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Validation of Multiangle Imaging Spectroradiometer (MISR) aerosol optical thickness measurements using Aerosol Robotic Network (AERONET) observations over the contiguous United States

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[1] Aerosol optical thickness (AOT) data retrieved by the Multiangle Imaging Spectroradiometer (MISR) in 2001 were compared with AOT measurements from 16 Aerosol Robotic Network (AERONET) sites over the contiguous United States. Overall, MISR and AERONET AOTs were strongly correlated ($r = 0.73$). Regression analysis showed that the root mean square error (RMSE) of MISR AOT was 0.05. The overall retrieval error of MISR AOT was within $\pm 0.04 \pm 0.18 \times$ AOT. This result as well as the regression slope and intercept were comparable with previous results using AOT retrievals from MISR or Moderate Resolution Imaging Spectroradiometer (MODIS). The agreement between MISR and AERONET AOTs was improved ($R^2 = 0.90$, RMSE = 0.04) when data from three western inland sites were excluded. A paired t test indicated that MISR systematically overestimated AOT by 0.02 ± 0.007. It was also shown that this positive bias in MISR AOT was greater during the spring and summer as well as in western United States. Together, these results suggest that MISR AOT measurements may be suitable for quantitative analysis of aerosol abundance. Finally, it is unlikely that the current results will vary when using alternative MISR AOT parameters since our analysis also showed the MISR AOT parameters (best fit, regional mean, and weighted regional mean AOTs) to be highly comparable. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0933 Exploration Geophysics: Remote sensing; 9350 Information Related to Geographic Region: North America; *KEYWORDS:* MISR, AOT, AERONET

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1. Introduction

[2] NASA's Earth Observing System (EOS) Terra satellite [*Kaufman et al.*, 1998] was launched into Earth orbit in December 1999 with the mission of comprehensively measuring the Earth's climate system. Operating in a Sun-synchronous orbit, Terra crosses the equator from north to south at approximately 10:45 a.m. local time with an orbital period of 99 minutes and repeats its ground track every 16 days. Among the five instruments aboard Terra, MISR was designed to measure tropospheric aerosol properties with repeat coverage over a specific scene between two and nine days depend on the latitude of the scene [*Diner et al.*, 1998, 1989; *Kaufman et al.*, 1998]. MISR employs nine cameras pointed at fixed angles to observe reflected and scattered sunlight in four wavelength bands. This unique design enables it to retrieve tropospheric AOT, defined as the integral of aerosol extinction coefficients from surface to top of the atmosphere, and aerosol size distribution over both land and ocean at a spatial resolution of 17.6 km [*Diner et al.*, 1998]. Unlike other aerosol remote sensing instruments, MISR performs aerosol retrieval over land utilizing the presence of spatial contrasts within the 17.6 × 17.6 km region to separate surface-leaving and atmospheric path radiances. The surface-leaving radiation field is then used to determine the best fitting aerosol compositional models and associated AOTs by comparing the results with synthesized values which are calculated from predefined aerosol compositional models, each consisting of a mixture of prescribed basic aerosol components [*Jet Propulsion Laboratory* (*JPL*), 2002]. Valid aerosol mixtures and associated AOTs are identified when the residuals between observed and synthesized radiation fields are below the thresholds specified by a set of chi-squared statistics [*Martonchik et al.*, 1998].

[3] Since MISR is still in its early stage of operation, most existing MISR related publications focus on instrument operations, radiometric and geometric calibrations as

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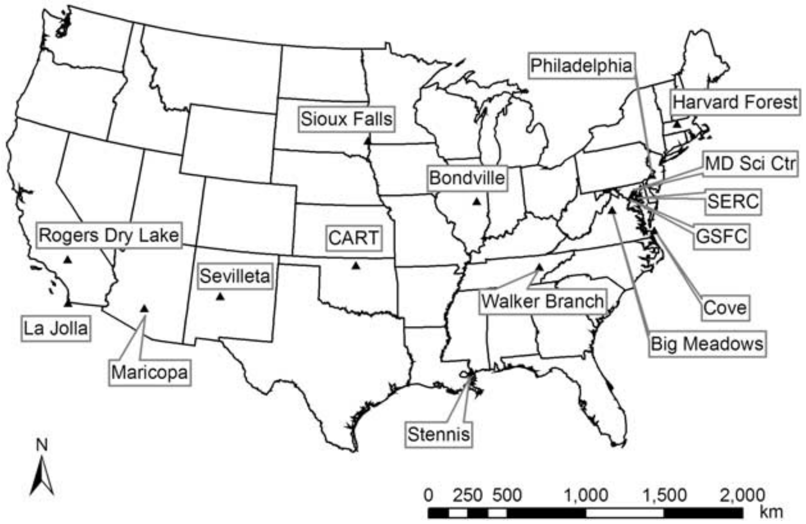

Figure 1. Selected 16 AERONET sites in the contiguous United States.

well as studies of land surface and cloud properties [*Bruegge et al.*, 2002; *Chrien et al.*, 2002; *Jovanovic et al.*, 2002]. To date, MISR aerosol measurements have been undergoing extensive validation with few published results. *Diner et al.* [2001] compared a small sample of the regional mean aerosol optical depth, computed from early MISR measurements with AOT observations from the Aerosol Robotic Network (AERONET) in southern Africa. Their results showed that MISR had a positive bias (0.02) across the range of the data and overestimated AOT measurements by 10%.

[4] AERONET is a global measurement network of ground-based Sun photometers (CIMEL Electronique, France) supported by NASA's EOS and other international institutions [*Holben et al.*, 1998]. Starting its operation in 1993, AERONET has expanded worldwide to over 340 sites by 2002. The AERONET system provides columnar aerosol optical properties at up to eight wavelengths ranging from 340 nm to 1020 nm. Extensive research showed that AERONET data have relatively high accuracy ($<\pm 0.01$ for $\lambda > 440$ nm and $<\pm 0.02$ for shorter wavelengths) and precision (less than 1%) [*Eck et al.*, 1999; *Holben et al.*, 1998; *Smirnov*, 2000]. Because of its long operating history, global coverage and high data quality, AERONET data has been used in various satellite and model validation studies as the reference standard for AOT measurements [*Chu et al.*, 2002; *Torres et al.*, 2002a, 2002b; *Zhao et al.*, 2002].

