10). Figure 6 and Table 4 compares results of IL and XIL methods with the following screening conditions applied to 38 sets of real Langley plot data at TUS site for four months from February through May 2017:

$$m_2/m_1 \geq 2, \quad b(\text{SL}) < 10, \quad 0.8 \leq b(\text{IL}), \quad \text{and} \quad b(\text{XIL}) \leq 1.2, \quad \varepsilon_a(\text{IL}), \quad \text{and} \quad \varepsilon_a(\text{XIL}) \leq \varepsilon_{a0}, \quad (17)$$

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where  $m_1$  and  $m_2$  are lower and upper limits of airmass in the ILP. The threshold residual  $\varepsilon_{i0}$  is given as 0.02, 0.03 and 0.05. The figure and table indicate that the  $a$ -value from SL is largely scattered, suggesting determination of  $F_0$  by SL at turbid sites like Tokyo is not recommendable. On the other hand,  $a$ -values from IL and XIL converge on a regression line within differences of 2-3%, with a tendency of systematically smaller values by IL than those from XIL method by amounts of  $\varepsilon_{i0}$  and  $\varepsilon_{i0}/2$ , respectively. Although the difference between IL and XIL is not large as far as we select low noise data, we would like to recommend the XIL method to be applied to 5 to 10 Langley plot data sets in order to secure the accuracy of 1% to 2% in  $F_0$  using the screening conditions of Eq. (17). The figure also shows that we can detect a long-term decreasing trend of  $a$ -value by about 10% during the period at the TUS site.

#### 4. Sky radiance calibration for the sky radiometer

Several methods have been proposed for on-site calibration of the sky radiance measured by the sky radiometer, such as solar disk scan method, point-source method or lamp scan method, and diffuse plate method (Nakajima et al., 1986, 1996; Boi et al., 1999). Among them, the solar disk scan method has been routinely used in the SKYNET measurement of the SVA of the sky radiometer by scanning a circumsolar domain (CSD) of  $\pm 1^\circ$  by  $\pm 1^\circ$  around the sun with every  $0.1^\circ$  interval.

The irradiance received by the radiometer, which is aimed at the direction  $(x, y)$  in a Cartesian coordinate system of angular distance from the center of the solar disk at origin  $(x=0, y=0)$ , is an angular integration of radiances weighted by the response function of the radiometer  $f_R$  in the field of view (FOV),

$$F(x, y) = \iint_{FOV} dx' dy' f_R(x' - x, y' - y) L(x', y'). \quad (18)$$

In the case of diffuse sky radiance measurement, the SVA of the radiometer is given from Eqs. (1) and (18) as,

$$\Delta\Omega = \iint_{FOV} dx' dy' f_R(x', y'). \quad (19)$$

In the case of the solar disk scan, the main term for  $F$  is given as follows under conditions of small contribution from diffuse sky radiation in the CSD,

$$F(x, y) = \iint_{FOV} dx' dy' f_R(x' - x, y' - y) L_d(x', y'), \quad (20a)$$

where  $L_d$  is the radiance distribution of the solar disk. The angular aperture of the sky radiometer is about  $1^\circ$ , whereas the solar disk radius is about  $0.5^\circ$ , so that we can measure the solar disk-averaged value of the radiometer response function as,

$$\bar{f}_R(x, y) = \frac{F(x, y)}{F_d} \quad (20b)$$

From Eqs. (1), (20a) and (20b), the following normalization condition has to be fulfilled,

$$\bar{f}_R(0, 0) = 1. \quad (20c)$$

The SVA can be obtained by the angular integration of the radiance in the CSD as,

$$\begin{aligned} I &= \iint_{CSD} dx dy \bar{f}_R(x, y) = \frac{1}{F_d} \iint_{CSD} dx dy \iint_{FOV} dx' dy' f_R(x' - x, y' - y) L_d(x', y') \\ &= \frac{1}{F_d} \iint_{FOV} dx' dy' L_d(x', y') \iint_{CSD} dx dy f_R(x' - x, y' - y) = \Delta\Omega \end{aligned} \quad (20d)$$

The last expression is obtained by Eqs. (19) and (20c), if the size of CSD is large enough to include FOV or the contribution outside the CSD is small. These equations indicate flatness of the response function around the optical axis should be secured in manufacturing the sky radiometer for stable measurement of the direct solar radiation through Eq. (20b). The perfect flatness is realized by optics without an objective lens, which is useful for moving platform such as aircraft and ship (Nakajima et al., 1986).

Analyzing data from the solar disk scan, Uchiyama et al., (2018b) found an underestimation of SVA from the disk scan method of 0.5 % to 1.9 % and proposed a correction method by extending CSD size up to scattering angle of 2.5° assuming an extrapolation function as illustrated in Fig. 7. They also discussed that the SVA error by the disk scan can exceed 1% for large AOT conditions such as AOT550>0.5 and proposed a subtraction method using sky radiance calculated from the size distribution retrieved from the relative radiance. This subtraction method can reduce the error to 0.5% for AOT550< 2 for sky radiance measurements with the minimum scattering angle  $\Theta=3^\circ$ . The recent CEReS system has introduced a QC control for setting the optimal value of SVA for each site including Uchiyama's method, but no other sub-networks implement these correction methods in their operational analysis.

Though not performed routinely, a Xe-lamp scan has been performed in CEReS for the current version of the sky radiometer (Manago et al., 2016). The merit of the method is that we can narrow the size of the point source below 0.5° and can extend the CSD size beyond ±1° without significant effect of the sky light. Then, measured SVAs were compared with those derived from the solar disk scan in daytime. From the experiments, uncertainty in SVA was estimated to be less than ±0.01 msr or ±4% (Irie et al., 2019). This value is larger than that of Uchiyama et al. (2018b) and more experiments may be needed for more precise estimates and a unit variety.

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## 5. Retrievals of parameters for atmospheric constituents

Once the values of radiometer calibration constants,  $F_0$  and  $SVA$ , are determined by the calibration methods described in the preceding two sections, the geophysical parameters of aerosols, clouds, water vapor and ozone are retrieved by inversion of  $F$  and/or  $R$  in Eqs. (2a) and (2c) at full or specific scattering angles (Fig. 3). Aerosol retrievals are done using Skyrad pack version 4.2 and/or version 5. The former is based on inversion scheme of the Phillips-Twomey type solution of the first kind of Fredholm integral equation with homogeneous smoothing constraint and the latter is based on the second kind of the equation with inhomogeneous constraint with a priori climate data for aerosols (Twomey, 1963) to retrieve the inherent aerosol optical properties. These methods can be generalized by minimization of a cost function  $\phi$  for realization of an observation vector  $\mathbf{y}$  as a function of a state vector  $\mathbf{x}$  with observation error  $\mathbf{e}$  by a multi-term least square method (LSM) (Dubovik and King, 2000; Dubovik, 2004, Dubovik et al., 2011),

$$\mathbf{y} = \mathbf{f}(\mathbf{x}) + \mathbf{e}, \quad (21a)$$

$$\phi = \mathbf{e}'\mathbf{S}_e^{-1}\mathbf{e} + \phi_1 + \phi_2, \quad (21b)$$

$$\phi_1 = (\mathbf{x} - \mathbf{x}_a)'\mathbf{S}_a^{-1}(\mathbf{x} - \mathbf{x}_a), \quad \phi_2 = \mathbf{x}'\mathbf{G}\mathbf{x}, \quad (21c)$$

where superscript  $t$  stands for matrix transpose operation,  $\mathbf{S}_e$  is the error covariance matrix,  $\phi_1$  is the norm of the solution from the a priori data  $\mathbf{x}_a$  with its associated covariance  $\mathbf{S}_a$ ,  $\phi_2$  is a cost for smoothness of the solution with  $\mathbf{G}$  matrix related with the norm of the second derivatives of  $\mathbf{x}$ . The AERONET analysis uses both the constraints,  $\phi_1$  and  $\phi_2$ , but with only two elements for  $\phi_1$  at the smallest and largest size bins and with the value at the largest size bin as small as to give a contribution to AOT440 wavelength (Dubovik et al., 2006). Skyrad pack versions 4.2 and 5 respectively adopt a third and second term of rhs Eq. (21b), but not both. The latter case of version 5 corresponds to the Maximum a Posteriori solution (MAP) based on the Bayesian theorem (Rodgers, 2000). The MRI version of Skyrad pack uses a  $\phi_1$  constraint similar to version 5. An iterative search of the nonlinear solution is made by the Gauss-Newton method as

$$\mathbf{x}_{i+1} = \mathbf{x}_i + (\mathbf{K}_i'\mathbf{S}_e^{-1}\mathbf{K}_i + \mathbf{S}_a^{-1} + \mathbf{G})^{-1}[\mathbf{K}_i'\mathbf{S}_e^{-1}(\mathbf{y} - \mathbf{f}(\mathbf{x}_i)) - \mathbf{S}_a^{-1}(\mathbf{x}_i - \mathbf{x}_a) - \mathbf{G}\mathbf{x}_i], \quad (22a)$$

$$\mathbf{K}_i = \nabla_{\mathbf{x}}\mathbf{F}(\mathbf{x})\Big|_{\mathbf{x}=\mathbf{x}_i}. \quad (22b)$$

