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UTILIZATION OF SAGE AEROSOL PROFILES IN THE ANALYSIS OF MAUNA LOA STRATOSPHERIC LIDAR DATA

FINAL REPORT - NASA Contract NAGW-479

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Introduction:

Lidar observations of the stratosphere have been routinely collected at NOAA's Mauna Loa Observatory since 1974. A number of uncertainties hamper the analysis of these data. Some are related to the lidar system itself, and are therefore unique to this data set. Others are related to the boundary conditions and the aerosol scattering models used in the analysis, and are common to all stratospheric lidar observations. NASA's SAGE (Stratospheric Aerosol and Gas Experiment) satellite measurements (e.g. Chu and McCormick 1979, McCormick 1983, and Kent and McCormick 1984) have provided data that can be used to reexamine the boundary conditions that go into the analysis of the MLO (Mauna Loa Observatory) lidar observations. SAGE 1000 nm stratospheric aerosol extinction ratio profiles collected in the vicinity of Mauna Loa during 1980 and 1981 have been used for this purpose.

Data Sets:

Mauna Loa lidar data collected between April 1980 and December 1981 have been compared with SAGE soundings retrieved within 10 degrees latitude and 25 degrees longitude of Mauna Loa. The MLO lidar can interrogate the atmosphere from a few kilometers above the lidar to a height of roughly 40 kilometers. Over this range the lidar return can vary by more than four orders of magnitude. The eight-bit digitization and single gain amplification of the lidar data acquisition system limits the recorded signal amplitude range to approximately two orders of magnitude. This in turn limits the region of the atmosphere from which useable data can be collected. Prior to 1982 only one data acquisition setting, adjusted to provide data from approximately 10 to 30 kilometers above sea level, was used. Returns from below approximately 10 kilometers saturated the 8-bit digitizer, while those above 30 km fell to baseline levels.

The backscattered lidar returns versus range were recorded and no independent measurements of the baseline signals were available. The baseline signal levels, therefore, have to be infered indirectly from the analysis. This has been accomplished by iteratively adjusting the baseline until the solution yields a "reasonable" aerosol amount at heights between 27 and 29 km. One of the primary uses of the SAGE data has been to establish this estimate of the mean aerosol backscatter ratio between 27 and 29 km for use as one of the boundary conditions in the analysis of the MLO lidar data. The constraining effect of this initialization rapidly diminishes as the return signal increases above baseline levels at lower heights.

Lidars are inherently difficult to calibrate. One accepted procedure applied to stratospheric lidar observations (e.g. Russell et al., 1979) is to assume that the upper troposphere in the vicinity of the tropopause is either free of aerosols or contains a "known" small amount of aerosols. Returns from other heights can then be normalized to the returns from this calibrated region. SAGE data have confirmed the existence of a "minimum aerosol" region and have been used to establish the equivalent lidar backscatter ratios of these regions and the errors associated with this assumption.

Aerosol Scattering Model:

Aerosol scattering models have been used to synthesize aerosol backscattering profiles at 694 nm from the 1000 nm SAGE extinction ratio profiles so that a direct comparison can be made between the SAGE and MLO lidar data sets. They have also been used to define the 694 nm extinction to backscatter ratio profile employed in the analysis of the lidar data. The models that were developed for use in interpreting the SAM II and SAGE satellite data (Russell et al. 1981 a,b and 1983) have been used for this purpose.

The MLO lidar observations (DeLuisi et al. 1984), the MLO optical depth measurements, the NASA Langley lidar observations (Swissler et al. 1982), and the SAGE data (Kent and McCormick 1984) all show that between 1977 and 1979 the stratosphere's aerosol loading fell to a minimum. Volcanic activity in 1979, 1980 and 1981 (e.g. Kent and McCormick 1984, Kent and Philip 1980, Fujiwara et al. 1982 and Reiter et al. 1980 and 1982) introduced some aerosols to the stratosphere and increased the stratospheric optical depth above the 1977-1979 minimums. They were still well below the 1974 peaks attributed to the eruption of Volcan de Fuego (e.g. Russell et al., 1976 and McCormick et al., 1978) and the current levels resulting from the El Chichon eruption of March 1982 (Swissler et al. 1983). NASA's SAMII/SAGE aerosol optical models for the background stratosphere were used in these analyses. They are considered to be reasonably representative as there were no large volcanic perturbations during this time period.

These models characterize the size distributions in terms of the University of Wyoming's dustsorde channel ratios. Table 1 lists their low latitude channel ratio profile. Table 2 lists the "Cold Refractive Index Model" (Russell and Hamill 1983) 694 nm backscatter to 694 nm extinction ratio and the 1000 nm extinction to 694 nm backscatter ratio for selected channel ratios. Tables 1 and 2 (provided by T. J. Swissler) have been combined to give Table 3, the aerosol optical properties required for the analysis and comparison of the SAGE and Mauna Loa lidar data.

Data Analysis and Results:

Eighty-eight SAGE 1000 nm extinction ratio profiles were reduced to their equivalent 694 nm backscatter profiles. The minimum backscattering ratios in the upper troposphere at heights below fifteen kilometers and the mean scattering ratio between 27 and 29 km were selected from each profile. These results are plotted in Figs. 1 and 2. Both plots indicate a gradual rise in the scattering ratio with time from March 1980 to November 1981. The curves in these figures (a least squares cubic fit through the points) give the scattering ratio values used to initialize the lidar data analysis. The error bars on each point show the one standard error of the SAGE derived scattering ratios.