[5] Because of their relatively high resolution and wide coverage over land, the latest generation of spaceborne aerosol sensors such as MISR and MODIS are promising data sources for regional scale studies on fine particle pollution characterization and related public health issues. A case study in Texas has shown that MODIS, in conjunction with ground-based observations, can create a cost-effective and accurate pollution monitoring system [*Hutchison*, 2003]. MISR or MODIS data may be especially beneficial in developing countries with limited ground monitoring network and financial resources. To date, no study has specifically focused on evaluating MISR data over relatively populated and polluted areas for long sampling durations. The main objective of this study, therefore, is to evaluate the accuracy of MISR AOT data under various geographical and climatic conditions over the contiguous United States using information from the AERONET network. To choose the appropriate AOT parameters for use in the current analysis, the relationships among different AOT parameters provided by the MISR data product were also examined.

2. Methods

2.1. Measurements of AOT

2.1.1. MISR Level 2 Aerosol Data Product

[6] MISR level 2 aerosol data [*Bothwell et al.*, 2002] in 2001 were downloaded from Atmospheric Sciences Data Center at NASA Langley Research Center (http://edg.larc.nasa.gov/~imswww/imswelcome/index.html). It should be noted that the MISR aerosol retrieval algorithm as well as the product maturity level have been constantly evolving. In the current analysis, the maturity level of 2001 data is version 12, with the exception of less than 1% of the data, which varies from version 8 to version 11. The MISR AOT parameters (all reported at 558 nm wavelength) [*JPL*, 2002] of interest include:

[7] 1. Best fit AOT (corresponding MISR fieldname RegBestFitSpectralOptDepth) indicating the columnar aerosol optical depth with smallest chi-square fitting parameter from all aerosol mixtures [*Martonchik et al.*, 1998]; denoted as $\text{MISR}_{\text{bestfit}}$ in this analysis.

[8] 2. Regional mean AOT (corresponding MISR fieldname RegMeanSpectralOptDepth) indicating the columnar aerosol optical depth computed as the average optical depths of all valid ("successful") aerosol mixtures; denoted as $\text{MISR}_{\text{regmean}}$.

[9] 3. Weighted regional mean AOT (corresponding MISR fieldname RegWgtdMeanSpectralOptDepth) indicating the columnar aerosol optical depth computed as the average optical depths for all aerosol mixtures weighted by the inverse of the chi-square statistics; denoted as $\text{MISR}_{\text{wgtdmean}}$.

2.1.2. AERONET Level 2 Data Product

[10] Level 2 (validated) AOT data in 2001 from 16 AERONET sites over contiguous United States (see Figure 1) were downloaded from the AERONET data

Table 1. Geographic Information of Selected AERONET Sites in the United States

Site ID	Site Name	State	Elevation, m	Latitude, deg	Longitude, deg	Land Use and Land Cover Type[a]
1	Rogers Dry Lake	CA	680	34.926	117.885	rural, grassland and shrub
2	La Jolla	CA	0	32.500	117.160	urban, ocean, grassland and build-up land
3	Maricopa	AZ	0	33.071	111.972	rural, shrub land
4	Sevilleta	NW	1477	34.355	106.885	rural, shrub land
5	CART	OK	315	36.610	97.410	rural, dry land, crop land and pasture
6	Sioux Falls	SD	500	43.736	96.626	rural, dry land, crop land and pasture
7	Stennis	MS	20	30.368	89.617	rural, evergreen needleleaf forest, dry land, cropland and pasture
8	Bondville	IL	212	40.053	88.372	rural, dry land, cropland and pasture
9	Walker Branch	TN	365	35.958	84.287	suburban, broadleaf forest, build-up land
10	Big Meadows	VA	1082	38.522	78.436	rural, mixed forest
11	GSFC	MD	50	39.030	76.880	urban, build-up land
12	MD Science Center	MD	15	39.283	76.617	urban, build-up land
13	SERC	MD	10	36.883	76.500	suburban, broadleaf forest, ocean
14	Cove	VA	0	36.900	75.710	ocean platform, 40 km from shore
15	Philadelphia	PA	20	40.036	75.005	urban, build-up land
16	Harvard Forest	MA	322	42.532	72.188	rural, broadleaf forest

[a] Land use and land cover information was obtained from National Atlas of the United States of America by U.S. Geological Survey (http://www.nationalatlas.gov).

archive (http://aeronet.gsfc.nasa.gov). Each site was assigned a unique ID with the geographical information (i.e., latitude, longitude, elevation, location and land use type) about these sites listed in Table 1. Parameters provided by this AERONET data product include AOTs at different wavelengths, relative errors of AOTs, Angstrom exponents (α) among different bands as well as sampling dates and time.

2.2. Data Processing

[11] The coordinates of the AERONET sites were spatially matched with the center coordinates of the corresponding MISR regions in ArcGIS (ESRI Inc.; Redlands, CA). All three MISR AOT measurements from the matched MISR regions were extracted and matched with 10–11 a.m. average AERONET AOT measurements on the same days. For areas where the center regions did not have valid measurements for certain MISR parameter, averages were taken from the surrounding eight regions and flagged for lower quality. To reduce noise level introduced by spatial averaging, averaged MISR AOT values were only computed from those regions with at least three valid measurements for every MISR AOT parameter. As suggested by MISR researchers (David Diner, personal communication), MISR AOTs greater than 1.50 were likely erroneous and caused by inadequate cloud screening. Consequently, these points were removed to reduce possible data contamination. This threshold was further justified in that only four out of a total of 81,500 AOT measurements collected at the 16 AERONET sites in 2001 exceeded 1.50 (interpolated to 558 nm). The final data set contained 269 data records.