The version 4.2 uses Eq. (22a) without  $\mathbf{S}_a$  terms and the version 5 uses the one without  $\mathbf{G}$  terms. Observation and state vectors are given as:

$$\mathbf{y} = \{\tau_a(\lambda_i), R(\lambda_i, \theta_j, \phi_j)\}_{i=1, \dots, N_\lambda; j=1, \dots, N_\theta}, \quad (23a)$$

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$$\mathbf{x} = \{\ln(V_j), \ln(\tilde{n}_r(\lambda_j), \ln \tilde{n}_i(\lambda_j)) | i = 1, \dots, N_r; j = 1, \dots, N_v\}. \quad (23b)$$

where geophysical parameters for the state vector are aerosol volume SDF as a function of logarithm of particle radius  $r$ ,  $x = \ln r$ , and real and imaginary parts of CRI, i.e.  $\tilde{n} = \tilde{n}_r - \tilde{n}_i i$ , as functions of wavelength. The SDF is represented by a linear combinations of base functions  $\{f_k\}$ .

$$v(x) = \frac{dV}{dx} = \sum_{k=1}^{N_v} V_k f_k(x), \quad x = \ln r. \quad (24a)$$

The package allows two types of base functions, i.e. box-car functions or log-normal functions with mode radii  $\{x_k\}$  regularly spaced in  $x$ -axis,

$$f_k(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{x-x_k}{\sigma}\right)^2\right]. \quad (24b)$$

The standard analysis in sub-networks assumes twenty log-normal base functions ( $N_v = 20$ ) from  $r = 0.02 \mu\text{m}$  to  $20 \mu\text{m}$  with dispersion  $\sigma = 0.4$ , though there is a discussion for a narrower value (Momoi et al., 2020). A priori value of the CRI is usually given as  $\tilde{n} = 1.5 - 0.005i$ . The version 4.2 retrieves  $\mathbf{x}$  through the following four steps: (Step-1) The SDF for  $\mathbf{x}_a$  are assumed to be a bimodal log-normal size distributions ( $N_v = 2$ ) with  $r_1 = 0.1 \mu\text{m}$ ,  $r_2 = 2 \mu\text{m}$ , and  $\sigma_1 = 0.4$ ,  $\sigma_2 = 0.8$ , and volumes of the two modes are set as same,  $V_1 = V_2$ , and estimated from the forward radiance data ( $\Theta \leq 30^\circ$ ). (Step-2) Retrieve  $\tilde{n}_r$  from the radiance data in ( $20^\circ, 70^\circ$ ). (Step-3) Retrieve  $\{V_k\}$  from the forward radiance data to revise  $\mathbf{x}_a$ . (Step 4) Retrieve SDF and CRI from the full angle scan data. The step 4 is iterated until a conversion criteria is fulfilled. On the other hand, the version 5 follows Step-1, 2, and 4 without step-3. The standard analysis at sub-networks does not treat asphericity of mineral dust and sea-salt particles and assumes Mie particles, other than in research studies.

The package adopts the IMS method for solar aureole radiance calculation (Nakajima and Tanaka, 1988) for full scalar radiative transfer code, Rstar, with polarization correction by Ogawa et al. (1989) to save computing time. A full polarization vector code, Pstar (Ota et al., 2010), is also used for research purpose (e.g., Momoi et al., 2020). Asphericity is treated by an approximation of Pollack and Cuzzi (1980) and by several aspherical kernels. Those softwares are available at OpenCLASTR. Other than polar region measurements, the surface albedo is prefixed as 0.05 or 0.1 at wavelengths shorter than 400nm and 0.1 at longer wavelengths.

Figure 8(a) and Table 5 compare observed AOT values with those of AERONET at four co-located sites of Chiba/Japan, Pune/India, Valencia/Spain, and Seoul/Korea (Khatri et al. 2016). They found RMSDs were 0.019 at 675nm and about 0.015 at 870nm and 1020nm with some site dependence as 0.010, 0.033, 0.009, and 0.022 at 870nm at the four sites, respectively.

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Che et al. (2008) reported that AOTs between sky radiometer (POM02) and Cimel sunphotometer at a Beijing site, China agreed within a relative AOT RMSD of about 1% without a large wavelength dependence, i.e. 0.91, 1.03, 0.82, 1.27% at  $\lambda = 440, 6700, 870, 1020\text{nm}$ , respectively, which corresponds to  $\epsilon_r = 0.005$  for a representative optical airmass of 2 or  $\sigma_r = 0.6\%$  in Eq. (10) for a representative AOT of 0.3 at the site. The value of the Ångström exponent agrees within 6% between 440nm and 870nm and 1% between 500nm and 870nm. F

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though not shown in a table. Che et al.(2008) compared the AOTs between POM-02 skyradiometer and Cimel CE-318 sunphotometer at the top of Institute of Atmospheric Physics(IAP) in Beijing which belongs to SKYNET and AERONET respectively. The POM-02 data were processed by Skyrad pack 4.2. They found RMSD of 0.025 at 440nm and 0.018 at other wavelengths, which are similar to those of Khatri et al, even with the mean AOT at this site as large as 0.33 at 675nm. RMSDs of the Ångström exponent were 0.19 between 440nm and 870nm and 0.28 between 500nm and 870nm, though not shown in a table.

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SKYNET instruments are regularly compared with Precision Filter Radiometer (PFR) instruments belonging to the World optical depth Research and Calibration center (WORCC) and the Global Atmospheric Watch PFR network. Results of three POM instruments compared with the reference WORCC triad in 2015 showed differences less than 0.005 and 0.01 in all cases and for 500nm and 865 nm respectively during the 4<sup>th</sup> filter radiometer comparison (Kazadzis et al., 2018a). At the same campaign Ångström exponent mean differences were less than 0.5. Under low aerosol conditions, a small relative bias in the AOT determination at 500nm and 865nm can theoretically lead to large deviations in the calculated Ångström Exponents (AE). As an example, for AODs of about 0.05 and 0.02 at 500 and 865 nm, respectively, AOT differences of 0.01 and 0.005, respectively, can lead to AE differences up to ~1. Since 2015 PFR vs POM long-term comparisons have been performed at various stations, i.e. Valencia/Spain, Chiba/Japan, Davos/Switzerland and in the QUATRAM campaign at Rome/Italy (Kazadzis et al., 2018a; personal communication by Campanelli), Figure 8(b) and Table 5 compare AOTs at Davos from those of PMOD PFR. The PFR comparison uses the result from SUNRAD pack (Estelles et al., 2012a) where only direct measurements from the sky radiometer are used to retrieve AOT, having an higher time resolution with respect to direct measurement performed during the almucantar scenarios. They found RMSD as small as 0.007 and 0.001 at 500nm and 870nm, respectively.

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Using multi-radiometer observation data since 2016 at Yonsei University, Korea in a validation study for the upcoming Geostationary Environment Monitoring Satellite (GEMS) (Kim et al., 2020), Go et al. (2020) compared AOTs from Cimel sunphotometer, Ultraviolet Multifilter Rotating Shadowband Radiometer (UV-MFRSR), NASA Pandora sun spectrometer, and POM-02 sky radiometer. As shown in Table 5, they found RMSDs between AOT values from POM-02 and Cimel sunphotometer as 0.029 to 0.036 for  $\lambda < 440\text{nm}$  and 0.009 to 0.015 for  $\lambda \geq 500\text{nm}$ .