The lidar data analysis followed the procedures outlined by Fernald (1984) and Fernald et al. (1972). Recent discussions of the analysis of stratospheric lidar observations (e.g. Russell et al., 1979, Whitten et al., 1982) have presented solutions that use "standard" attenuation profiles to correct for aerosol extinction. This method works well when the stratospheric

HEIGHT km.	CHANNEL RATIO	STND. DEV.
1.0	10.02	8.76
2.0	10.97	5.23
3.0	11.58	7.18
4.0	10.45	9.07
5.0	11.48	14.55
6.0	9.57	7.89
7.0	7.20	4.27
8.0	6.61	4.73
9.0	6.51	5.56
10.0	7.31	5.94
11.0	5.55	3.44
12.0	4.55	2.50
13.0	4.17	2.13
14.0	4.06	1.27
15.0	3.89	0.95
16.0	4.31	0.80
17.0	4.11	0.73
18.0	3.99	0.68
19.0	3.68	0.45
20.0	3.56	0.69
21.0	3.58	0.74
22.0	3.63	1.07
23.0	3.85	1.25
24.0	4.20	1.61
25.0	4.35	2.02
26.0	4.78	2.79
27.0	5.81	3.29
28.0	6.61	3.64
29.0	8.28	5.59
30.0	6.90	4.02

TABLE 1. Low Latitude Channel Ratio Profile

CHANNEL RATIO	B(.69)/ E(.69)	Stnd dev	E(1.0)/ B(.69)	Stnd dev
1.2	0.0451	0.0094	28.0	5.0
1.5	0.0290	0.0079	32.0	6.0
2.0	0.0212	0.0045	35.0	4.5
2.5	0.0182	0.0030	37.0	3.0
3.0	0.0168	0.0022	36.0	2.0
3.5	0.0163	0.0017	35.0	2.0
4.0	0.0161	0.0014	33.0	2.0
4.5	0.0162	0.0012	32.0	2.0
5.0	0.0164	0.0012	30.0	2.0
5.5	0.0167	0.0012	29.0	2.0
6.5	0.0176	0.0013	27.0	1.2
7.5	0.0187	0.0015	23.0	1.2
8.5	0.0199	0.0018	21.0	1.2
12.0	0.0243	0.0031	15.0	2.0
16.0	0.0291	0.0048	12.0	3.0

TABLE 2. SAM II/SAGE Background Aerosol Optical Model

	------ a ------		------ b -------	
HEIGHT km.	E(.69)/ B(.69)	Stnd. dev	B(.69)/ E(1.0)	Stnd. dev
1.0	46.3	23.3	0.0558	0.0479
2.0	43.8	14.5	0.0610	0.0293
3.0	42.2	19.4	0.0643	0.0399
4.0	45.2	24.1	0.0582	0.0497
5.0	42.5	38.2	0.0638	0.0795
6.0	47.5	21.1	0.0534	0.0431
7.0	54.5	14.9	0.0415	0.0275
8.0	56.5	16.4	0.0377	0.0305
9.0	56.8	19.1	0.0371	0.0358
10.0	54.1	20.3	0.0422	0.0383
11.0	59.7	11.4	0.0346	0.0090
12.0	61.7	5.9	0.0314	0.0106
13.0	62.0	5.4	0.0306	0.0044
14.0	62.1	5.4	0.0304	0.0030
15.0	61.9	5.8	0.0299	0.0037
16.0	61.9	4.9	0.0308	0.0024
17.0	62.0	5.2	0.0305	0.0023
18.0	62.1	5.5	0.0302	0.0029
19.0	61.6	6.1	0.0291	0.0023
20.0	61.4	6.4	0.0287	0.0029
21.0	61.5	6.3	0.0288	0.0030
22.0	61.5	6.4	0.0290	0.0040
23.0	61.9	6.0	0.0297	0.0046
24.0	62.0	5.2	0.0306	0.0035
25.0	61.8	5.1	0.0309	0.0042
26.0	61.3	6.2	0.0324	0.0118
27.0	58.9	10.9	0.0352	0.0086
28.0	56.5	12.9	0.0377	0.0235
29.0	51.0	18.6	0.0467	0.0232
30.0	55.5	14.1	0.0396	0.0259

TABLE 3. Aerosol optical model parameters required (a) for the lidar data analysis and (b) for deriving the 694 nm backscatter ratio profile from the SAGE 1000nm extinction ration profile.

aerosol attenuation is small and the primary result is a profile of the aerosol's backscattering cross section. They can be updated iteratively to approximate the actual aerosol extinction. Fernald (1972 and 1984) has presented an analytical solution that incorporates aerosol extinction directly in this analysis. This solution relies on the assumption that the ratio between the aerosol extinction cross section and the aerosol backscatter cross section is known and remains constant within the layer under consideration. By selecting a number of shallow layers in which the extinction to backscatter ratio can be assumed constant the analysis can be easily extended to cases where the extinction to backscatter ratio is varying with height.

Hawaii radiosonde data can be reasonably approximated by the tropical standard atmosphere which has been used to calculate the molecular atmosphere's contribution to the net lidar return. Russell et al., 1979 have concluded that the use of standard atmospheres introduce density profile errors on the order of 3%. This uncertainty has been used in our error analysis. As discussed earlier, the NASA aerosol scattering models were used to establish the profile of the aerosol's extinction to backscatter ratio and its uncertainties (Table 3) used in the analysis of the lidar data.