[12] AERONET AOT measurements at 440 nm and 675 nm were interpolated to 558 nm using the Angstrom exponents ($\alpha_{440-675\ \mathrm{nm}}$) provided in the AERONET data sets to allow for straightforward interpretation of the results. (The spectral dependence of AOT was parameterized through the Angstrom exponent (α) defined as $\alpha_{\lambda 1-\lambda 2} = -d \ln \tau_\lambda / d \ln \lambda = -\ln(\tau_{\lambda 1}/\tau_{\lambda 2})/\ln(\lambda 1/\lambda 2)$ where $\tau_{\lambda 1}$ and $\tau_{\lambda 2}$ were AOT values at wavelengths λ_1 and λ_2. Because $\alpha_{440-675\ \mathrm{nm}}$ information was not available at Sioux Falls, $\alpha_{440-870\ \mathrm{nm}}$ was used instead.) Averages of AERONET AOTs measured between 10–11 a.m. local time (denoted as $\mathrm{AERONET}_{10\mathrm{am}}$ in this analysis) were calculated and compared with MISR AOT measurements. The values of $\alpha_{440-675\ \mathrm{nm}}$ was also used as a categorical indicator of aerosol size distribution [*Eck et al.*, 1999; *Kaufman et al.*, 2000; *Thulasiraman et al.*, 2002]. For $\alpha_{440-675\ \mathrm{nm}}$ values less than 0.75, supermicron particles such as desert dusts (referred to as coarse particles in this analysis) were dominant. For $\alpha_{440-675\ \mathrm{nm}}$ values greater than 1.7, submicron particles such as fresh biomass burning smoke and urban/industrial aerosol (referred to as fine particles) were dominant. For $\alpha_{440-675\ \mathrm{nm}}$ values between 0.75 and 1.70, a mixture of coarse and fine particles is present.

[13] For the current analysis, the average temporal spacing between two consecutive MISR-AERONET observations for a given site was approximately 20 days, which is substantially longer than the residence time of tropospheric aerosols. Besides the fact that the narrow MISR swath ($\sim$400 km) allows a global coverage in seven days on average, this large temporal spacing observed in this data set is likely because MISR cannot retrieve aerosol properties when a scene is covered by clouds or the terrain lacks spatial contrast. In addition, many of the AERONET sites did not operate during the entire sampling period. Based on the above findings, therefore, all the data points were treated as independent observations.

[14] Data were characterized using descriptive statistics, graphical displays, and goodness-of-fit tests (Kolmogorov-Smirnov test and Cramer-von Mises test). Paired t tests, Spearman's correlation coefficients (to account for the lognormality of the data shown later in the analysis) and simple linear regression were used to examine the agreement between MISR and AERONET AOT measurements. Results were presented with two decimal places or at least one significant digit. Statistical significance of parameter estimates was reported at the $\alpha = 0.05$ level, which represents the probability of the tested quantity being equal to zero in a t test.

[15] Finally, a general linear model was used to study the impact of geographical and seasonal factors on the associ-

ation between MISR and AERONET AOT measurements. This model was expressed as:

$$\text{MISR AOT} = \beta_0 + \sum_{i=1}^{j} \beta_i \times Var_i + \beta_{j+1} \times \text{AERONET}_{10\text{am}} + \sum_{k=j+2}^{n} \beta_k \times \text{Var}_k \times \text{AERONET}_{10\text{am}}.$$

$\text{AERONET}_{10\text{am}}$ was treated as a continuous variable, and all other factors were categorical variables classified by different levels. Var_i represents a categorical variable; and β_1 is the parameter estimate corresponding to each level of Var_i. The term $\beta_0 + \sum_{i=1}^{j} \beta_1 \times \text{Var}_i$ represents the model intercept. β_{j+1} is model slope independent of all categorical variables. $\text{Var}_k \times \text{AERONET}_{10\text{am}}$ represents the interaction between a specific categorical variable and $\text{AERONET}_{10\text{am}}$. $\beta_{j+1} + \sum_{k=j+2}^{n} \beta_k \times \text{Var}_k$ represents the overall model slope. It also has one value for each combination of variable levels. One level of the categorical variable and its interaction with $\text{AERONET}_{10\text{am}}$ have been chosen as the reference state and their corresponding estimates are set to zero. The parameter estimates, the standard errors of the estimates and the significance levels (p values) were all calculated against the reference level. All statistical analyses were conducted using the SAS system (SAS Institute Inc.; Cary, NC).

3. Results and Discussion

3.1. Relationships Among MISR AOT Parameters

[16] Histograms showed that both MISR and AERONET AOT measurements exhibited similar right-skewed, monomodal distributions (Figure 2). Goodness-of-fit tests indicated that all AOT parameters were lognormally distributed. The results above agreed with the findings from a multiyear, multistation study of AERONET AOT data [*O'Neill et al.*, 2000]. To simplify data analysis, the relationships among $\text{MISR}_{\text{bestfit}}$, $\text{MISR}_{\text{regmean}}$ and $\text{MISR}_{\text{wgtdmean}}$ were first examined using paired t tests and linear regression analyses. Mean $\text{MISR}_{\text{wgtdmean}}$ was slightly smaller than mean $\text{MISR}_{\text{regmean}}$ (difference = 0.007, $p < 0.0001$) while the difference between $\text{MISR}_{\text{bestfit}}$ and $\text{MISR}_{\text{regmean}}$ was insignificant ($p = 0.97$). $\text{MISR}_{\text{bestfit}}$, $\text{MISR}_{\text{regmean}}$ as well as $\text{MISR}_{\text{wgtdmean}}$ were strongly correlated and had excellent linear relationships (Figure 3). The quality flags for each AOT parameter did not have significant impacts on the associations among these parameters. The small differences among them, shown as the small intercepts and the slopes that differed from 1.0, were probably caused by the variation of retrieved AOTs from different aerosol mixtures because the three MISR AOT parameters were calculated differently (see definitions in section 2). The above results suggested that the three MISR AOT parameters could be used interchangeably. For the purpose of this analysis, $\text{MISR}_{\text{regmean}}$ was chosen as the representative MISR AOT parameter.