Those statistics shown in Table 5 indicate that the RMSD took a value less than 0.02 for  $\lambda \geq 500\text{nm}$  and a larger value about 0.03 for shorter wavelengths in city areas, whereas mountain comparisons show smaller RMSDs less than 0.01. This location difference can be understood

by  $F_{\rho}$  uncertainties around from 0.5% to 2.4% in Tokyo and Rome and smaller values around 0.3% to 0.5% at the mountain sites of IOA and Davos as discussed in Section 3, though uncertainties in AOT comparisons can include other error sources, such as pointing error, time variation and errors in the retrieval software. Estellés et al. (2012b) discussed this point by comparison of AERONET AOT values with those retrieved by their SUNRAD pack for the same sunphotometer, but with two different analysis modes, i.e. mode-1 which implements the SKYNET extinction model and mode-2 with AERONET-like model. As listed in Table 5, they found RMSD about 0.01 for  $\lambda \geq 440\text{nm}$  and larger value in UV channels with mode-1 setup, whereas mode-2 setup give a very small RMSD less than 0.005. Therefore more than half of the RMSDs found in the comparison between SKYNET and AERONET can be attributed to differences in the analysis software. Skyrad pack assumes a simplified extinction model with a plane parallel assumption in the optical airmass formula, ignores water vapor absorption in IR channels, and the ozone absorption extinction model in the UV channels is different from the AERONET model. Slightly larger values at 1020nm than at 875nm may be due to omitting water vapor absorption. Further work is needed to study the effects of these simplifications, which need improvements. For example, SKYNET poses an IL operation limit as  $m_{\rho} \leq 3$ , instead of  $m_{\rho} \leq 5$  in the data analysis of Estellés et al. (2012b) shown in Table 5.

Table 6 lists reported SSA differences from other networks. SSA values from SKYNET are known to be overestimated as pointed out by Che et al. (2008). Mean values of SSA in Beijing retrieved from the PREDE skyradiometer were significantly larger than those from the Cimel sunphotometer, with differences reaching 0.06 to 0.07 for  $\lambda \geq 870\text{nm}$ , whereas the mean differences were less than 0.03 at shorter wavelengths. This wavelength dependence can be understood by a tendency of error to increase with decreasing AOT (Dubovik et al., 2000). Similarly Khatri et al. (2016) had a positive difference of about 0.07 RMSD for  $\lambda \geq 675\text{nm}$  from AERONET values at the four sites (Chiba, Pune, Valencia, and Seoul). And they found the values can be reduced to around 0.03, if various corrections are applied. The major error source was SVA underestimation of 1.4% to 3.7% causing an SSA increase of 0.03 to 0.04. There were AOT underestimation of 0.02 RMSD at 675nm, as shown in Table 5, which caused an SSA increase of 0.02 at 675nm and less than 0.004 at longer wavelengths. Version 4.2 of Skyrad pack tended to give larger SSA than version 5, but the difference was less than 0.01 for usual aerosol conditions in their case. Effects of surface albedo and asphericity to the SSA difference were less than 0.01. These effects are consistent with those obtained by sensitivity simulations by Pandithurai et al. (2008) and Hashimoto et al. (2012) in a similar way to one described by Dubovik et al (2000). Pandithurai et al. found errors such as 5% error in  $F_{\rho}$ , SVA and 0.5° error in azimuth angle pointing in SKYNET which can induce an error of 0.03 in retrieved AOT and

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mean and maximum differences in retrieved SSA are about 0.004 and 0.02. Hashimoto et al. found in a numerical simulation at 500nm as shown in Table 6, i.e. a positive SSA retrieval error of +0.03 can be caused by SVA underestimation of about 5%, AOT underestimation of about -0.02, and ground albedo underestimation of about -0.1.

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5 Aerosol properties in the UV spectral region were extensively measured in the KORUS-AQ campaign (<https://espo.nasa.gov/korus-aq/content/KORUS-AQ>), Mok et al. (2018) compared SSA retrievals as shown in Fig. 9 and Table 6 from SKYNET SR-CEReS, AERONET, and Pandora AMP radiometers, from April to August 2016 at Yonsei University, Korea. They found differences around 0.02 for  $\lambda \leq 500\text{nm}$  and a larger value as 0.05 at 870nm as similar to those of

10 Che et al. (2008) and Khatri et al. (2016) shown in Table 6. They also found that the SSA difference increased by 0.004 to 0.008 in short wavelengths when they adopted a spectrally fixed ground albedo  $A_g$  at 0.1 assumed in the SKYNET analysis, instead of original setup of spectrally varying AERONET ground albedo  $A_g$ .

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15 Cloud contamination is another significant error source as studied by Hashimoto et al. (2012). They studied a case of cirrus contamination detected by a lidar observation in Beijing, and found that Skyrad pack version 4.2 retrieved SSA values larger by 0.017 to 0.035 than those from version 5 as shown in Table 6. Version 4.2 simply retrieves a cloud particle volume as coarse mode aerosol volume with the smoothness constraint  $\phi_2$  in Eq. (21), but the version 5 can filter out the cloud particles owing to a priori constraint  $\phi_1$  on SDF. This robustness of

20 version 5 to cloud contamination makes the inversion of the aerosol SDF robust to various noises as reported by Che et al. (2014) and Jiang et al. (2019) who demonstrated a clear aerosol bimodal size distribution over Beijing in China by using Skyrad pack version 5. Hashimoto et al. (2012), therefore, proposed a data screening protocol to reject unusually large coarse particle volume: (C1)  $\text{AOT}_{500} < 0.4$ , (C2)  $\varepsilon_c < 0.07$ , and (C3)  $2 \times V_{2.4\mu\text{m}} < \max(V_{7.7\mu\text{m}}, V_{11.3\mu\text{m}}, V_{16.5\mu\text{m}})$ .

25 Application of this screening protocol reduced SSAs by version 4.2 closer to version 5 and AERONET values within 0.03 for eight to nine month data at Pune (India) and Beijing (China).

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In order to study the consistency of retrieved parameters, sky radiometer users attended inter-comparison campaigns with other networks, like ... cloud contamination is another ... [9]

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30 It is also interesting to compare the sky radiometer method with other methods. Kim et al. (2004, 2005) compared SSAs from a sky radiometer with those estimated by the diffuse direct method (King and Herman, 1976) using data from a collocated pyranometer network in the APEX campaign (Asian Atmospheric Particle Environmental Change Studies) (Nakajima et al., 2003). This method is especially beneficial for the climate study community, because the method gives effective SSA values consistent with the earth radiation budget. They found RMSD at 500nm about 0.03 from data in Amami-Oshima Island. This value is consistent with other values in Table 6.



One reservation about the SSA retrieval by version 5, though, is that it tends to underestimate the SSA due to underestimation of the coarse aerosols when the a priori SDF for constraint tends to zero for radii larger than 10 $\mu$ m. Hashimoto et al. (2012) showed by their numerical simulation of an enhanced mineral dust case that the version 5 tends to underestimate SSA by 0.017 to 0.035 compared to version 4.2, as shown in Table 6, because the version 5 mistakenly filter out coarse aerosols by the a priori SDF data  $x_c$  in Eq. (21c). Estellés et al. (2018) found similar underestimation of the coarse aerosols by version 5 compared to aircraft in-situ observations (Marenco et al., 2018; Ryder et al., 2018) for African dust events in the sunphotometer Airborne Validation Experiment in Dust (SAVEX-D) campaign during 16-25 August 2015 as shown in Fig. 10. The figure indicates the version 4.2 retrieved coarse mode SDF similar to the observed one though the error bar is large. These examples suggest an improvement of the a priori SDF data is needed for severe dust storm cases.

