Extending the late 1963 to 1964 Mt Agung rescued searchlight aerosol profiles dataset at 32ºN, from early 1963 to 1975.

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Abstract: A set of 11 aerosol turbidity profiles (ATP) and 2 aerosol extinction profiles (AEP) at $\lambda = 0.55$ µm, observed with searchlight in New Mexico at 32ºN, has been digitized from plots in scientific articles. They cover the period February to June 1963 and September 1965 to May 1975, complementing the already rescued and previously published 105 individual AEP, corresponding to 36 days, between December 1963 and December 1964. Eleven AEP are calculated (AEPc) from the ATP, and the corresponding stratospheric aerosol optical depth (sAOD) between 12 and 25 km is also derived. Estimates of the digitization errors for the AEPc and the sAOD are also calculated using information available in the literature. The combined set of rescued AEP reported here and the earlier rescued set of AEP from searchlight observations, are the only AEP dataset covering the period between the 1963 Mt Agung and the 1974 Fuego eruptions at northern midlatitudes. In this regard two relevant features identified in the AEP and the sAOD are described here. The first, using AEPc from March and April 1963 identified what could be the date of arrival of the stratospheric aerosols from the Mt. Agung first eruption on March 17th 1963. This would challenge the accepted criteria that the stratospheric aerosols from Mt Agung arrived at the northern hemisphere midlatitudes in the second half of 1963. The second feature evidences two anomalous increases of the sAOD during a period supposed to be the decay of the sAOD from Mt. Agung eruption. They show our limited knowledge and understanding of the 1963 Mt Agung volcanic stratospheric aerosol transport. Finally, we describe evidences found in the literature pointing to the possible existence of the original searchlight raw signals and its processing software. The dataset described in this work is available at: https://doi.pangaea.de/10.1594/PANGAEA.992616, (Antuña-Marrero et al., 2026).

1 Introduction

The 1963 Mt Agung eruptions, Bali, Indonesia at 8.3°S, the third biggest volcanic eruption of the second half of the 20th century, consisted in a series of eruptions (Fontijn et al., 2015). Two of these eruptions, on March 17th and May 16th, injected 4.7 Tg SO_2 and 2.3 Tg SO_2 into the stratosphere respectively (Self and Rampino, 2012). Before 1979, the so-called pre-satellite era, the only atmospheric observational dataset of stratospheric aerosols (SA) used by the Coupled Model Intercomparison

Project (CMIP) is derived using an aerosol microphysical model with the input ice core data (Gao et al., 2008) and two datasets of SA optical depth (sAOD) (Arfeuille et al., 2014). The two sAOD observations sets are the one from Sato et al. (1993), mainly based on astronomical observations and summarized by Dyer and Hicks (1968), and the one from Stothers (2001), based on observations of atmospheric attenuation of starlight and direct sunlight.

The mentioned datasets are the only used; however, other relevant data sources exist and could be relevant for research purposes. Since the later years of the 50's of the 20th century, aircrafts and balloons conducted observations of the particle size distributions and chemical composition of the upper troposphere and SA (Antuña-Marrero et al., 2025). Furthermore, vertical profiles of the upper tropospheric and SA backscattering/extinction were observed with lidars/searchlight (e.g., Fiocco and Grams (1964), Clemesha et al. (1966), Elterman (1975)). Although the results of the analysis of information generated by those observational datasets were published long time ago, and can be found in the literature, the datasets have not been available until the present.