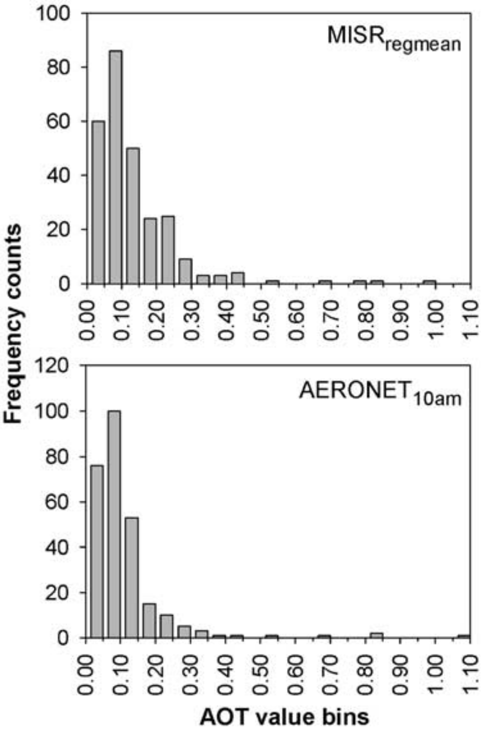

Figure 2. Distributions of MISR and AERONET AOT parameters (N = 269). Because $\text{MISR}_{\text{bestfit}}$, $\text{MISR}_{\text{regmean}}$ and $\text{MISR}_{\text{wgtdmean}}$ are highly comparable, only the histogram of $\text{MISR}_{\text{regmean}}$ is shown.

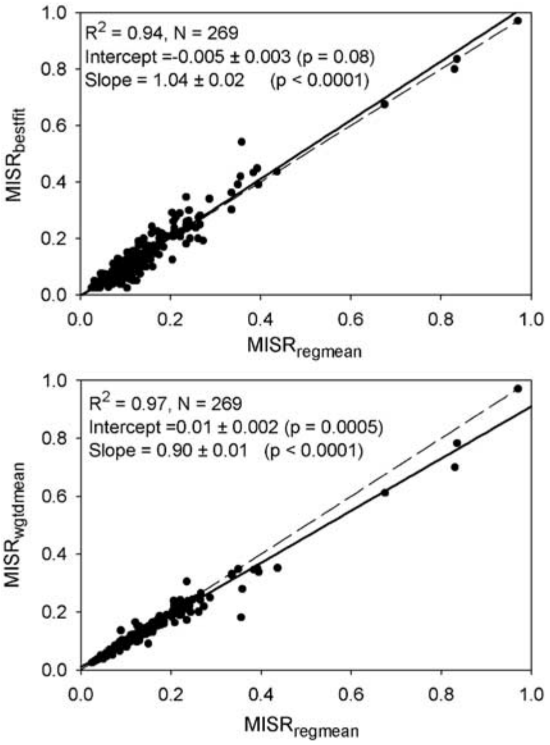

Figure 3. Scatterplots of $\text{MISR}_{\text{regmean}}$ versus $\text{MISR}_{\text{bestfit}}$ (upper) and $\text{MISR}_{\text{regmean}}$ versus $\text{MISR}_{\text{wgtdmean}}$ (lower). Results of linear regression are shown as solid lines. The 1:1 lines are shown as the dashed lines for reference.

3.2. Summary Statistics and Comparison of Means

[17] Summary statistics for $\text{MISR}_{\text{regmean}}$ and $\text{AERONET}_{10\text{am}}$ values for the entire data set as well as stratified by season, aerosol size distribution, and by location are presented. Results showed that $\text{AERONET}_{10\text{am}}$ had a slightly wider range (0.01–1.08) as compared to

Table 2. Yearly and Seasonal Statistics for MISR$_{regmean}$ and AERONET$_{10am}$ as Well as Their Differences[a]

	Variables	N[b]	Mean	SD[c]	Minimum	Maximum	Difference (Standard Error)[d]	Relative Error,[e] %
Annual	MISR$_{regmean}$[f]	269	0.13	0.11	0.02	0.97		
	AERONET$_{10am}$[g]	269	0.11	0.12	0.01	1.08	0.02 (0.007)	18
Winter	MISR$_{regmean}$	55	0.08	0.07	0.02	0.44		
	AERONET$_{10am}$	55	0.06	0.04	0.01	0.25	0.02 (0.007)	33
Spring	MISR$_{regmean}$	61	0.14	0.08	0.04	0.38		
	AERONET$_{10am}$	61	0.11	0.08	0.02	0.52	0.03 (0.01)	27
Summer	MISR$_{regmean}$	71	0.19	0.17	0.07	0.97		
	AERONET$_{10am}$	71	0.16	0.19	0.04	1.08	0.03 (0.02)	19
Fall	MISR$_{regmean}$	82	0.10	0.07	0.03	0.39		
	AERONET$_{10am}$	82	0.09	0.07	0.02	0.42	0.01 (0.008)	11

[a] Winter is December through February, spring is March through May, summer is June through August, and fall is September through November.

[b] N refers to sample size.

[c] SD refers to arithmetic standard deviation.

[d] Difference is calculated as MISR$_{regmean}$ − AERONET$_{10am}$.

[e] Relative error of MISR$_{regmean}$ is calculated as (MISR$_{regmean}$ − AERONET$_{10am}$)/AERONET$_{10am}$.

[f] MISR$_{regmean}$ refers to regional mean MISR AOT at 558 nm.

[g] AERONET$_{10am}$ refers to hourly AERONET AOT at 558 nm at 10–11a.m. local time.

MISR$_{regmean}$ (0.02–0.97). MISR$_{regmean}$ values were 0.02 ± 0.007 greater than AERONET$_{10am}$, approximately 20% of the annual mean AOT (Table 2), which constituted a significant difference (paired t test, $p < 0.0001$). Geographically, coastal sites such as La Jolla, Cove, MD Science Center generally had higher and more variable AOT values than inland sites such as Rogers Dry Lake, Maricopa, and Sevilleta (Figure 4). AOT values varied greatly by season with the mean values for both MISR and AERONET AOTs in the summer shown to be more than twice as high as in the winter. The difference between MISR$_{regmean}$ and AERONET$_{10am}$ was significant in all seasons as shown by paired t tests ($p < 0.01$ in all seasons). The relative difference was larger in the winter (0.02, ~30% relative error) and the spring (0.03, ~30% relative error) as compared to the summer (0.03, ~20% relative error) or the fall (0.01, ~10% relative error). In terms of aerosol size distribution, paired t tests showed that the difference between mean MISR and AERONET AOTs was the largest under coarse particle dominant conditions (0.04) and smallest under fine particle dominant conditions (0.02) (Table 3). Paired t tests indicated that the difference between mean MISR and AERONET AOTs was the largest (0.05) in western sites and insignificant in midwest sites (Table 3).