Water vapor amount is retrieved from direct solar irradiance measurement in the 940nm channel.  $F_0$ -value in the water vapor channel is retrieved by the modified Langley plot (ML or MLP) method based on the following OT formula instead of Eq. (3),

$$y = \ln F_0 - a_g x, \quad (25a)$$

$$y = \ln F + m(\tau_a + \tau_R), \quad x = (m_g C_g)^{b_g}, \quad (25b)$$

where  $\tau_a$  and  $\tau_R$  are AOT and OT for molecular scattering, respectively, and  $C_g$  is the column-integrated burden of gaseous species, i.e.,  $PWV$  in this case;  $m_g$  is optical air mass for the gaseous species;  $a_g$  and  $b_g$  are two prescribed constants to approximate the beam transmittance due to the gaseous species;  $a_g$  can be regarded as an equivalent absorption coefficient for band-averaged absorption of the gaseous species. It is common to assume  $m_g$  to be as that of atmospheric air mass, i.e.,  $m_g = m$  in the water vapor case. The value of  $\tau_a$  is obtained by an interpolation of the AOT spectrum retrieved from the non-gas absorption channels. There are two algorithms for the SKYNET analysis. One is to use the measured spectral response function of the interference filter of the sky radiometer to prescribe values of  $a_g$  and  $b_g$  by the theoretical absorption calculation (Uchiyama et al., 2014). This method is similar to that of the AERONET method. The strong line absorption theory of the 930nm spectral band yields  $b_g = 0.5$  (Goody and Yung, 1989) in Eq. (25b). However, there is some dependence of  $b_g$  on the vertical structure of the atmosphere, so that an improved method is proposed by Campanelli et al. (2010, 2014, 2018) to determine  $a_g$  and  $b_g$  values by a statistical regression technique of daily observation data at the site. They obtained a range of  $b_g$  value as 0.53 to 0.61 as monthly mean values of three years from 2007 to 2009 at San Pietro Capofiume

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site (SPC; 44° 23' N, 11° 22' E, 11 m MSL), Italy, with some seasonal dependence. One complexity of this method, though, is a need for measurements of  $W$  for making the regression analysis. They used PWV either from radiosonde data or a proxy of PWV constructed from surface meteorological data of temperature and relative humidity. Figure 11 compares PWV by the two methods with GPS and AERONET retrievals in Tsukuba, Japan and Valencia, Spain for data taken in 2011. The figure shows RMSD from validation data is less than 0.2 cm by both the methods, with some systematic underestimation of the slope of the regression line of 10% in the former method. Estellés et al. (2012b) compared PWV at Valencia, Spain between AERONET values and those retrieved by SUNRAD pack for a same Cimel sunphotometer. They found RMSD of 0.20 cm when SUNRAD pack uses mode-1 (SKYNET-like) setup, whereas it is reduced to 0.17 cm if SUNRAD uses mode-2 (AERONET-like) setup, indicating performances of the two modes are similar to each other in water vapor retrievals, compared to a significant difference in the AOT case as shown in Table 5.

In order to get rid of the  $F_0$  retrieval process in the water vapor channel, Momoi et al. (2020) proposed a new method of using water vapor dependence of the relative radiance along the almucantar circle of the sky. Although this method has a limited range of retrievable PWV less than 2 cm, there is a merit in using the value from the method, say  $W_{sky}$ , as a proxy of  $C_g = W$  in Eq. (25b) to perform the MLP on site, similar to the IL method for the non-absorption channels, but with

$$x = W_{sky}^{b_g} \quad (26)$$

instead of Eq. (25b).

The columnar ozone amount ( $O_3$ ) is retrieved from the direct solar irradiance measurement of 315 nm channel for the Huggins band. Khatri et al. (2014) determined the  $F_0$ -value by a ML method Eq. (26) assuming  $b_g=1$  for ozone without a significant line absorption structure. The formula of  $m_g$  is given by Robinson (1966). In the  $F_0$  determination process, they simultaneously obtained an optimal value of the equivalent ozone absorption coefficient  $a_g$  which bring the slope of the ML plot to unity using data of ozone column burden  $C_g = U$  measured by the Dobson spectrometer. RMSD of the fitting for a campaign data at Tsukuba site from 13 December, 2012 to 8 January, 2013 was 13 Dobson Unit (DU) as shown in Fig. 12. They also reported a large degradation of filter transmission in the ozone channel.

Cloud microphysical properties have been obtained from diffuse sky radiance measurements from satellites (Nakajima and King, 1990). Similar approach can be applied to the ground-based radiance measurements. Chiu et al. (2010, 2012) retrieved cloud optical thickness (COT) and effective particle radius (CER) from AERONET data. SKYNET uses the

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POM-02 sky radiometer which has 1.6  $\mu\text{m}$  and 2.2  $\mu\text{m}$  channels (Kikuchi et al., 2006; Khatri et al., 2019). Figure 13 compares COT retrieved from POM-02 at zenith observations at the three sites of Chiba, Fukue and Hedo combined with retrievals from Himawari-8/AHI satellite-borne imager in a period of October 2015 to December 2016 (Khatri et al., 2019). Satellite retrieval results were obtained by the Comprehensive Analysis Program for Cloud Optical Measurement (CAPCOM) (Nakajima and Nakajima, 1995) in the system of AMATERASS (Takenaka et al., 2011; Damiani et al., 2018). Geostationary satellite observation has a merit of frequent time-matching with the ground-based observation. The figure shows there is a large scatter of RMSD as 10.2 and a correlation of 0.89. They also studied cloud effective particle radius, but did not find a significant correlation between SKYNET and AHI observations. Figure 14 also compares the broad-band radiance at zenith measured by a ground-based pyrhelimeter and with broad-band horizontal radiative flux measured by a pyranometer with those theoretically calculated using the cloud parameters from sky radiometer measurement. The figure indicates that the down-welling radiance at zenith was consistent between the two radiometers, but horizontal radiative flux were not well represented by the cloud optical properties retrieved from the sky radiometer at nadir. Figures 13 and 14 suggest that the inhomogeneity of cloud fields is a main source of differences between the cloud parameters obtained by the sky radiometer and satellite measurements.

## 6. Conclusions

The SKYNET community has undertaken efforts for improving the on-site calibration and analysis systems to provide retrieved aerosol and other atmospheric constituents.

An estimate of the retrieval accuracy of  $F_{0\lambda}$  is given by Eq. (10) for the IL method, which can serve as an approximation to observed monthly mean uncertainty in  $F_{0\lambda}$  as 0.5% to 2.4% in Tokyo and Rome sites and smaller values around 0.3% to 0.5% at the mountain sites of IOA and Davos. These values are consistent with RMSD values in the AOT comparisons with other networks less than 0.02 for  $\lambda \geq 500\text{nm}$  and a larger value about 0.03 for shorter wavelengths in city areas, and smaller values less than 0.01 in mountain comparisons. We also developed a new XIL method to correct an underestimation by the IL method in case of large aerosol retrieval errors.

Several causes of larger SSA values reaching 0.07 than those of other networks have been identified as underestimation of SVA measured by the disk scan method and a new lamp scan method, cloud contamination, and others. Recent reported values of the difference are found to be less than 0.03 after these corrections.

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Retrievals of other atmospheric constituents by the sky radiometer are also reviewed. We found accuracies of about 0.2 cm for the precipitable water vapor amount and 13 Dobson Units for the column ozone amount. A new on-site calibration method for water vapor has been developed. The cloud optical properties were found to have some but not large correlation with satellite remote sensing values, suggesting cloud inhomogeneity may be one source of error.

There are several aims for the next step of the SKYNET to make its system more reliable and useful for the science community. The reported useful improvements of the product quality are still in research phase and important to be introduced in the existing operational systems and future system of the ISDC. Also comparison studies showed that the analysis software Skyrad pack may need improvements in its simplified optical model. We want to pursue our on-site calibration system for sustainable operation of the network. However, continuous comparison of on-site calibrations of our standard sky radiometer with high mountain calibrations,

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We thank to Alexander Smirnov of NASA GSFC for useful discussion on the history of sun and sky measurements.

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are needed in order to continue verifying the on-site calibration quality.

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### Table and Figure captions

Table 1. Sites recognized by the International Skynet Committee.