This issue has been one of the focuses of attention and discussions by the Stratospheric Sulfur and its Role in Climate (SSiRC), recently renamed Stratospheric Aerosol Activity, an established APARC (Atmospheric Processes And their Role in Climate) activity, with APARC being a core project within the World Climate Research Program (WCRP). The implementation of the now Stratospheric Aerosol Data Rescue Activity (https://www.aparc-stratosphericaerosol.org/activities/data_rescue) in 2020 began addressing this issue. This activity has already rescued five datasets: four stratospheric lidar aerosol backscattering profiles (ABP) datasets and one searchlight aerosol extinction profile (AEP). The first four lidar ABP consist of two lidar datasets from two northern hemisphere lidar sites at Lexington, MA, USA, at 42ºN, and Fairbanks, AK, USA, at 64ºN after the 1963 Mt Agung, Indonesia, eruptions (Antuña-Marrero et al., 2021). The other two have been observed by lidars onboard two Soviet research ships conducting transects of the Atlantic Ocean after the 1991 Mt Pinatubo eruption (Antuña-Marrero et al., 2020a). Those four stratospheric ABP and their calculated stratospheric AEP have been stored respectively at the PANGAEA open access data repository (Antuña-Marrero et al., 2020b; 2020c). The fifth dataset consists of searchlight tropospheric and stratospheric AEP from White Sands, NM, USA, at 32ºN, after the Mt Agung eruption, covering the period December 1963 to December 1964 (both inclusive) that have been rescued and recalibrated (Antuña-Marrero et al., 2024). The original and the recalibrated tropospheric and stratospheric searchlight AEP have been stored at PANGAEA (Antuña-Marrero et al., 2023) like the other four stratospheric lidar AEP datasets cited above.

Two recent studies illustrate rescued lidar data applications. The first conducted by NASA scientists developing the Global Space-based Stratospheric Aerosol Climatology (GloSSAC), reported the recovering and archiving the SA backscatter profiles from five airborne lidar missions flown between July 1982 and January 1984 (https://asdc.larc.nasa.gov/project/NASA-Airborne-Lidar/NASA_Airborne_Lidar_Flights_1). They were used, together with the SA profiles from the NASA 48-inch ground-based lidar data and aerosol extinction profiles from SAM II, to fill the SAGE I/II gap from 1982 to 1984 (Thomason et al., 2018). The NASA Langley airborne missions data from July 1991 and May 1992, were also archived (https://eosweb.larc.nasa.gov/project/nasa_airborne_lidar_flights/nasa_airborne_lidar_flights_table) for future GloSSAC improvements (Thomason et al., 2018). The second application, used the January 1964 to August 1965 ground-based lidar datasets from Lexington (Antuña-Marrero et al., 2020; 2021) to evaluate the vertical extent of the Agung simulated volcanic SA (Dhomse et al., 2020). The article describing the development of GloSSAC also mention the existence of historical unexploited sources of data and considers worthwhile the potential efforts for its recovery (Thomason et al., 2018). A recent article about the stratospheric aerosol forcing datasets to be provided by the Coupled Model Intercomparison Project -phase 7 (CMIP7) to the participating modelling teams, mention that the five rescued datasets by the APARC Stratospheric Aerosol Activity Data Rescue could be considered to be incorporated to the aerosol optical properties dataset (Aubry et al., 2026).

Here we report the rescue of the available information to complete the New Mexico searchlight tropospheric and stratospheric AEP dataset with the available information from the scientific literature. The new searchlight AEP rescued dataset covers the periods February to June 1963 and September 1965 to May 1975, before and after the December 1963 to December 1964 already rescued searchlight dataset (Antuña-Marrero et al., 2023; 2024). As a result, the combination of the earlier rescued searchlight dataset and the one we report here, produces the only AEP dataset covering February 1963 to May 1975, providing unique information on the SA transported to the northern hemisphere midlatitudes from the 1963 Mt Agung as well as the Fuego eruption in Guatemala (14.5°N), on October 14th and 17th, 1974.

2 The searchlight tropospheric and stratospheric AEP observations at New Mexico 1963 to 1975

The US Air Force Cambridge Research Laboratories (AFCRL) carried out a program of tropospheric and stratospheric AEP observations with searchlight between 1963 and 1975 at White Sands (32°N), New Mexico. The cited program included the development and implementation of the processing algorithm to calculate the AEP (Elterman 1966a; 1966b). This series of AEPs include profiles under both SA background and under perturbed volcanic conditions, particularly from the eruptions of 1963 Mt Agung and Fuego in Guatemala in October 1974 (Elterman, et al., 1973; Elterman, 1966a; 1975; 1976).

Between February 1963 and May 1975, at least 359 individual tropospheric and stratospheric AEPs were collected, in many cases more than one in the same night (Listed in Table S1 in the Supplement). One hundred five of them, carried on between December 1963 to December 1964, were made public in form of individual AEP plots at an AFCRL report (Elterman, 1966b). This subset of searchlight AEPs has already been rescued (Antuña-Marrero et al., 2024). The other, at least 254, single AEPs are still missing, and they consist of 9 AEPs collected between February and June 1963 and 245 AEPs collected between September 1965 and May 1975.