3.3. Association Between MISR and AERONET AOT

3.3.1. Correlation Coefficients

[18] Overall, there was a strong correlation between MISR$_{regmean}$ and AERONET$_{10am}$ ($r = 0.73$, $p < 0.0001$). For all sites with more than nine observations, significant correlations existed ranging from $r = 0.49$ at Rogers Dry Lake to $r = 0.92$ at MD Science Center (Table 4). Western sites tended to have lower correlation coefficients as compared to eastern sites. In addition, as shown in Table 5, the

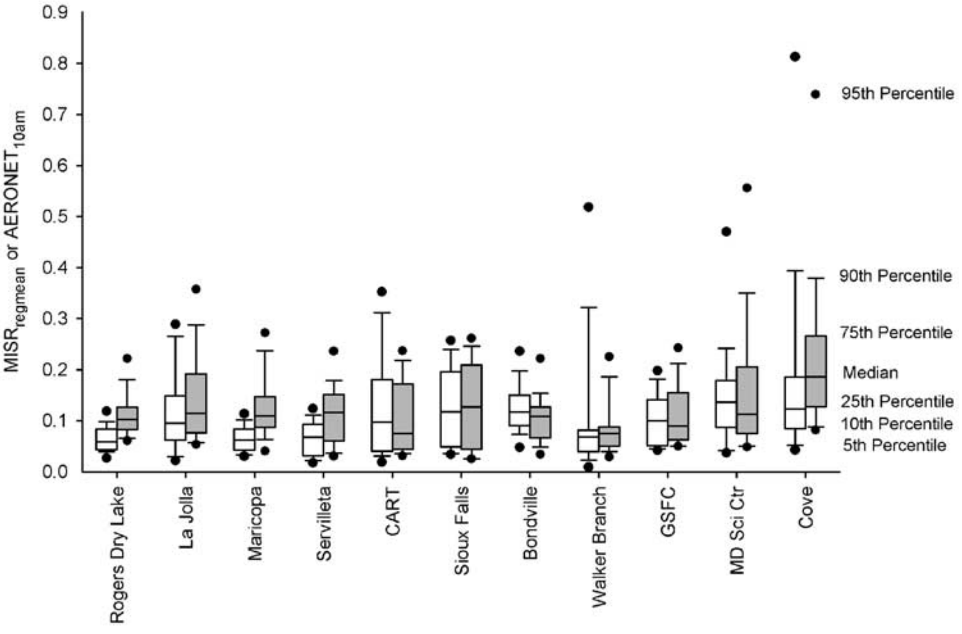

Figure 4. Box plots of AERONET$_{10am}$ (left box) and MISR$_{regmean}$ (right box) at different AERONET sites. Only sites with more than five data points are shown.

Table 3. Descriptive Statistics for MISR and AERONET AOT Variables by Aerosol Size Distribution and by Geographical Region

Variables	N	Mean	SD	Minimum	Maximum	Difference (Standard Error)	Relative Error, %
Coarse Mode Dominant: $\alpha_{440-675\ nm} < 0.75$							
$MISR_{regmean}$	26	0.13	0.07	0.02	0.36		
$AERONET_{10am}$	26	0.09	0.06	0.03	0.28	0.04 (0.01)	44
Mix of Coarse and Fine Mode: $1.70 > \alpha_{440-675\ nm} \geq 0.75$							
$MISR_{regmean}$	152	0.14	0.12	0.02	0.97		
$AERONET_{10am}$	152	0.11	0.13	0.02	1.08	0.03 (0.01)	27
Fine Mode Dominant: $\alpha_{440-675\ nm} \geq 1.70$							
$MISR_{regmean}$	91	0.12	0.11	0.02	0.83		
$AERONET_{10am}$	91	0.10	0.11	0.01	0.83	0.02 (0.01)	20
Western Sites[a]							
$MISR_{regmean}$	131	0.12	0.07	0.02	0.38		
$AERONET_{10am}$	131	0.07	0.04	0.01	0.30	0.05 (0.005)	71
Midwest Sites[b]							
$MISR_{regmean}$	56	0.11	0.07	0.02	0.27		
$AERONET_{10am}$	56	0.12	0.09	0.01	0.51	−0.01 (0.01)[c]	0
Eastern Sites[d]							
$MISR_{regmean}$	82	0.17	0.18	0.02	0.97		
$AERONET_{10am}$	82	0.15	0.18	0.02	1.08	0.02 (0.02)	13

[a] Western sites include Rogers Dry Lake, Maricopa, Sevilleta, and La Jolla.

[b] Midwest sites include CART, Sious Falls, Bondville, Walker Branch, and Big Meadows.

[c] The difference is insignificant (p = 0.08).

[d] Eastern sites include GSFC, MD Science Center, SERC, Cove, Philadelphia and Harvard forest.

correlation between $MISR_{regmean}$ and $AERONET_{10am}$ was stronger at coastal sites (r = 0.84) as compared to inland sites (r = 0.69). One possible explanation for this tendency may be that the western or inland sites generally had lower $PM_{2.5}$ concentrations as compared to eastern or coastal sites. Therefore the influence of retrieval errors in MISR AOT values could influence the correlation between $MISR_{regmean}$ and $AERONET_{10am}$ more substantially at those sites with lower $PM_{2.5}$ concentrations.

[19] The correlation between $MISR_{regmean}$ and $AERONET_{10am}$ was the weakest in the coarse particle dominant scenarios (r = 0.55) as compared to the mixed particles scenarios (r = 0.68) and the fine particle dominant scenarios (r = 0.85). As indicated by the lower mean Angstrom exponents (Table 4), western or inland sites tended to have more frequent coarse particle dominant scenarios as compared to eastern or coastal sites. Therefore another possible explanation to the variation of correlation coefficients among different sites could be because that the retrieval errors in $MISR_{regmean}$ were larger when a larger proportion of coarse particles was present in the atmosphere.