Name	Owner	Country	Location (Lat)	Location (Lon)	Location (MSL, m)	Sub-net analyzers	ISDC
Halley	British Antarctic Survey	Antarctica	75.350S	26.340W	30 m	ESR	
Rothera	British Antarctic Survey	Antarctica	67.340S	68.080W	0m	ESR	
Showa	NIPR	Antarctica	69.006S	39.590E	30m	-	x
Chajnantor, Atacama	Universidad de Santiazgo de Chile	Chile	33.451S	70.686W	5100 m	ESR	
Beijing/CAMS	CMA	China	39.933N	116.317E	106m	CAMS	
Beijing/IAP	IAP-CAS	China	39.977N	116.381E	92m	CAS	
Dunhuang	IAP-CAS	China	40.146N	90.799E	1120m	CAS, Chiba-U	
Hefei	AIOFM-CAS	China	31.897N	117.173E	30m	CAS, U-Toyama	
Lanzhou	Lanzhou-U	China	35.570N	104.133E	1965m	Lanzhou-U	
Qionghai	IAP-CAS	China	19.230N	110.46E	24m	CAS	
Xi'an	XAUT	China	34.25N	108.983E	396.9m	XAUT	
Orleans	NIES	France	47.965N	2.113E	131m	Chiba-U	x
Lindenberg	Meteorologisches Observatorium Lindenberg/Mark	Germany	52.209N	14.121E	120 m	ESR	
Amaravati	IMD	India	16.573N	80.358E	343m	IMD	
Aurangabad	IMD	India	19.876N	75.343E	568m	IMD	
Gangtok	IMD	India	27.339N	88.607E	1650m	IMD	
Guwahati	IMD	India	26.100N	91.580E	54m	IMD	
Hanle	Indian Institute of Astrophysics	India	32.779N	78.964E	4500m	IIAP, Chiba-U	x
Hyderabad	National Remote Sensing Agency, India	India	17.469N	78.486E	811m	IMD, U-Toyama	
Jaipur	IMD	India	27.175N	75.955E	431m	IMD	
Jodhpur	IMD	India	26.300N	73.020E	224m	IMD	
Kolkata	IMD	India	22.650N	88.450E	88m	IMD	
Merak	Indian Institute of Astrophysics	India	33.480N	78.360E	4258m	IIAP, Chiba-U	x
Minicoy	IMD	India	8.274N	73.050E	2m	IMD	
Nagpur	IMD	India	21.100N	79.050E	310m	IMD	

New Delhi/IITM	Indian Institute of Tropical Meteorology	India	28.629N	77.174E	240m	IMD, Chiba-U	
New Delhi/IMD	IMD	India	28.580N	77.210E	216m	IMD, U-Toyama	
New Delhi/NPL	National Physical Laboratory, India	India	28.637N	77.174E	223m	IMD, U-Toyama	
Port Blair	IMD	India	11.670N	92.720E	79m	IMD	
Puducherry	IMD	India	11.942N	79.808E	3m	IMD	
Pune/IITM	Indian Institute of Tropical Meteorology	India	18.537N	73.805E	559m	IMD, Chiba-U	
Pune/IMD	IMD	India	18.530N	73.850E	559m	IMD	
Raipur	IMD	India	21.251N	81.630E	298m	IMD	
Ranichauri	IMD	India	30.250N	78.080E	1800m	IMD	
Rohtak	IMD	India	28.830N	76.580E	214m	IMD	
Sagar	IMD	India	23.839N	78.738E	427m	IMD	
Trivandrum	IMD	India	08.480N	76.950E	60m	IMD	
Varanasi	IMD	India	25.300N	83.020E	90m	IMD	
Visakhapatnam	IMD	India	17.720N	83.230E	18m	IMD	
Aosta	ARPA-VDA	Italy	45.742N	7.357E	570 m	ESR	
Bologna	CNR-ISAC	Italy	44.650N	11.650E	8m	Chiba-U	
Bologna	CNR-ISAC	Italy	44.520N	11.340E	60m	Chiba-U	
Messina	Italian Air force	Italy	38.200N	15.500E	0m	ESR	
Monte Cimone	Italian Air force	Italy	44.190N	10.700E	2165 m	ESR	
Novara	Italian Air force	Italy	45.530N	8.670E	169 m	ESR	
Paganella	Italian Air force	Italy	46.110N	11.040E	2129 m	ESR	
Rome	CNR-ISAC	Italy	41.905N	12.548E	70.0m	ESR	
Signonella	Italian Air force	Italy	37.405 N	14.919 E	30 m	ESR	
Vigna di Valle	Italian Air force	Italy	42.080N	12.210E	270 m	ESR	
Abashiri	U-Toyama	Japan	44.018N	144.280E	45m	U-Toyama	
Chiba	Chiba-U	Japan	35.625N	140.104E	21m	Chiba-U, U-Toyama	x
Etchujima	Tokyo Univ. Marine Sci.	Japan	35.664N	139.796E	35.0m	Chiba-U, U-Toyama	x
Fuji Hokuroku	AIST	Japan	35.433N	138.750E	1150m	Chiba-U, U-Toyama	x
Fukue	Chiba-U	Japan	32.752N	128.682E	80m	Chiba-U, U-Toyama	x
Fukuoka	Kyushu-U	Japan	33.524N	130.475E	28m	Chiba-U, U-Toyama	x
Fukuoka	MRI	Japan	33.552N	130.365E	31m	MRI	
Fussa	U-Toyama	Japan	35.751N	139.323E	141m	U-Toyama	



Hedo	Chiba-U	Japan	26.867N	128.248E	65m	Chiba-U, U-Toyama	x
Ishigaki	JMA	Japan	24.337N	124.164E	6m	JMA	x
Itabashi	Tokyo Kasei Univ.	Japan	35.775N	139.721E	70m	U-Toyama	
Jodo	U-Toyama	Japan	36.566N	137.606E	2839m	U-Toyama	
Kamiyukawa	U-Toyama	Japan	34.062N	135.516E	535m	U-Toyama	
Kanazawa	Kanazawa Institute of Technology	Japan	36.533N	136.629E	26m	U-Toyama	
Kofu	Chiba-U	Japan	35.650N	138.567E	300m	Chiba-U, U-Toyama	x
Minamitorishima	MRI	Japan	24.300N	153.970E	7m	MRI	
Minamitorishima /JMA	JMA	Japan	24.288N	153.983E	7m	JMA	x
Miyakojima	MRI	Japan	24.737N	125.327E	50m	MRI, Chiba-U	
Moshiri	NIES	Japan	44.366N	142.260E	288m	Chiba-U, U-Toyama	x
Nagasaki	Nagasaki-U	Japan	32.786N	129.865E	35m	Chiba-U, U-Toyama	
Okayama	AIST	Japan	34.664N	133.931E	13m	U-Toyama	
Osaka	Kinki-U	Japan	34.642N	135.587E	19m	Chiba-U, U-Toyama	
Saga	Saga-U, NIES	Japan	33.233N	130.283E	8m	Chiba-U	x
Sapporo/ILTS	U-Toyama	Japan	43.084N	141.339E	30m	U-Toyama	
Sapporo/ILTS,MRI	U-Toyama	Japan	43.084N	141.339E	30m	U-Toyama	
Sapporo/JMA	JMA	Japan	43.060N	141.329E	17m	JMA	x
Sendai	Tohoku-U	Japan	38.260N	140.840E	153m	Chiba-U, U-Toyama	x
Shigaraki	U-Toyama	Japan	34.854N	136.105E	295m	U-Toyama	
Suzu, Ishikawa	U-Toyama	Japan	37.451N	137.359E	15m	U-Toyama	
Takayama	Gifu-U	Japan	36.145N	137.423E	1420m	Chiba-U, U-Toyama	x
Takikawa	U-Toyama	Japan	43.547N	141.897E	40m	U-Toyama	
Toyama	U-Toyama	Japan	36.700N	137.187E	30m	U-Toyama	
Tsukuba	Tsukuba-U	Japan	36.114N	140.096E	27m	Chiba-U, U-Toyama	x
Tsukuba/MRI	MRI	Japan	36.056N	140.125E	30m	MRI	
Kagurazaka	Tokyo Univ. of Science	Japan	35.699N	139.741E	70m	-	
Mandargovi	Chiba-U	Mongolia	45.743N	106.264E	1393m	Chiba-U	x