The source of the rescued AEPs presented here, are the aerosol turbidity profiles (ATPs) reported by Elterman, et al. (1973) and Elterman (1975; 1976). ATP(z) were calculated using equation (1) where $AEP(z)$ is the original aerosol extinction profile and $REP(z)$ is the Rayleigh (molecular) extinction profile at λ = 0.55 µm, tabulated in Elterman (1964). The ATP averages at monthly, bi-monthly and multi-monthly temporal scales, were calculated and published in plots in the above cited articles.

$$ATP(z) = \frac{AEP(z)}{REP(z)} \qquad (1)$$

2.1. ATP and AEP plots: its digitization and ATP conversion to AEP.

In total 16 profiles, fourteen ATPs and two AEPs, were reported in Elterman et al. (1973) and in Elterman (1975; 1976). Within the current study 11 ATP and 2 AEP have been digitized from plots contained in the three cited papers, covering several temporal scales: three single daily profiles, three monthly, two bi-monthly and three multi-monthly averaged profiles. Three of the ATPs have not been digitized, by reasons listed in Table S2 in the Supplement. The 11 ATPs and 2 AEPs plots, and consequently the corresponding digitized profiles, mainly contain information between 10 to 26 km, (Table S3). The plot digitization was conducted using the WebPlotDigitizer software (Rohatgi, 2024), at the 0.5 km resolution, producing the digitized aerosol transmission profiles (ATPd) and digitized aerosol extinction profiles (AEPd) from the plotted ATP and AEP respectively. Then the ATPd were interpolated to 1 km resolution to match the resolution of the REP(z) from Table 5.11 in Elterman (1964), followed by the calculation of the corresponding AEP using Eq(1). The final step was interpolating those calculated AEP to produce the final AEP (AEPc) at the searchlight instrumental vertical resolution of 58 levels in the altitude range from 2.76 to 35.28 km (Elterman, 1966b).

The AEPc are listed in Table 1, where the first column contains the date and, for the single day profiles, the hour the observation was conducted, in Mountain Standard Time (MST), UTC-7. The second column reports the numbers of single raw searchlight profiles used in the respective calculations. The superscripts in the date column identify the profiles having both digitized ATP and AEP: a single daily profile (November 11th, 1974) and a bi-monthly mean profile (October and November 1970). Those digitized AEP and the corresponding AEPc were used to estimate the AEPc uncertainties, attributed to its determination from the ATP, described in the following section. The number in brackets after the number of profiles for the bi-monthly mean profile 1970-Oct-Nov is the number of days the observations were conducted, nine days. It is the only case where that is information is available.

Table 1: Listing of the original eleven ATP plots, the number of single profiles reported for each one and its respective source article, and the number of the Figure source on it. In the case of existing several profiles in the same Figure, the individual profile identifiers are included after the figure number. Superscripts (1) and (2) identify a single daily and a bi-monthly mean profile that have both theirs AEP and ATP plotted and were digitized.

Single Daily (Hour MST)	**Profiles**	**Source**
1963-Mar-28 (02:36)	1	Elterman, 1973; Fig. 3
1963-Apr-20 (23:45)	1	Elterman, 1973; Fig. 3
1974-11-11(1) (22:17)	1	Elterman, 1975; Fig. 2
Monthly mean		
1974-Nov	12	Elterman, 1976; Fig. 1b
1975-Jan	10	Elterman, 1976; Fig. 1c
1975-May	19	Elterman, 1976; Fig. 1d
Bi-Monthly mean	**Profiles**	**Source**
1963-Feb-Mar	3	Elterman, 1973; Fig.2 G1
1970_Oct-Nov(2)	41(9)	Elterman, 1973; Fig.2 G7
Multi-Monthly mean		
1963-Apr-Jun	6	Elterman, 1973; Fig.2 G2

1965-Sep_1966-Ene	50	Elterman, 1973; Fig.2 G6
1973-Sep_1974-Jul	113	Elterman, 1976; Fig. 1a

In Table 2 the two AEP digitized (AEPd), complementing the ATP information for the same periods in Table 1. They will be used below to validate the results of the AEP calculation from the digitized ATPd.