Table 4. Spearman's Correlation Coefficients (r) Between $MISR_{regmean}$ and $AERONET_{10am}$ at Different AERONET Sites and the Corresponding Significance Levels

Site Name[a]	State	N	$\alpha_{440-675\ nm}$[b]	r	p Value[c]
All sites		269	1.49	0.73	<0.0001
Rogers Dry Lake	CA	39	1.21	0.49	0.002
Bondville	IL	14	1.23	0.57	0.04
Maricopa	AZ	31	1.00	0.60	0.0003
Walker Branch	TN	10	2.45	0.70	0.02
Sevilleta	NM	40	1.31	0.76	<0.0001
CART	OK	13	1.65	0.78	0.002
La Jolla	CA	21	1.32	0.86	<0.0001
GSFC	MD	19	1.90	0.87	0.0003
Sioux Falls	SD	14	1.42	0.88	<0.0001
Cove	VA	18	1.75	0.91	<0.0001
MD Science Center	MD	20	1.94	0.92	<0.0001

[a] Calculation was only conducted at sites with no less than 9 observations.

[b] Angstrom exponents at 440–675 nm.

[c] Probability that r is not significantly different from 0.

3.3.2. Regression Analysis

[20] A linear regression between $MISR_{regmean}$ and $AERONET_{10am}$ yielded an R^2 of 0.80 and an RMSE of 0.05 after two possible outliers (marked by site names in Figure 5) were excluded. ($R^2 = 0.77$, RMSE = 0.06, slope = 0.85 ± 0.03 and intercept = 0.04 ± 0.005 when the two possible outliers were included.) The positive intercept (0.04 ± 0.005) reflects the retrieval bias in $MISR_{regmean}$ shown by the previous paired t test. Some possible explanations for this positive bias might include: uncertainties related to the assumptions of vertical profiles and aerosol models, inadequate cloud screening, imperfect aerosol cli-

Table 5. Correlation Coefficients (r) and Corresponding Significance Levels Between $MISR_{regmean}$ and $AERONET_{10am}$ by Different Classifications

Factor	Level	N	r[a]
Dust[b]	coarse particle dominant	26	0.55
	mixture of coarse and fine particles	152	0.68
	fine particle dominant	91	0.85
Coast[c]	inland sites	178	0.69
	coastal sites	91	0.84

[a] All the correlation coefficients are highly significant (p < 0.0001).

[b] Dust is the classification for different aerosol size distribution. $\alpha_{440-675\ nm} < 0.75$ for coarse particle dominant scenarios, $\alpha_{440-675\ nm} \geq 1.70$ for fine particle dominant scenarios, and $1.70 > \alpha_{440-675\ nm} \geq 0.75$ for mixtures of coarse and fine particles.

[c] See notes in Table 3.

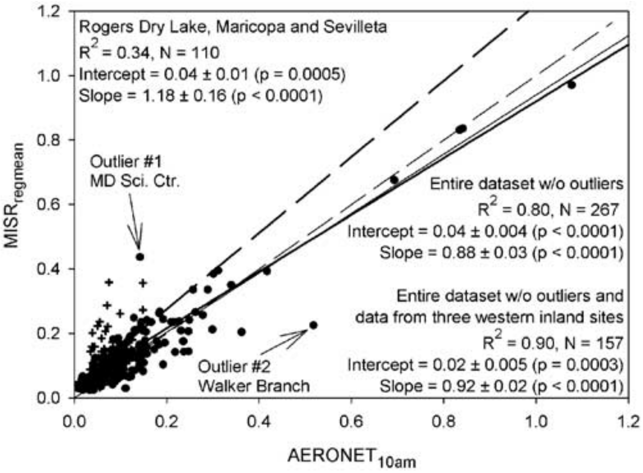

Figure 5. Scatterplots of $\mathrm{MISR_{regmean}}$ versus $\mathrm{AERONET_{10am}}$. Two possible outliers are marked by their site names. The linear regression line for all sites without the outliers is shown as the thick solid line. Data points from Rogers Dry Lake, Maricopa and Sevilleta are shown as crosses. The linear regression line with the outliers and data from these three sites excluded is shown as the thin solid line. The associated parameter estimates of both lines are given at the upper left corner of the plot. The linear regression line for data from these three sites is shown as the thick dashed line and the associated parameter estimates are given at the upper left corner. The 1:1 line is shown as the thin dashed line for reference.

matology as well as the dependency on monthly averaged meteorological data rather than real time data. Quantitative characterization of the retrieval bias is beyond the scope of this paper. The slope (0.88 ± 0.03), intercept as well as the RMSE of this regression line are all comparable with those reported in the work of *Chu et al.* [2002] where comparison of MODIS and AERONET AOTs yielded an uncertainty of ±0.05 on the intercept, ±0.2 on the slope and an RMSE of 0.1. It should be noted that *Diner et al.* [2001] conducted their measurements in relatively dry and cloud free conditions, which likely explains the slightly lower retrieval bias they found as compared to the current analysis.

[21] As shown in Figure 5, there was substantial scatter at low AOT level. Much of this scatter was found from the three western inland sites, i.e., Rogers Dry Lake, Maricopa and Sevilleta. A linear regression using data points from these three sites had an R^2 of 0.33 and an RMSE of 0.05. The slope of the regression line was greater than 1.0 with substantial uncertainty (1.18 ± 0.16). This might be due to a larger proportion of coarse particles present in western sites as discussed in the correlation analysis. In addition, western sites, especially in southern California, generally have a different aerosol composition from eastern sites [*Malm et al.*, 1994]. The large scatter observed at these three sites might indicate that those aerosols are not well characterized by the current aerosol model assumptions in MISR retrieval algorithm. Regression using data from the rest of the sites had an R^2 of 0.90, an RMSE of 0.04 and a slope of 0.92. Based on the above analysis, the overall retrieval accuracy of MISR AOT may be expressed as within ±0.04 ± 0.18 × AOT following the expression in the work of *Chu et al.* [2002]. When data from the three western inland sites as well as the two possible outliers were excluded, the retrieval accuracy of MISR AOT was improved to within ±0.02 ± 0.10 × AOT.