The SAGE derived calibration reference scattering ratios (Fig. 1) and the mean scattering ratio at the maximum range of the system used to estimate the baseline (Fig. 2) have been assigned input errors of 2%-3% and 4%-6% respectively. These values are based on the errors in the SAGE infered 694 nm backscatter ratios as indicated in Figs 1 and 2, and are

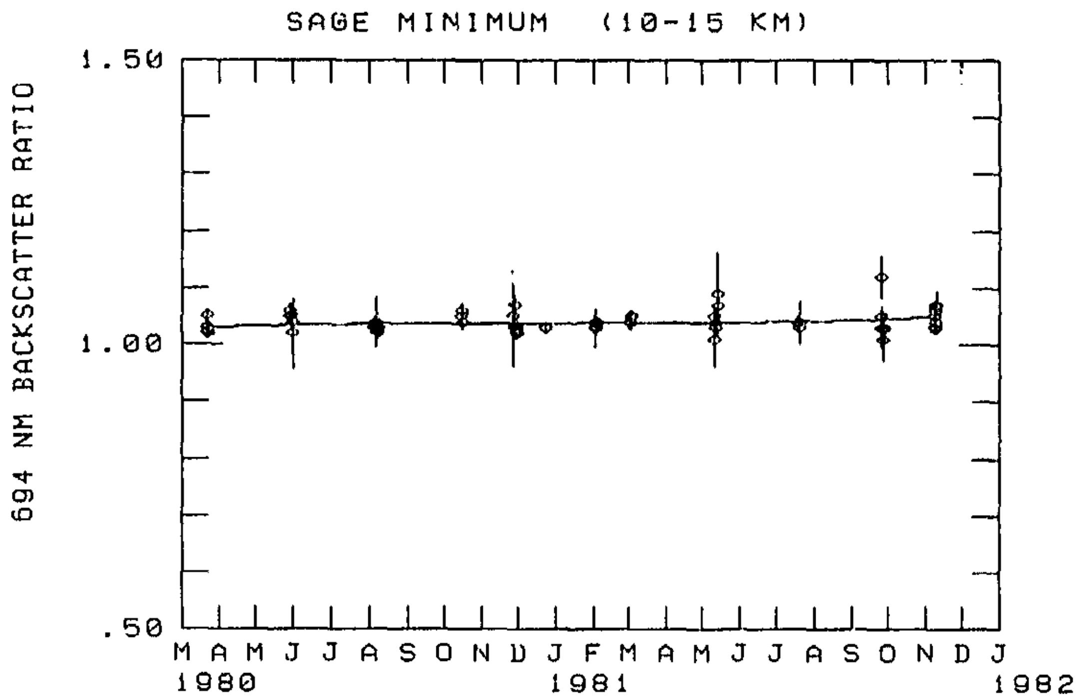

Fig. 1. Lidar calibration reference: Minimum 694 nm backscatter ratio between 10-15 km derived from SAGE 1000 nm extinction ratio profiles

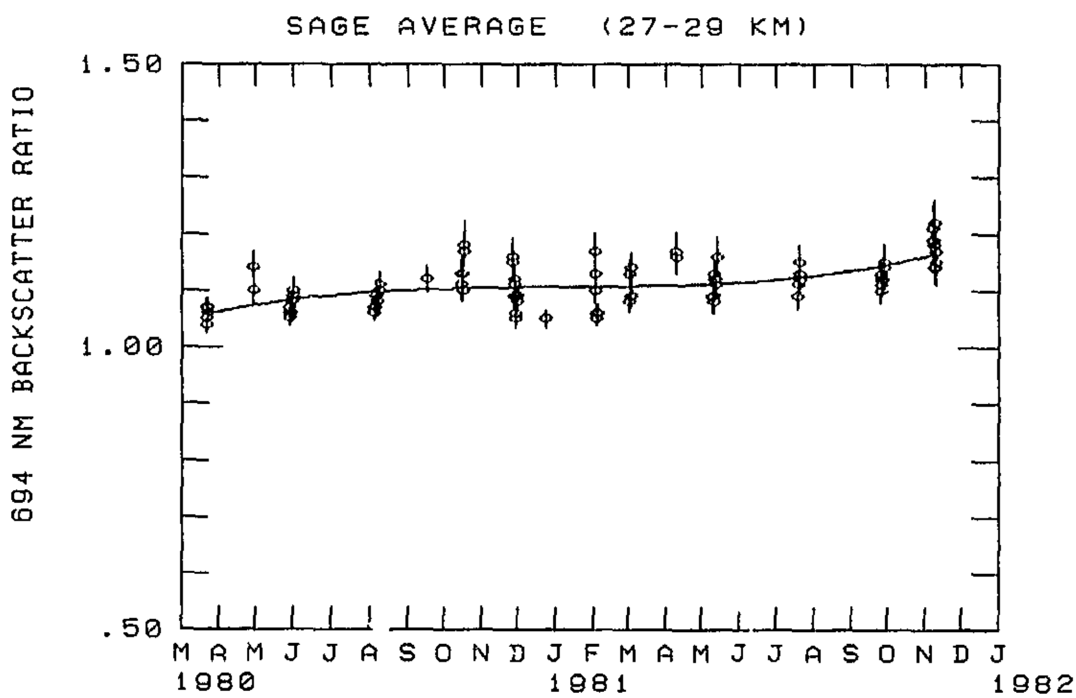

Fig. 2. Lidar baseline reference: Average 694 nm backscatter ratio between 27 and 29 km derived from the SAGE 1000 nm extinction ratio profiles

consistent with the variance in the least squares fit through the points.

As noted above one of the major problems with the MLO lidar data is a lack of an independently measured baseline signal. In order to infer the most reasonable "baseline", the analysis proceeds by initially setting this signal to the average of the lidar return between 27 and 29 km, and then iteratively adjusting the baseline until the average scattering ratio over this range agreed with the values shown in Fig. 2. In each case the lidar returns were calibrated by forcing the minimum scattering ratio between 12 and 15 km to the SAGE determined minimums shown in Fig. 1.

Thus, besides the lidar data, the analysis requires (1) an atmospheric density profile from which the backscatter and extinction cross sections of the molecular atmosphere can be derived, (2) a profile of the aerosols extinction to backscatter ratio so that aerosol extinction can be an integral part of the analysis, (3) an estimate of the minimum upper tropospheric backscatter ratio to be used as a calibration reference, and (4) in the case of the MLO lidar observation an estimate of the aerosol scattering ratio at the maximum range of the system so that reasonable values can be assigned to the baseline signal.