Table 2: Idem Table 1, but for the two AEP plotted.

Single Daily (Hour MST)	**Profiles**	**Source**
1974-11-11(1) (22:17)	1	Elterman, 1975; Fig. 1
Bi-Monthly mean profile		**Source**
1970_Oct-Nov	41 (9)	Elterman et al., 1973; Fig. 1

2.2. Estimated errors:

The estimated errors for the originally determined AEP, between 15% and less than 25%, were reported by Wells (1968). Three error sources were only considered for this estimate: neglecting both the multiple scattering from the searchlight beam and the ozone absorption, and for use of the Reeger–Siedentopf aerosol phase function, measured at the surface in Germany (at 50ºN) during a period when no volcanic aerosols were in the stratosphere (Reeger and Siedentopf, 1946). The error associated to the first two sources were determined to be negligible, with the aerosol phase function accounting for the all the error. A recent error estimation considered all the significant error sources, conducted for same originally determined AEP, rescued from tables in Elterman (1966b) for the period December 1963 to December 1964, increase the former range to between 69% and 84%. The same estimate was conducted for the recalibrated AEP dataset resulted in ranges between 54% and 69% for the recalibrated tropospheric AEP and between 40% and 55% (Antuña-Marrero et al., 2024).

2.2.1 Estimated errors of the ATP_d and the calculated sAOD:

Table 3 shows the quantitative information reported in Tables 1 and 2 in Elterman et al. (1973). The first column list date (period) from a daily profile (average for the period). The second reports the maximum (mean maximum) turbidly value for the respective ATP. The third shows the sAOD (mean sAOD) in the 12 to 25 km layer calculated from the corresponding AEP. Column four reports the maximum (mean maximum) ATPd and the five the sAOD (mean sAOD) in the 12 to 25 km layer, calculated from the AEPc reported by this study. Columns two and three are the only tabulated available information about some of the ATP and sAOD that we have rescued. We use it to get an estimate of the errors associated to the digitization of the ATP plot. To do it, we used the mean relative error (MRE), for each of the variables defined by the equation:

$$MRE = \frac{1}{N}\sum_1^N \frac{V_c - V_r}{V_r} x100 \qquad (2)$$

Where V_c is the the ATPd value in column 2 (sAOD value in column 3), and V_r is the reference ATP in column 3 (sAOD value in column 4). The MRE for the turbidity maximum is in the order of 2%, providing information about the error introduced by the digitization procedure. In the case of the sAOD the MRE is 5%, a reasonable value considering the magnitude of the digitization error and the fact that the sAOD is the integral of the AEPc between 12 and 25km. Those values are in the same order of magnitude than the 1.2% reported in the digitization of the plots of the AEP from December 1963 to December 1964, thus making the rescued dataset of AEP reported here consistent with the AEP reported in Antuña-Marrero et al. (2024).

Table 3: Values of the mean maximum turbidity and the sAOD between 12 and 25 km, reported by Elterman et al. (1973) in columns 2 and 3 respectively. Columns 4 and 5 report the maximum turbidity value and the sAOD derived from the digitized ATP and the calculated AEP respectively.

Date/Period	Elterman et al., 1973		ATPd and AEPc	
	Mean Max. Turbidity	Mean sAOD	Maximum Turbidity	sAOD
Feb.- Mar. 1963	1.4	1.8E-02	1.5	2.0E-02
28 March 1963	1.4	1.9E-02	1.4	1.9E-02
20 April 1963	4.5	3.9E-02	4.3	4.0E-02
Apr.-June 63	3.4	3.1E-02	3.1	3.3E-02
Sept. 65-Jan. 66	1.9	2.2E-02	1.8	2.3E-02
Oct., Nov. 1970	1.5	2.0E-02	1.5	1.9E-02