Ulaanbaatar	MUST, Chiba-U	Mongolia	47.886N	106.906E	1350m	Chiba-U	x
Lauder	NIWA, NIES	New Zealand	45.038S	169.681E	370m	Chiba-U	x
Ny-Alesund	NIPR	Norway	78.930N	11.861E	50m	U-Toyama	x
Belsk	Polish Academy of Science	Poland	51.837N	20.792E	190m	ESR, U-Toyama	
Anmyon	SNU	Republic of Korea	36.517N	126.317E	45m	SNU, U-Toyama	
Kongju	Kongju National Univ.	Republic of Korea	36.280N	127.080E	70m	SNU, U-Toyama	
Seoul	SNU	Republic of Korea	37.460N	126.950E	150m	SNU, Chiba-U, U-Toyama	x
Yongin	Hankuk University of Foreign Studies	Republic of Korea	37.336N	127.268E	167m	SNU, U-Toyama	x
Yonsei	Yonsei-U	Republic of Korea	37.570N	126.980E	60m	SNU	x
Barcelona	Universitat de Barcelona	Spain	41.385N	2.118E	97 m	ESR	
Valencia-Burjassot	Universitat de Valencia	Spain	39.507N	0.420W	60 m	ESR, Chiba-U	
Bangkok	TMD	Thailand	13.667N	100.605E	60m	Chiba-U	
Phimai	Chiba-U	Thailand	15.184N	102.565E	212m	Chiba-U, U-Toyama	x
Sri-samrong	Chiba-U	Thailand	17.157N	99.867E	50m	Chiba-U, U-Toyama	
Cambridge	British Antarctic Survey	United Kingdom	52.215N	0.080E	30 m	ESR	
Cardington	Met-Office	United Kingdom	52.100N	0.421W	30 m	ESR	
London	University College London-UAO	United Kingdom	51.524N	0.131W	45 m	ESR	
Plymouth	Plymouth Marine Lab.	United Kingdom	50.366N	4.148W	0m	ESR	
Aurora, Colorado	AIST	USA	39.400N	104.500W	1674 m	ESR	
Golden	National Renewable Energy Laboratory	USA	39.740N	105.180W	1829 m	ESR	

[Table 2. Geophysical parameter products, versions of Skyrad pack, and availability of the known data archives.](#)

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ESR:<http://www.euroskyrad.net>

5 L2 products: AOT, AE, SDF, SSA, CRI, phase function, asymmetry factor, lidar ratio and linear depolarization ratio

Analysis software: Skyrad pack v4.2, MRI v2

Data availability: L2 data are open by web system

SR-CEReS: <http://atmos3.cr.chiba-u.jp/skynet/>

10 L2 products: AOT, AE, SDF, SSA, CRI

Analysis software: Skyrad pack v5

Data availability: L2 data are open by web system

Toyama U: <http://skyrad.sci.u-toyama.ac.jp/>

L2 products: AOT, AE, SDF, SSA, CRI

Analysis software: Skyrad pack v4.2, 5

15 Data availability: L2 data are open by individual request

MRI

L2 products: AOT, AE, SDF, SSA, CRI, phase function, asymmetry factor, Lidar ratio, Linear depolarization ratio

Analysis software: Skyrad pack MRI v1 and v2

20 Data availability: L2 data are available from PIs by request

CAMS-SKYNet

Operational L2 products: AOT, AE, SDF, SSA, CRI

Analysis software: Skyrad pack v4.2 and 5

Data availability: L2 data are used by CMA, data available from PIs by request

25 IMD

Operational L2 products: AOT, AE, SDF, SSA

Analysis software: Skyrad pack v4.2

Data availability: L2 data are used by IMD, no open web system

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Table 3. (a) Monthly mean values of  $\mu$ ,  $\tau_a$  and  $\sigma_{a,II}$  obtained by ILP at Tokyo University of Science (TUS) site averaged for a period of February-May 2017 and (b) those at Roman site averaged for Oct 2017 and May-Sept 2019, other than \*380nm data which was taken only in Oct 2017. Estimates of  $\sigma_{a,II}$  are also given by Eq. (10) assuming  $\gamma$ -value of 7% for Tokyo and 15% for Rome. All wavelength means are shown in the bottom of each table.

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(a) Tokyo

$\lambda$ (nm)	$\langle n \rangle$	$\langle \tau_a \rangle$	$\langle \sigma_{a,IL} \rangle$ (%)	Eq. (10) (%) $\gamma = 7\%$
340	230	0.363	1.43	1.54
380	189	0.343	2.37	1.61
400	223	0.321	1.26	1.38
500	271	0.241	1.02	0.94
675	257	0.159	0.77	0.64
870	184	0.121	0.54	0.57
1020	202	0.100	0.47	0.45
mean	222	0.235	1.12	1.02

(b) Rome

$\lambda$ (nm)	$\langle n \rangle$	$\langle \tau_a \rangle$	$\langle \sigma_a \rangle$ (%)	Eq. (10) (%) $\gamma = 15\%$
340	360	0.178	1.25	1.29
*380	135	0.099	0.98	1.18
400	366	0.171	1.51	1.23
500	360	0.120	0.87	0.87
675	336	0.081	0.56	0.61
870	321	0.061	0.57	0.47
1020	315	0.057	0.61	0.44
mean	313	0.110	0.91	0.85

Table 4. Estimates  $a$  and  $b$  values at  $\lambda = 500\text{nm}$  and their RMSD values ( $\sigma_a, \sigma_b$ ) in the  $F_0$ 

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5 retrieval by IL and XIL methods for ILP data at Tokyo University of Science (TUS) site for four months from February through May 2017. Results of three screening conditions of Eq. (17) with  $\varepsilon_{i0} = 0.05, 0.03,$  and  $0.02$  are listed.

$\varepsilon_{i0} = 0.05$				
method	$a$	$\sigma_a$	$-b$	$\sigma_b$
SL	-8.220	0.389	0.296	0.321
IL	-8.247	0.050	0.968	0.082
XIL	-8.219	0.069	1.035	0.117
$\varepsilon_{i0} = 0.03$				
method	$a$	$\sigma_a$	$-b$	$\sigma_b$
SL	-8.253	0.238	0.237	0.163
IL	-8.249	0.039	0.973	0.070
XIL	-8.233	0.039	1.019	0.073
$\varepsilon_{i0} = 0.02$				
method	$a$	$\sigma_a$	$-b$	$\sigma_b$
SL	-8.190	0.168	0.247	0.160
IL	-8.243	0.030	0.990	0.064
XIL	-8.233	0.031	1.025	0.075

Table 5. Statistics of AOT differences from other networks. RMSD values of Estellés et al. (2012b) are differences between AERONET values and SUNRAD values for the same Cemil-CE318 sunphotometer data with mode-1 (SKYNET-like) and mode-2 (AERONET-like) algorithms.

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source	statistics	340	380	440	500	675	870	1020
Che et al. (2008), Beijing w AERONET	mean			0.536	-	0.330	0.248	0.211
	RMSD			0.025	-	0.018	0.018	0.018
Fig.8(a), 4 sites* Khatri et al. (2016) w AERONET	mean					0.124	0.089	0.080
	RMSD					0.019	0.015	0.016
Fig.8(b), Davos Kazadzis et al. (2018a,b) w PFR	mean				0.041	-	0.037	-
	RMSD				0.007	-	0.001	-
Go et al. (2020), Seoul w AERONET	mean	0.263	0.235	0.205	0.173	0.119	0.088	0.087
	RMSD	0.036	0.033	0.029	0.015	0.009	0.007	0.015
Estellés et al. (2012b) Valencia								
	RMSD	0.018	0.013	0.011	0.010	0.010	0.008	0.010
	AERONET (mode-1)							
AERONET (mode-2)	RMSD	0.005	0.004	0.002	0.002	0.002	0.001	0.002

\* 4 sites: Chiba, Pune, Valencia, Seoul

Table 6. Reported SSA differences from other networks: mean bias (Che et al., 2008) and RMSD (Kim et al., 2005; Khatri et al. 2016; Mok et al., 2018). Simulated changes of SSA between Skyrad pack versions 4.2 and 5 and SSA retrieval errors of version 4.2 in an enhanced mineral dust case are also obtained by a numerical simulation (Hashimoto et al., 2012).