Figs. 3 and 4 each show a pair of SAGE and MLO lidar observations that were reasonably close in space and time. The data in Fig. 3 were collected respectively 8 and 10 days following the October 7, 1980 eruption of Ulawun (5S, 151E). Fig.4 represents a typical example from near the end of the

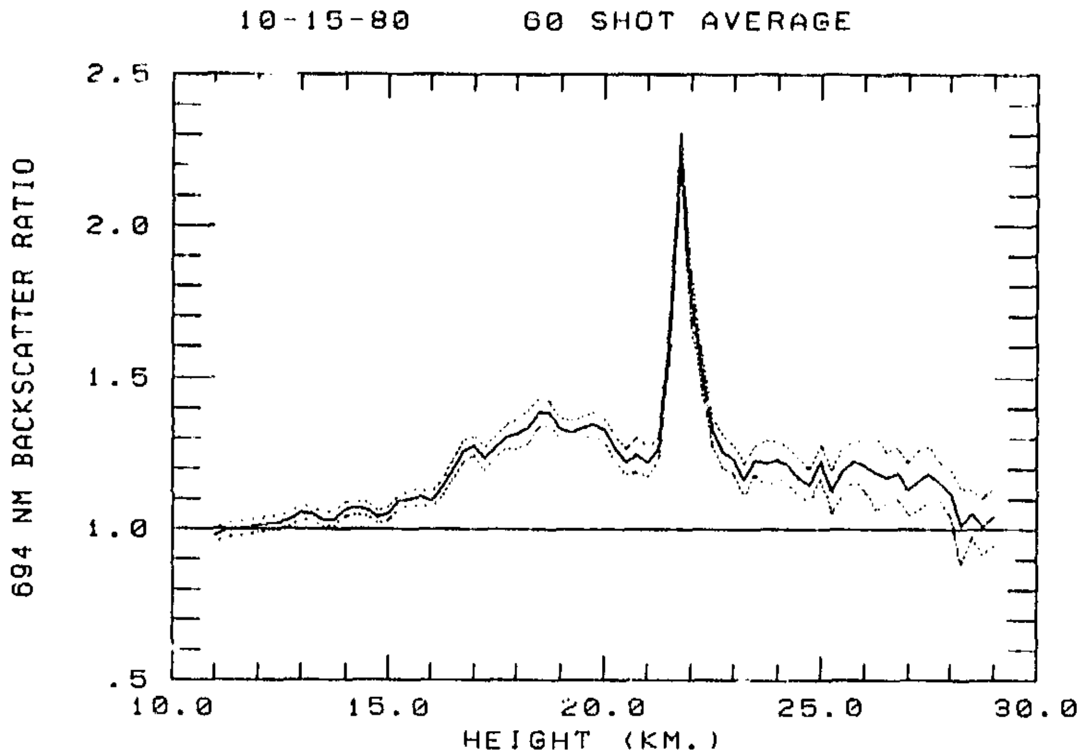

Fig. 3a. October 15, 1980 MLO lidar observation.

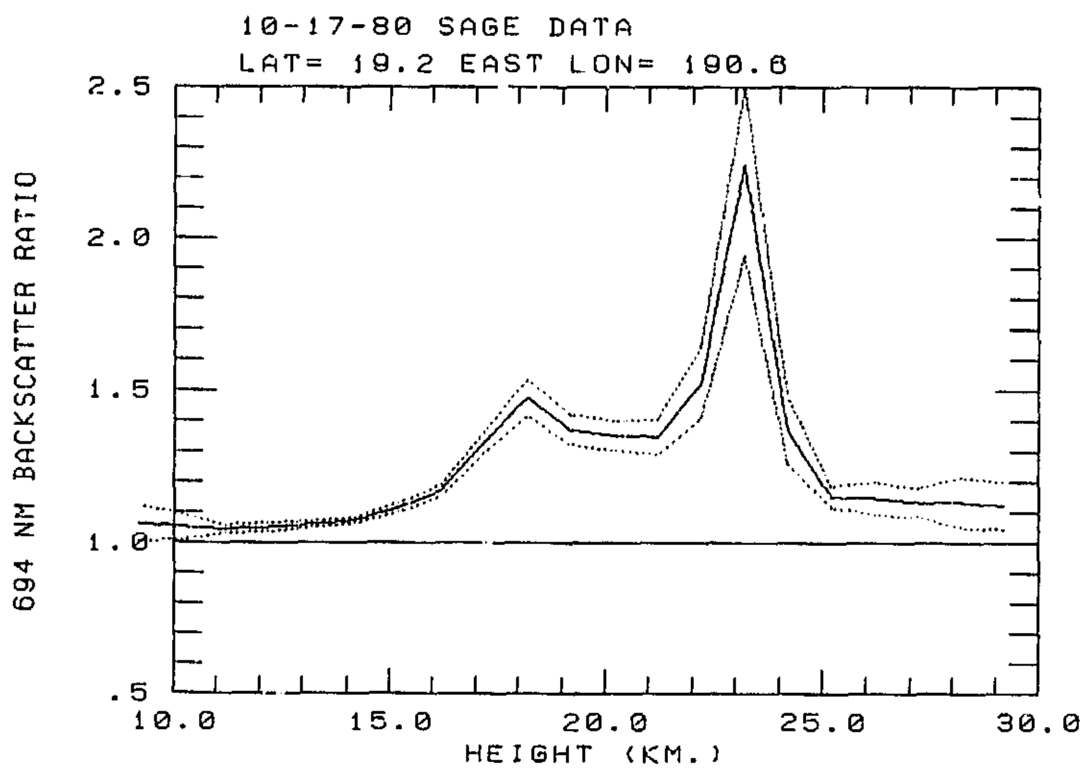

Fig. 3b. October 17, 1980 SAGE observation.