2.2.2 Estimated error of the AEPc:

To estimate the MRE in the current set of 11 AEPc calculated from the ATPd with Eq. 1, we use the November 11th 1974 at 22:17 MST digitized AEPd and ATPd, from figures 1 and 2 respectively in Elterman (1975). We also use the October and November 1970 average AEPd and ATPd, from figures 1 and 2, respectively, in Elterman et al. (1973). Figure 1 shows in the left panel the plot of the daily AEPc and AEPd for Nov 11th 1974 and in the right panel for the AEPc and AEPd averages for the period October - November 1970. In both cases a very good match is appreciated, a feature supported by the MRE values of -1.03 and -1.05 % respectively. Those values are in the same order of magnitude than the MRE associated to the digitization of the ATP. The very low magnitude of the MRE allows to consider that the magnitudes of the AEPc using Eq. 1 match the original AEP, that was the primary source to calculate the ATP reported both in Elterman et al. (1973) and Elterman et al. (1976).

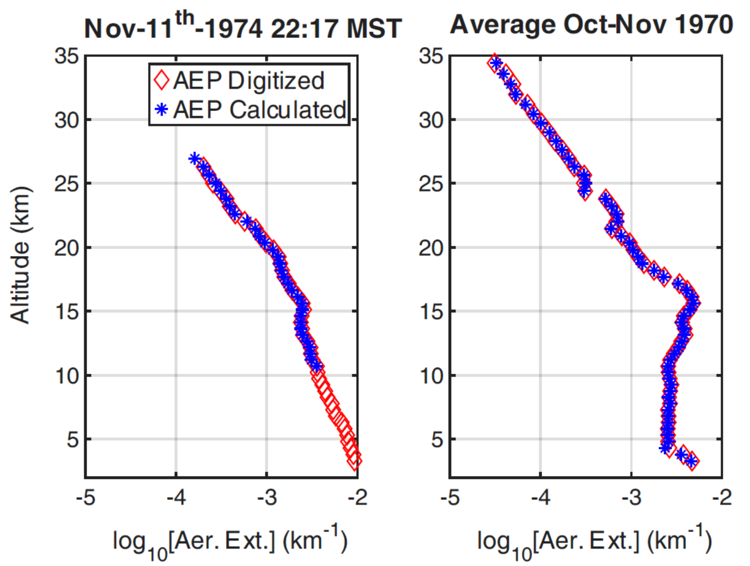

Figure 1: Plot of the digitized and calculated AEP from the November 11th 1974 at 22:17 MST and October - November 1970 average profiles, reported in plots in Elterman (1975) and Elterman et al. (1973) respectively. Both pairs of digitized AEPd and AEPc show good agreements.

3. Some volcanic SA features present in the 1963-1975 rescued searchlight AEP and sAOD series.

The discussion and analysis of the two features described in this section are beyond the purpose of this paper focussed on describing the rescued dataset, the methods applied for that purpose and guarantee the dataset storage in an open access data repository. However, they demonstrate applications of the rescued dataset we report. The first, showing the cross hemispheric of volcanic SA across the equator, provides information and at the same motivates future research to address our current limited knowledge and understanding of the 1963 Mt Agung volcanic stratospheric aerosol transport. The second, provides unique and consistent AEP and sAOD information from two volcanic events in the pre – satellite era, with the same ground-based instrument and processing algorithm.

3.1 The transport of the SA from the 1963 Mt. Agung eruption from 8ºS to 32ºN.

The ATPs derived from searchlight observations on 28th and April 20th 1963, reported in figure 3 in Elterman et al. (1973), identified the arrival of the Mt Agung SA to White Sands, NM. Figure 2 shows on panel a) both ATPs digitized and in panel b) the AEPc from the former ones. Those two, as well as the other two AEPs, consisting in the average of 3 profiles taken in January and February 1963 and the average of 6 profiles between April and June 1963 provided unique information about the time, vertical distribution and stratospheric AOD of the SA from the first, March 17th 1963, Mt. Agung eruption.