[22] Similar to results from the correlation analysis, factors such as geographical location and aerosol size distribution could influence the strength of the association between $\mathrm{MISR_{regmean}}$ and $\mathrm{AERONET_{10am}}$. These factors were analyzed using general linear models. A Fisher's exact test indicated that aerosol size distribution, represented by different levels of Angstrom exponents, was highly correlated with geographical regions, with coarse particle dominant scenarios taking place more frequently in the west. When both aerosol size distribution and geographical region were included in the model, aerosol size distribution became insignificant, suggesting the variation of the agreement between $\mathrm{MISR_{regmean}}$ and $\mathrm{AERONET_{10am}}$ could be better modeled by geographical region. Therefore aerosol size distribution was not included in the general linear model. The summary statistics of this data set also indicated that the agreement between $\mathrm{MISR_{regmean}}$ and $\mathrm{AERONET_{10am}}$ varied by season, thereby validating the inclusion of seasonal variation in the model.

[23] This model had an R^2 of 0.86 and an RMSE of 0.04 with the two possible outliers excluded and its parameter estimates were given in Table 6. Model intercept was not significantly different from zero, indicating that season, geographical region and site distance from coast were able to fully explain the positive bias in MISR AOT retrieval. The parameter estimates for different seasons indicated that the retrieval bias was approximately 0.03 higher in the spring and summer as compared to the winter and fall. In addition, inland sites generally had a higher retrieval bias (0.02) as compared to coastal sites. Finally, retrieval bias also differed in geographical regions, with highest bias found in the western sites and lowest in the midwest sites.

Table 6. Parameter Estimates of the General Linear Model in Estimating $\mathrm{MISR_{regmean}}$ Using $\mathrm{AERONET_{10am}}$, Geographical and Seasonal Factors as Well as Their Interactions With $\mathrm{AERONET_{10am}}$[a]

Parameter	Estimate	Standard Error[b]	p Value[c]
Intercept	0.01	0.007	0.07
Season			
Winter	0.005	0.008	0.53
Spring	0.03	0.008	0.001
Summer	0.04	0.008	<0.0001
Fall[d]	0.00	N/A	N/A
Distance from coast			
Inland sites	0.02	0.01	<0.0001
Coastal sitesd	0.00	N/A	N/A
Region			
West	0.02	0.008	0.02
Midwest	−0.02	0.009	0.01
East[d]	0.00	N/A	N/A
$\mathrm{AERONET_{10am}}$	0.91	0.03	<0.0001
Distance from coast × $\mathrm{AERONET_{10am}}$			
Inland sites	−0.21	0.07	0.003
Coastal sites[d]	0.00	N/A	N/A

[a] Model R^2 = 0.86, RMSE = 0.04, N = 267.

[b] The standard error of a parameter estimate.

[c] Parameter estimates are not significantly different from the reference state if p < 0.05.

[d] Reference states. Parameter estimates are set to zero.

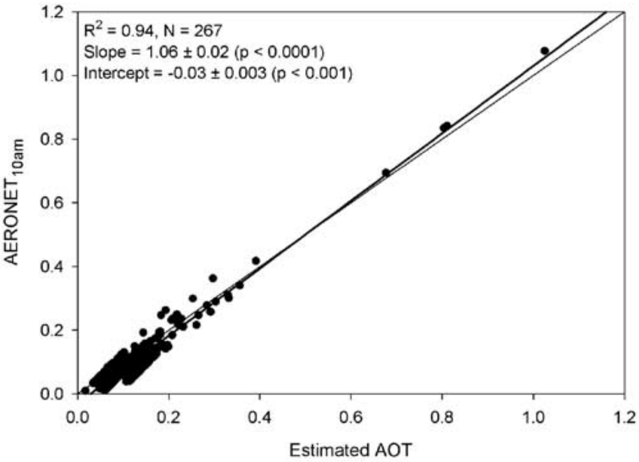

Figure 6. Scatterplot of model estimated AOT versus $AERONET_{10am}$. The regression line is shown as the thick solid line. The 1:1 line (thin solid line) is shown for reference.

[24] The slope for inland sites was estimated to be 0.70, which was significantly different from the estimated slope for coastal sites (0.91). As previously discussed, this deterioration in the agreement between MISR and AERONET AOT measurements was mainly due to data from Rogers Dry Lake, Maricopa and Sevilleta. *Chu et al.* [2002] found weaker association between MODIS and AERONET AOTs at coastal sites with greater RMSE than inland sites, which was mainly attributed to water contaminated signals near the coast. Because MISR and MODIS adopted different aerosol retrieval algorithms over land, the findings with MODIS data might not necessarily apply to MISR data. The performance of this model was evaluated by comparing $AERONET_{10am}$ with predicted AOT values. As shown in Figure 6, the regression yielded an R^2 of 0.94 and an RMSE of 0.02 with the slope of the regression line close to unity (1.06 ± 0.02).

4. Conclusions

[25] MISR AOTs were strongly correlated with corresponding AERONET AOTs measured between 10 and 11 a.m. in all 16 sites. Following the expression in the work of *Chu et al.* [2002], the overall retrieval accuracy of MISR AOT is within $\pm 0.04 \pm 0.18 \times$ AOT. This result was comparable with previous results using MISR or MODIS AOT measurements. The agreement was further improved to within $\pm 0.02 \pm 0.10 \times$ AOT (RMSE = 0.04) when data from three western inland sites, i.e., Rogers Dry Lake, Maricopa and Sevilleta were excluded from the regression. The results of current analysis support the use of MISR AOT as a quantitative analysis tool for tropospheric aerosol research. Further research is required to resolve the retrieval bias of approximately 0.02 ± 0.007 in MISR AOT as well as its seasonal and geographical variation revealed by the general linear model. The weaker agreement at Rogers Dry Lake, Maricopa and Sevilleta might indicate that the aerosol size distribution and composition in this region was not well represented by the aerosol model assumptions in MISR retrieval algorithms. Therefore caution should be given when using MISR AOT quantitatively in this region.