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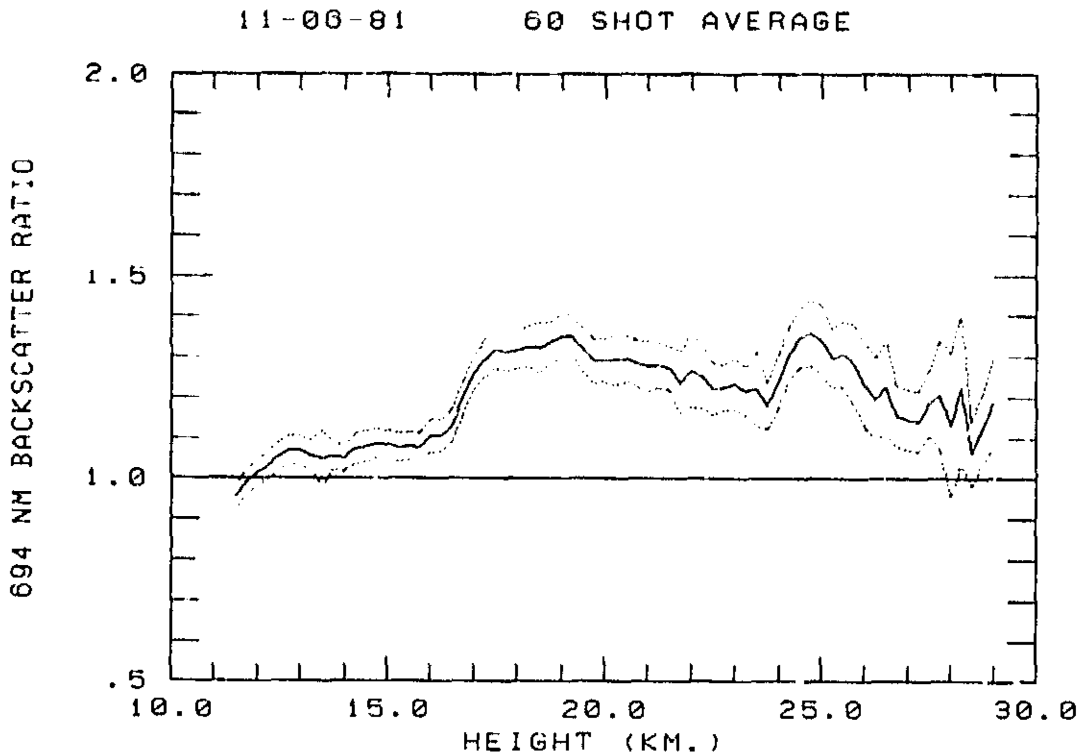

Fig. 4a. November 6, 1981 MLO lidar observation.

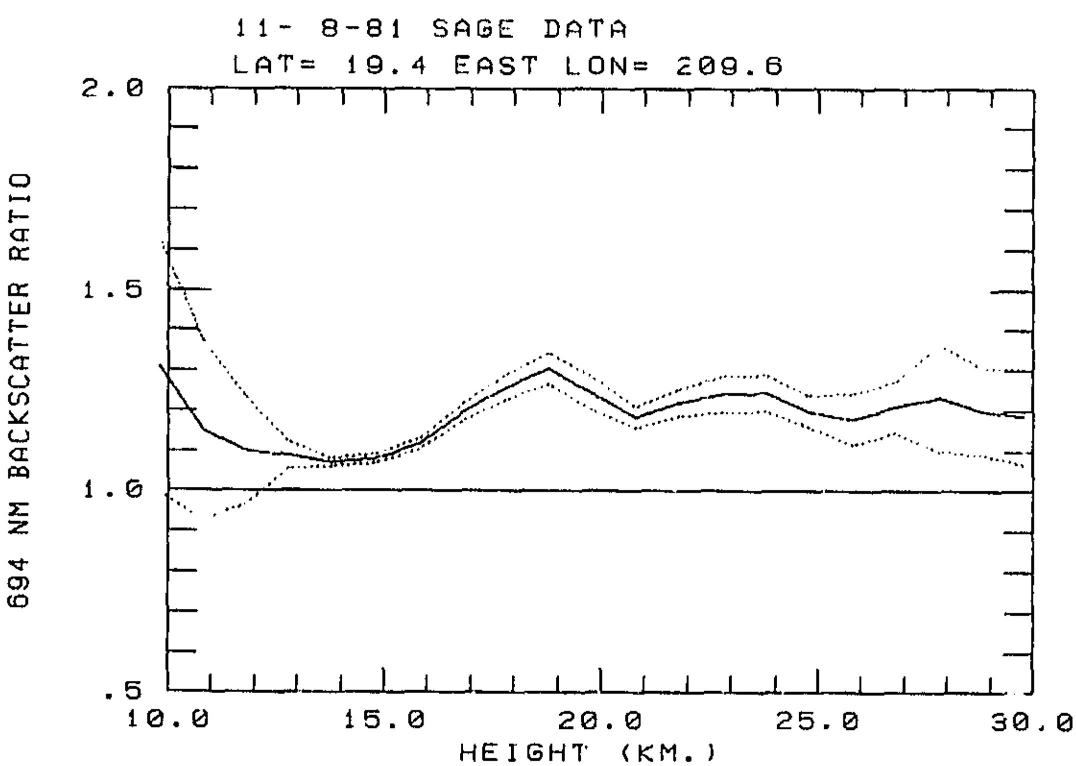

Fig. 4b. November 8, 1981 SAGE observation.

comparison period. The enhanced aerosol layer between 20 and 25 km in Fig. 3 can possibly be attributed to the Ulawun eruption. The SAGE sounding (Fig. 3b) was selected specifically because it showed this enhanced layer as a sharp relatively shallow layer similar to the lidar observation in Fig. 3a. This enhanced layer was not uniformly distributed throughout the region surrounding Mauna Loa (19.7N, 205E). It did not appear on the preceding SAGE sounding (Oct 17, 1980 at 19.6N, 214.6E), but other soundings within the 10 degrees latitude and 25 degrees longitude of Mauna Loa did show significant aerosol enhancements throughout the stratosphere. It was not apparent in the MLO lidar observation collected one week prior to and one week after the October 15, 1980 observations displayed in Fig 3a.