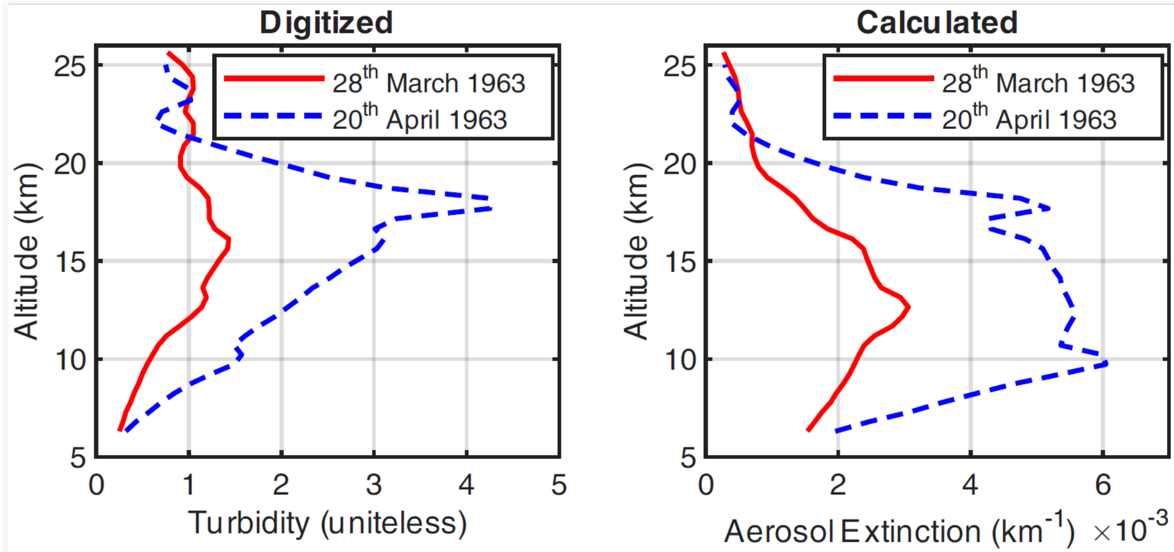

Figure 2: Plots of the digitized ATP (left panel) and the calculated AEP (right panel) for March 28 and April 20, 1963.

The two daily AEP from 1963 in Figure 2 allowed Elterman et al. (1973) to specify with a margin of error of ~ ± 10 days the date of arrival at White Sands of the SA cloud from the Agung eruption. Furthermore, both profiles allowed to quantify the values of the sAOD of 0.019 and 0.040 before and after the arrival of the SA cloud respectively, listed in Table 3 above.

3.2 Series of sAOD observations at Sacramento Peak, New Mexico, 1963 to 1975.

The series of sAOD calculated between 12 and 25 km, combining the 36 days observations between December 1963 and December 1964 already rescued (Antuña-Marrero et al., 2024), and the observations of the sAOD calculated from the 11 rescued AEPc reported here are shown in Figure 3. The 4 AEPc from February to June 1963, depict the arrival to 32ºN of the SA from the first, March 17th, Mt Agung eruption. It was identified and reported by Elterman et al. (1973). The magnitude of 0.040 of the sAOD in April 20th is among the highest registered in the joint sAOD series, with only three observations showing higher sAOD magnitudes, all of them in the first half of 1964: February 14th and 16th, with sAOD of 0.048 and 0.045 respectively and 0.050 on June 12th 1964. It should be emphasized that the cited sAOD value on June 12th, together with the increase in the magnitudes of the four daily AEPs observed from June 9th to 12th 1964, represents an anomaly in the expected decay state of the SA from the Mt Agung eruptions on March 17th and May 16th 1963. It could be associated to one of the eruptions registered in the northern hemisphere with a Volcanic Explosive Index (VEI) equal or higher than 3. A similar situation is present also for Mt Agung 1963 eruption, but in the rescued lidar record at Lexington, MA, at 42ºN. There the sAOD from lidar AEPs shows peaks with magnitudes inconsistent with the SA decay in November and December 1964 and between March and July 1965 (Antuña-Marrero et al., 2021). Further research is necessary to identify the sources of SA in all those cases.