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source	method	340	380	440 <sup>1</sup>	500	675	870	1020
Kim et al. (2005) rmsd	Diffuse to direct				0.027			
Che et al. (2008) w AERONET, mean				0.01	0.03	0.03	0.06	0.07
Khatri et al. (2016), 4sites <sup>2</sup> , w AERONET rmsd	before correction					0.069	0.074	0.068
	after correction					0.027	0.030	0.037
Mok et al. (2018) w AERONET rmsd	spectral Ag	0.017	0.015	0.016	0.025		0.047	
	Ag=0.1	0.025	0.018	0.020	0.024		0.048	
Hashimoto et al. (2012), simulation mean difference	Beijing observed cirrus contamination, v4.2-v5			0.017	0.023	0.029	0.035	0.023
	enhanced mineral dust case, v4.2			0.008	0.004	-0.005	-0.013	-0.017
	v5			-0.013	-0.017	-0.026	-0.031	-0.030

<sup>1</sup>400nm in Hashimoto et al. (2012)

<sup>2</sup>Chiba, Pune, Valencia, Seoul

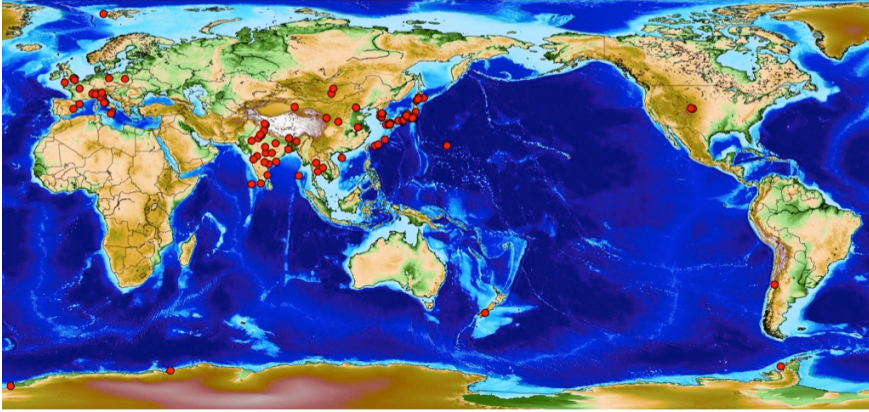


Fig. 1. A map of the sky radiometer sites.

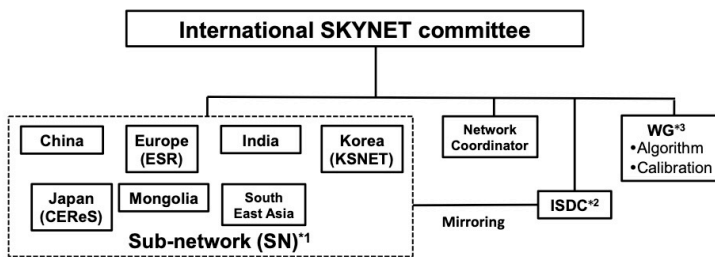


Fig. 2. The structure of the International SKYNET committee.

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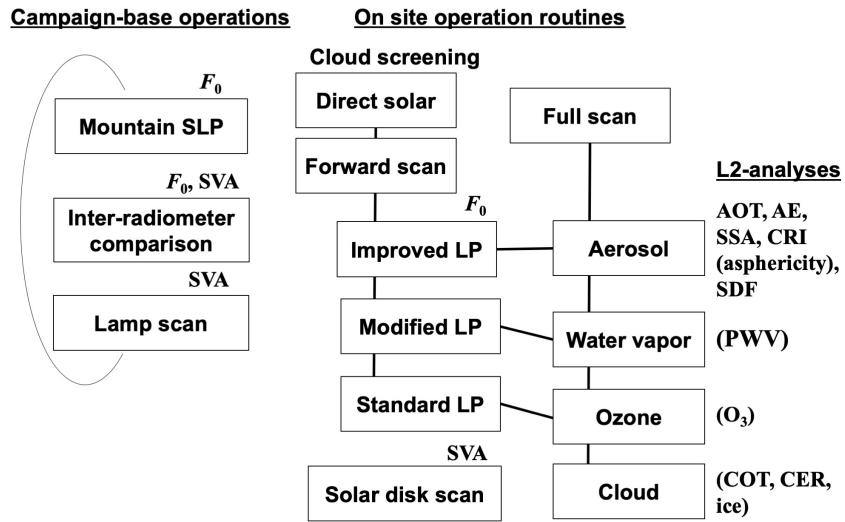
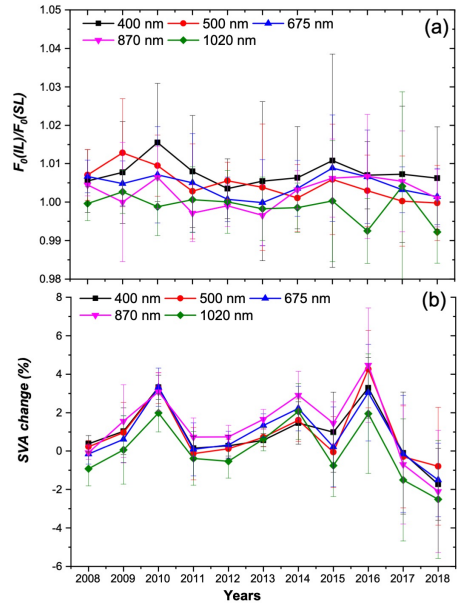


Fig. 3. A flow chart of the SKYNET analysis. Quantities in parentheses are research products.

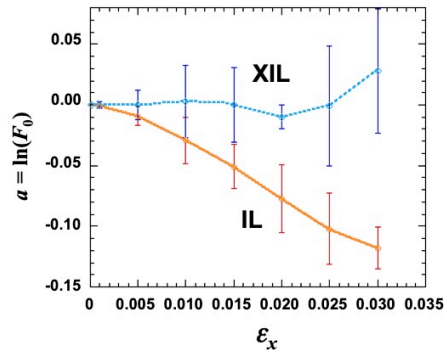
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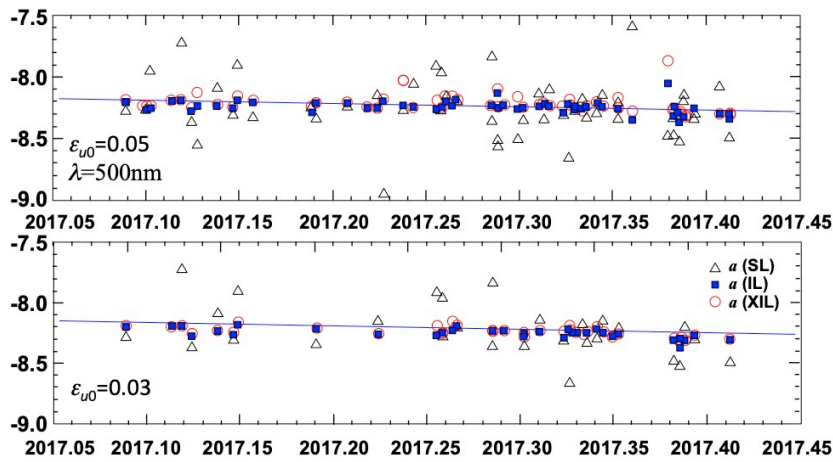
5 Fig. 4. Time series of the ratio of  $F_0$ -values from SL and IL methods (a) and SVA (b) from the observation taken by a single instrument (POM-01) at two pristine sites, IAO-Hanle during



January 2008 - December 2010 and June 2015 - December 2018 and Merak during January 2011 - May 2015. The error bar indicates a representative monthly RMSD in each year.



5 Fig. 5. Retrieved values of  $a = \ln(F_0)$  from IL and XIL methods with ten ensemble runs of an idealized experiment ( $n=20$  and  $m=1.3$  to  $3.5$ ) as a function of normal random error  $\varepsilon_x$  in  $x$ . True values are assumed as  $F_0=1$ ,  $\omega=1$ ,  $\tau=0.1$ .



10 Fig. 6. Time series of estimated  $a$ -values by IL and XIL methods for ILP data at Tokyo University of Science (TUS) site for four months from February through May 2017. Presented are results of two screening conditions of Eq. (17) with  $\varepsilon_{u0}=0.05$  and  $0.03$  at  $\lambda=500\text{nm}$ .