Errors Analysis and Comparisons:

One of the primary purposes of this research effort has been to quantify the errors that enter into the analysis of the MLO lidar observations. A full error analysis was added to the lidar data processing program. This followed the procedures outline by Bevington (1969) for tracing the propagation of errors through the analysis as applied to lidar aerosol measurements (Russell et al. 1979). The standard error limits of the plotted results (Figs. 3 and 4) are indicated by the dotted lines. An abbreviated table of the contribution of the various sources of error to the net uncertainties of the MLO lidar results are given in Tables 4 and 5. They list the relative error by source (relative error * 100 = percent error) contributing to the net error. The column labels representing the error sources are:

HEIGHT	SCAT-RAT	-------RELATIVE ERROR BY SOURCE-------					NET
		SIGNAL	BASE	E1/B1	B2	RCALIB	ERROR
29.00	1.04	0.125	0.040	0.001	0.044	0.022	0.140
28.00	1.12	0.082	0.029	0.001	0.041	0.022	0.099
27.00	1.13	0.085	0.022	0.001	0.038	0.022	0.098
26.00	1.21	0.070	0.016	0.001	0.035	0.022	0.083
25.00	1.22	0.045	0.012	0.001	0.032	0.022	0.060
24.00	1.23	0.035	0.009	0.001	0.029	0.022	0.051
23.00	1.23	0.031	0.007	0.001	0.025	0.022	0.046
22.00	1.77	0.036	0.003	0.001	0.022	0.021	0.047
21.00	1.22	0.027	0.004	0.001	0.019	0.021	0.039
20.00	1.33	0.010	0.002	0.001	0.016	0.021	0.029
19.00	1.33	0.012	0.001	0.000	0.013	0.021	0.028
18.00	1.31	0.029	0.001	0.000	0.010	0.021	0.037
17.00	1.27	0.014	0.000	0.000	0.007	0.021	0.026
16.00	1.09	0.008	0.000	0.000	0.004	0.020	0.022
15.00	1.05	0.009	0.000	0.000	0.001	0.020	0.022
14.00	1.07	0.009	0.000	0.000	0.002	0.020	0.022
13.00	1.05	0.008	0.000	0.000	0.005	0.019	0.022
12.00	1.01	0.009	0.000	0.000	0.008	0.019	0.023

HEIGHT	OP-DEPTH	-------RELATIVE ERROR BY SOURCE-------					NET
		SIGNAL	BASE	E1/B1	B2	RCALIB	ERROR
15.00	.00835	0.039	0.019	0.037	0.056	0.105	0.132

TABLE 4a. 694 nm aerosol backscatter ratio profile and 15 km optical depth error summary from the analysis of the Oct. 15, 1980 MLO lidar observations.

HEIGHT	OP-DEPTH	RELATIVE ERROR
15.00	.0144	0.375

TABLE 4b. Error associated with the 694 nm optical depth at 15 km infered from the 1000 nm SAGE extinction measurements collected on Oct. 17, 1980 at 19.2N and 190.6E.

		-------RELATIVE	ERROR BY	SOURCE-------			NET
HEIGHT	SCAT-RAT	SIGNAL	BASE	E1/B1	B2	RCALIB	ERROR
29.00	1.19	0.111	0.049	0.001	0.044	0.033	0.133
28.00	1.13	0.147	0.041	0.001	0.044	0.033	0.162
27.00	1.15	0.047	0.031	0.001	0.041	0.033	0.077
26.00	1.23	0.071	0.023	0.001	0.037	0.033	0.090
25.00	1.34	0.043	0.016	0.001	0.034	0.033	0.066
24.00	1.24	0.040	0.013	0.001	0.031	0.033	0.061
23.00	1.23	0.032	0.010	0.001	0.028	0.033	0.055
22.00	1.26	0.056	0.007	0.001	0.025	0.032	0.070
21.00	1.28	0.030	0.005	0.001	0.022	0.032	0.050
20.00	1.29	0.017	0.004	0.001	0.019	0.032	0.041
19.00	1.35	0.025	0.002	0.000	0.016	0.032	0.044
18.00	1.32	0.008	0.001	0.000	0.012	0.032	0.035
17.00	1.26	0.011	0.001	0.000	0.009	0.031	0.034
16.00	1.10	0.022	0.001	0.000	0.006	0.031	0.038
15.00	1.08	0.010	0.000	0.000	0.003	0.030	0.032
14.00	1.05	0.000	0.000	0.000	0.000	0.030	0.030
13.00	1.07	0.016	0.000	0.000	0.003	0.030	0.034
12.00	1.01	0.008	0.000	0.000	0.006	0.029	0.031

		-------RELATIVE	ERROR BY	SOURCE-------			NET
HEIGHT	OP-DEPTH	SIGNAL	BASE	E1/B1	B2	RCALIB	ERROR
15.00	.00752	0.047	0.029	0.034	0.071	0.185	0.208

TABLE 5a. 694 nm aerosol backscatter ratio profile and 15 km optical depth error summary from the analysis of the Nov. 6, 1981 MLO lidar observations.

HEIGHT	OP-DEPTH	RELATIVE ERROR
15.00	.00760	0.550

TABLE 5b. Error associated with the 694 nm optical depth at 15 km infered from the 1000 nm SAGE extinction measurements collected on Nov. 8, 1981 at 19.4N and 209.6E.