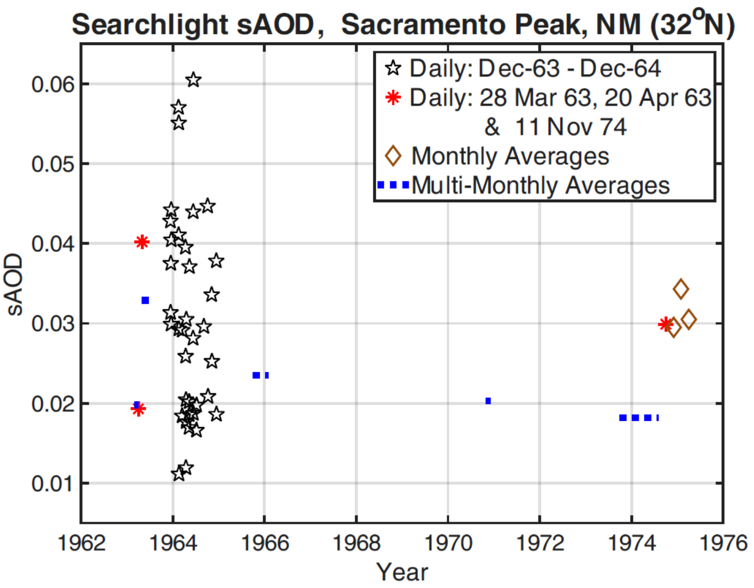

Figure 3: Joint SA optical depth (sAOD) of the 36 daily AEP from December 1963 to December 1964 already rescued (blue stars), and the 11 profiles (in red). The different markers used for the rescued sAOD represent their variable temporal resolutions. The red asterisks are the sAOD from daily single profiles: 28th March 1963, 20th April 1963 and 11th November 1974. The red diamonds are the sAOD of the monthly averaged AEP profiles for November 1974, January and May 1975. The sections of discontinuous line represent the sAOD of the multi-monthly averaged AEP profiles, whose length is determined by the 15th days of the beginning and ending months of the averages for February-March and April-June 1963, September 1965-January 1966, October-November 1970 and September 1973-July 1974.

The final section of the AEP and the sAOD series provides information about almost a year before the October 14th and 16th, 1974 Fuego eruptions, and also after it. The volcanic signal is present in the AEP and sAOD on November 11th 1974, as well as in the monthly mean values of the AEP and sAOD for November 1974, January and May 1975. The high sAOD magnitude between 1959 and 1962 were reported on contemporary observations. In the tropics, positive anomalies of the Linke turbidity coefficient between 1958 and 1962 were reported at Mauna Loa Observatory, before the 1963 Agung eruption (Ellis and Pueschel, 1971). At northern midlatitudes, the ratio of observed scattering to Rayleigh scattering at 660 nm from twilight measurements at Blue Hill Observatory, conducted during the winter of 1959-60, are higher than 3 between 10 and 20 km in figure 2 from Volz (1964). The high sAOD values were attributed to the number of nuclear explosions in the atmosphere during that period that peaked between 1960 and 1962 (Kondratyev et al., 1974).

4 Data availability

Data described in this work is available at https://doi.pangaea.de/10.1594/PANGAEA.992616, (Antuña-Marrero et al., 2026).

5 Summary and outlook.

The present work is an important step forward to determine and to understand the temporal evolution of the SA's optical properties from the 1963 Mt Agung, the 1974 El Fuego volcanic eruptions and the background periods around them, in the northern hemisphere midlatitudes. However, as we pointed out above, the number of AEPs rescued represent less than half of the AEP searchlight observations conducted between 1963 and 1975. Those still missing AEPs will contribute to a deeper understanding of the SA evolution.

The search for the original searchlight ABPs and its original processing algorithm continues. The search in the available literature, revealed that the searchlight ABPs were processed by computer (Elterman, 1966a), using the processing output on punched cards to produce AEPs and ATPs plots and few partial tabulations that were published in articles and reports. Four software applications for the searchlight ABP processing, were reported to be implemented and stored at the Analysis and Simulation Branch of the Computation Centre at the AFCRL; at the time all the US government computer facilities conducted the transition from the storage of data and software in punched cards to magnetic tapes (Cronin, 1972). So far, the search for those digital records has been unsuccessful, but we will not give up.

Author contributions

JCAM, AC and VC contributed designing and leading the data rescue procedure. JP conducted the digitalization of the turbidity/aerosol profiles from the plots and their preliminary processing. All co-authors contributed to either advising the data recovery, the processing and analysis of the rescued data. RGH and JAA conducted detailed reviews of the paper final version.

Competing interests

The authors declare that they have no conflict of interest.

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