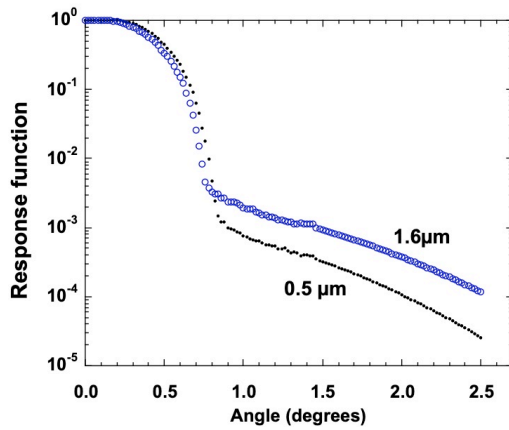
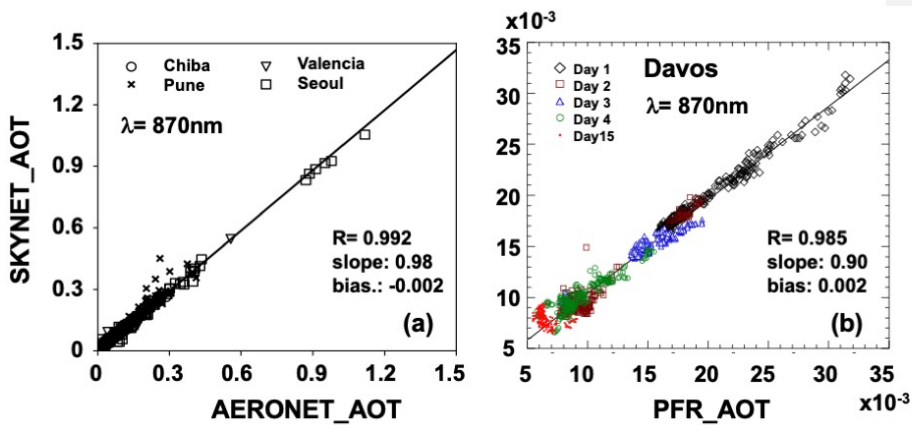


Fig. 7. Response functions of the sky radiometer at  $\lambda=0.5 \mu\text{m}$  and  $1.6\mu\text{m}$  measured by the solar disk scan method.



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Fig. 8. Comparison of AOT values at  $\lambda= 870\text{nm}$  obtained by sky radiometer, Cimel sunphotometer and PMOD PFR.

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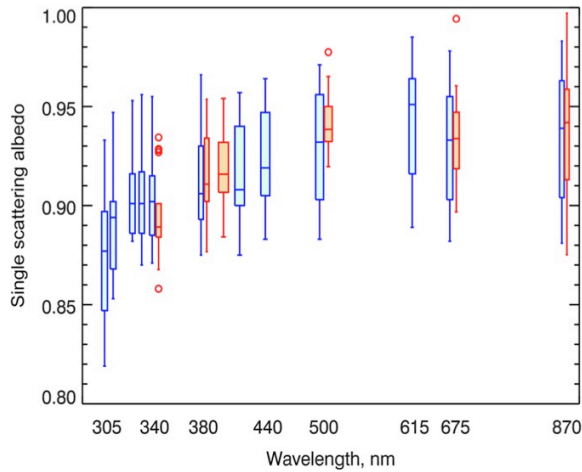
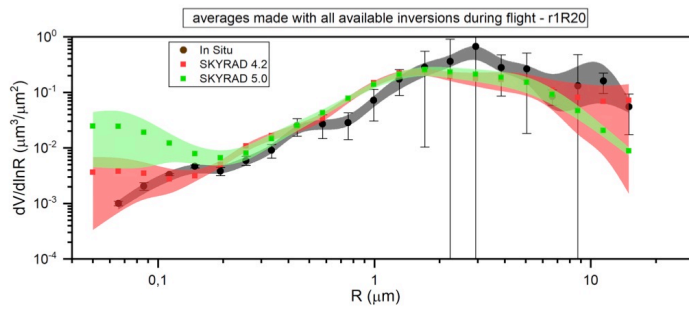


Fig. 9. Combined spectral SSA from AMP-retrievals (blue symbols) and SKYNET retrievals (orange symbols) using MODIS-derived surface albedo. The bottom and top edges of the boxes are located at the sample 25th and 75th percentiles; the whiskers extend to the minimal and maximal values within 1.5 IQR. The outliers are shown in circles. The center horizontal lines are drawn at the median values. The whisker-boxes are computed using  $AOD_{440} \geq 0.4$  criteria to correspond the best quality level 2 AERONET data. Cited from Mok et al. (2018).

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Fig. 10. Retrieved and observed aerosol size distribution functions in the African dust event cases in the sunphotometer Airborne Validation Experiment in Dust (SAVEX-D) campaign during 16-25 August 2015 (Estellés et al., 2018; Marenco et al., 2018; Ryder et al., 2018).

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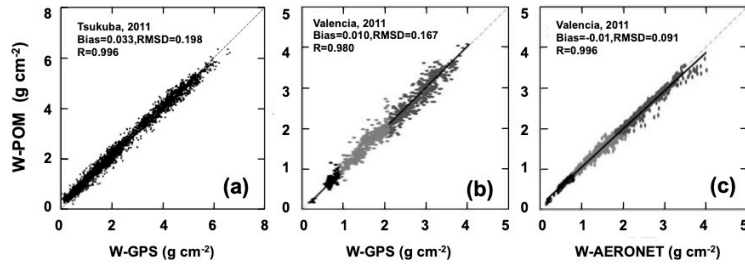
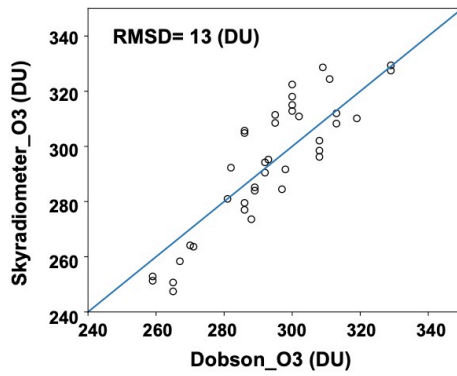


Fig. 11. Precipitable water retrieved by Uchiyama et al. (2014) in panel (a) and by Campanelli et al. (2018) in panels (b) and (c).



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Fig. 12. Comparison of column ozone amount (DU) retrieved from the sky radiometer at MRI Tsukuba-site and from Dobson spectrometer at JMA Tateno Observatory from 13 December, 2012 to 8 January, 2013.

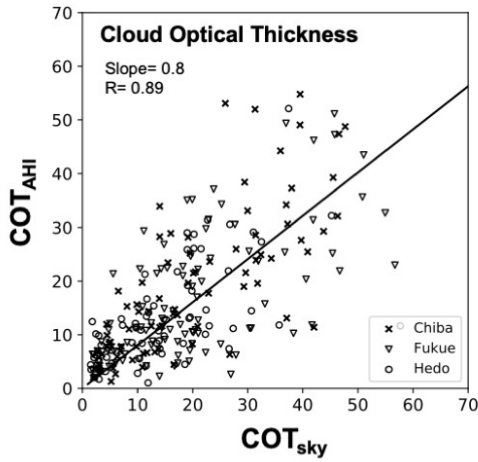


Fig. 13. Comparison of cloud optical thickness (COT) retrieved from sky radiometer at Chiba, Fukue and Hedo sites and Himawari-8/AHI satellite-borne imager in a period of October 2015 to December 2016 (Khatri et al., 2019). The regression line is with zero intercept constraint at the origin.

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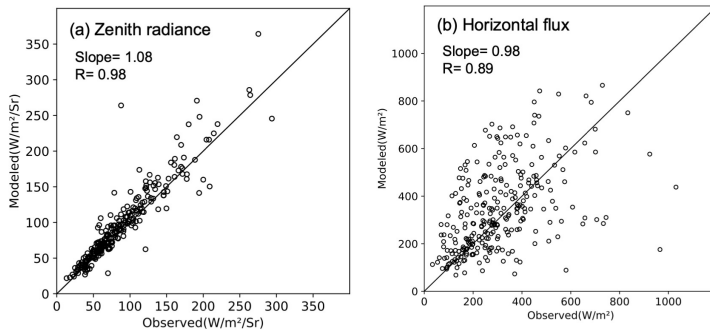


Fig. 14. Same as in Fig. 13 but for comparison between modeled and observed broad-band (a) radiances and (b) horizontal radiative fluxes. Regression lines are with zero intercept constraint at the origin.

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