SIGNAL = noise in the raw lidar data,
BASE = uncertainties associated with the baseline determination (Fig 2),
E1/B1 = uncertainties associated with E1/B1, the 694 nm aerosol extinction to backscatter ratio (Table 3a),
B2 = uncertainties associated with using the standard atmospheric density profile, (+/- 3%), and
RCALIB = uncertainties associated with the values assigned to the minimum aerosol backscattering ratio used as the calibration reference (Fig 1).

Tables 4a and 5a show that baseline uncertainties are most significant in the computation of the MLO lidar aerosol backscattering ratio profiles at the maximum range of the data. Their contribution to the net error rapidly diminishes at lower heights. Extinction to backscatter ratio uncertainties (errors in E1/B1) do not significantly effect the backscatter ratio profile determination within these very "clear" atmospheres. Atmospheric density uncertainties (errors in B2) have no effect at the calibration level (approximately 14 to 15 km) but become increasingly more apparent at atmospheric layers further away from (above or below) the calibration level. Uncertainties in the calibration assumption (RCALIB) apply uniformily to all levels.

Tables 4b and 5b show that the calibration assumption is the principle contributor to errors in the stratospheric optical depth above 15 km. The atmospheric density profile uncertainties (errors in B2) would be reduced considerably if actual radiosonde data were used in place of the standard atmosphere. It is not likely to expect a marked reduction of the uncertainties associated with the calibration assumption. For these relatively clean stratospheres where the calibration errors are the principle source of errors in the optical depth results, there is therefore no strong impetus to reduce the density profile errors by using actual radiosonde observations.

Optical depths lends themselves readily to comparison as they represent the integrated optical effects of the aerosols. Figs. 5 and 6 show the aerosol optical depths of the atmosphere above 15 km as determined respectively from the SAGE data and the MLO lidar data. Precession of the SAGE orbit brought the sun-set observation within 10 degrees latitude and 25 degrees longitude of Mauna Loa over a series of up to 9 consecutive obits. The points in Fig 5 were obtained by averaging together the SAGE soundings collected during each of these periods. The error bars show one standard error about the mean. These errors have been approximated by using the 1000 nm optical depth errors from the SAGE data tapes plus an additional error associated with the model used to derive the 694nm extinction from the 1000nm extinction. The September 1980 and April 1981 data points on this plot each represent a single SAGE sounding whose errors bars have not been plotted as they exceed the limits of the plot. Each point in Fig 6 represent the MLO lidar results of a single evenings observation period (generally the average of 60 lidar shots). Fig 7 plots the SAGE and MLO lidar optical depths along with the preliminary estimates of the stratospheric optical depths infered from surface MLO observations (provided by J. DeLuisi). The lidar derived optical depths tend to be slightly higher than the SAGE optical depths. These two data sets, however fall within each others standard error limits, and the agreement amongst all three data sets is good.

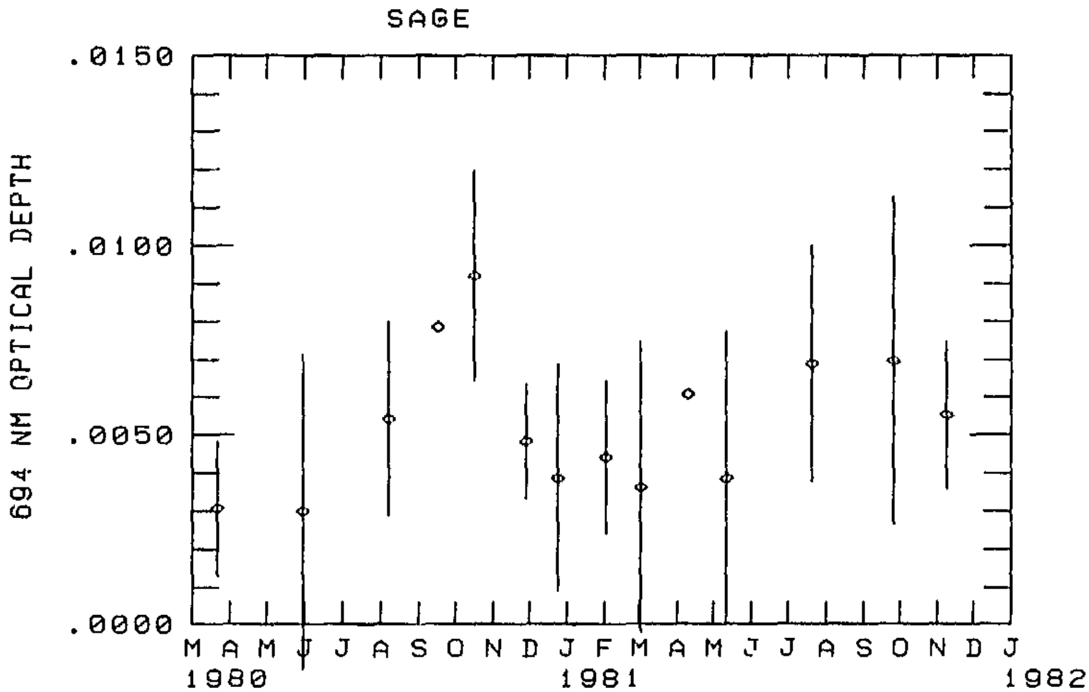

Fig. 5. Mean 694 nm SAGE optical depths above 15 km.