[26] The current analysis also showed that MISR AOT parameters (best fit, regional mean and regional weighted mean AOTs) were highly correlated and, thus, interchangeable. With MISR retrieval algorithm continuously being refined, it is likely that some of the difficulties in using MISR products will be addressed and MISR data quality will be improved. Finally, as aerosol optical properties can be related to $PM_{2.5}$ mass concentration, MISR data are especially promising for long-term $PM_{2.5}$ pollution monitoring at national or perhaps global scale.

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References

Bothwell, G. W., E. G. Hansen, R. E. Vargo, and K. C. Miller (2002), The Multi-angle Imaging Spectroradiometer science data system, its products, tools, and performance, *IEEE Trans. Geosci. Remote Sens.*, *40*(7), 1467–1476.

Bruegge, C., N. Chrien, R. R. Ando, D. Diner, W. A. Abdou, M. C. Helmlinger, S. H. Pilorz, and K. J. Thome (2002), Early validation of the Multiangle Imaging Spectroradiometer (MISR) radiometric scale, *IEEE Trans. Geosci. Remote Sens.*, *40*(7), 1477–1492.

Chrien, N., C. Bruegge, and R. R. Ando (2002), Multiangle Imaging Spectroradiometer (MISR) on-board calibrator (OBC) in-flight performance studies, *IEEE Trans. Geosci. Remote Sens.*, *40*(7), 1493–1499.

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanré, and B. N. Holben (2002), Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett.*, *29*(12), 8007, doi:10.1029/2001GL013205.

Diner, D., et al. (1989), MISR: A Multiangle Imaging Spectroradiometer for geophysical and climatological research from Eos, *IEEE Trans. Geosci. Remote Sens.*, *27*(2), 200–214.

Diner, D., et al. (1998), Multiangle Imaging Spectroradiometer (MISR) Instrument Description and experiment overview, *IEEE Trans. Geosci. Remote Sens.*, *36*(4), 1072–1087.

Diner, D., W. Abdou, C. Bruegge, J. E. Conel, K. A. Crean, B. J. Gaitley, M. C. Helmlinger, R. Kahn, J. Martonchik, and S. H. Pilorz (2001), MISR aerosol optical depth retrievals over southern Africa during the SAFARI-2000 dry season campaign, *Geophys. Res. Lett.*, *28*(16), 3127–3130.

Eck, T. F., B. Holben, J. Reid, O. Dubovik, A. Smirnov, N. T. O'Neill, I. Slutsker, and S. Kinne (1999), Wavelength dependence of the optical depth of biomass burning, urban, and desert aerosols, *J. Geophys. Res.*, *104*(D24), 31,333–31,349.

Holben, B., et al. (1998), AERONET: A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, *66*, 1–16.

Hutchison, K. D. (2003), Applications of MODIS satellite data and products for monitoring air quality in the state of Texas, *Atmos. Environ.*, *37*, 2403–2412.

Jet Propulsion Laboratory (JPL) (2002), Multiangle Imaging Spectroradiometer data product specifications, Pasadena, Calif.

Jovanovic, V., M. A. Bull, M. M. Smyth, J. Zong, R. R. Ando, and G. W. Bothwell (2002), MISR in-flight camera geometric model calibration and georectification performance, *IEEE Trans. Geosci. Remote Sens.*, *40*(7), 1512–1519.

Kaufman, Y. J., D. Herring, K. Ranson, and G. Collatz (1998), Earth Observing System AM 1 Mission to Earth, *IEEE Trans. Geosci. Remote Sens.*, *36*(4), 1045–1055.

Kaufman, Y. J., B. N. Holben, D. Tanre, I. Slutsker, A. Smirnov, and T. F. Eck (2000), Will aerosol measurements from Terra and Aqua polar orbiting satellites represent the daily aerosol abundance and properties?, *Geophys. Res. Lett.*, *27*(23), 3861–3864.

Malm, W., J. Sisler, D. Huffman, R. Eldred, and T. Cahill (1994), Spatial and seasonal trends in particle concentration and optical extinction in the United States, *J. Geophys. Res.*, *99*(D1), 1347–1370.

Martonchik, J. V., D. J. Diner, R. A. Kahn, T. P. Ackerman, M. M. Verstraete, B. Pinty, and H. Gordon (1998), Techniques for the retrieval of aerosol properties over land and ocean using multiangle imaging, *IEEE Trans. Geosci. Remote Sens.*, *36*(4), 1212–1227.

O'Neill, N. T., A. Ignatov, B. Holben, and T. F. Eck (2000), The lognormal distribution as a reference for reporting aerosol optical depth statistics: Empirical tests using multi-year, multi-site AERONET sunphotometer data, *Geophys. Res. Lett.*, *27*(20), 3333–3336.

Smirnov, A. (2000), Cloud-screening and quality control algorithms for the AERONET database, *Remote Sens. Environ.*, *73*(3), 337–349.

Thulasiraman, S., N. T. O'Neill, A. Royer, B. N. Holben, D. L. Westphal, and L. J. B. McArthur (2002), Sunphotometric observations of the 2001 Asian dust storm over Canada and the U.S., *Geophys. Res. Lett.*, *29*(8), 1255, doi:10.1029/2001GL014188.

Torres, O., P. K. Bhartia, J. R. Herman, A. Sinyuk, P. Ginoux, and B. Holben (2002a), A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements, *J. Atmos. Sci.*, *59*(3), 398–413.

Torres, O., J. R. Herman, P. K. Bhartia, and A. Sinyuk (2002b), Aerosol properties from EP-TOMS near UV observations, *Adv. Space Res.*, *29*(11), 1771–1780.

Zhao, T. X., L. Stowe, A. Smirnov, D. Crosby, J. Sapper, and C. McClain (2002), Development of a global validation package for satellite oceanic aerosol optical thickness retrieval based on AERONET observations and its application to NOAA/NESDIS operational aerosol retrievals, *J. Atmos. Sci.*, *59*(3), 294–312.

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