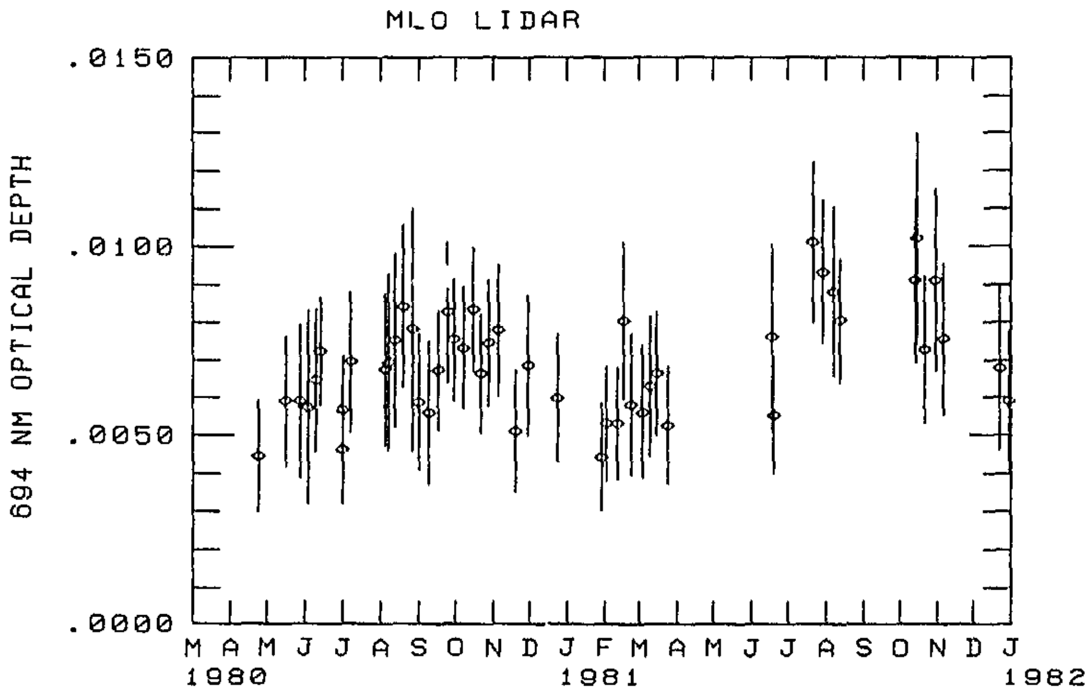

Fig. 6. 694 nm MLO lidar optical depths above 15 km.

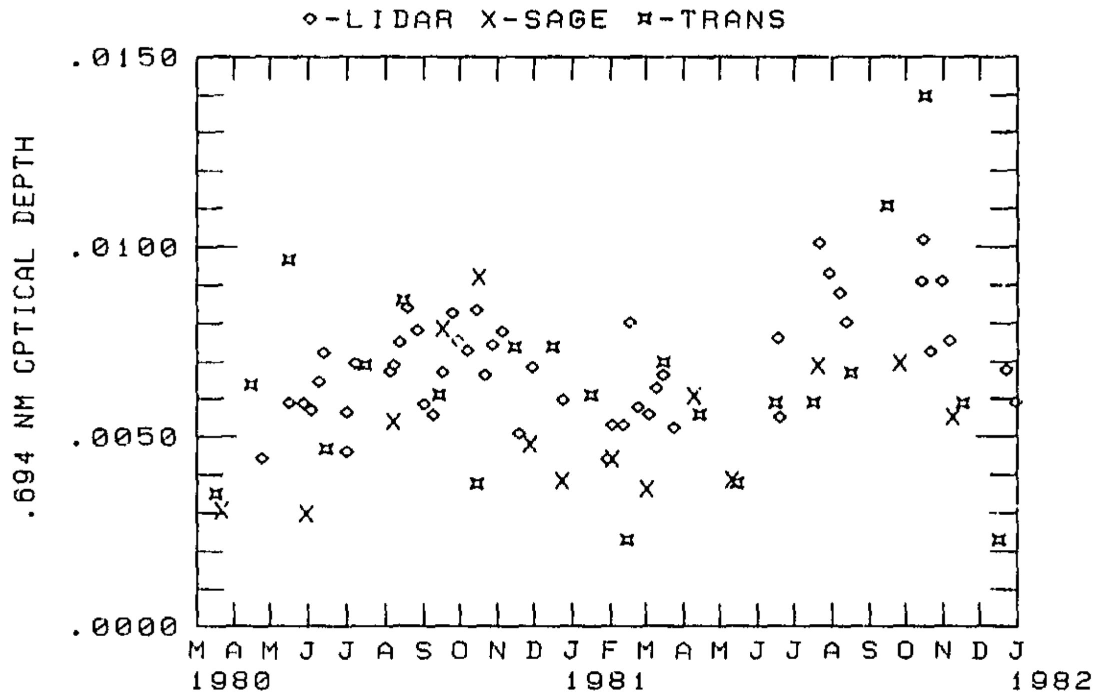

Fig. 7. 694 nm SAGE and MLO optical depths above 15 km, and preliminary MLO broad band visible transmissometer stratospheric optical depths.

Conclusions:

A systematic approach to the analysis of the MLO lidar data has been developed. It relies on parameters derived from SAGE extinction profile measurements to verify boundary conditions applied to analysis. It also provides a means of assessing the uncertainties associated with the various inputs, so that for the first time a good assessment of the accuracy of the analysis of the MLO lidar data is available.

The availability of good aerosol optical models has also allowed stratospheric optical depths to be determined from the MLO lidar observations. The stratosphere during the 1980-1981 period of this study was only mildly perturbed, and could be reasonably represented by the SAMII/SAGE background aerosol model. This model can be easily incorporated into the analysis of lidar data. The aerosol extinction properties can therefore be accurately portrayed, allowing reasonably accurate measurements of the stratospheric optical depths. MLO lidar observations collected during the 1980-1981 period have provided stratospheric optical depths with uncertainties that range between 15% and 25%. Uncertainties in the aerosol optical model have been shown to contribute errors of 3% to 4% in the computed optical depths. Most of the optical depth uncertainty has been associated with the "calibration assumption" in which no marked improvement can be expected.

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