Refinements to MISR’s radiometric calibration and implications for establishing a climate-quality aerosol observing system

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ABSTRACT

A number of factors affect the accuracy of aerosol retrievals from satellite imaging radiometers, including algorithm assumptions, the quality of the associated cloud masks, the prescribed aerosol optical and microphysical models, and calibration uncertainties. In this paper, we highlight a concerted effort by the Terra Multi-angle Imaging SpectroRadiometer (MISR) team to evaluate the accuracy and stability of the instrument's radiometric calibration, with the twofold objective of (1) making improvements in the absolute and relative calibration where supported by multiple lines of evidence, and (2) evaluating the effect of those calibration refinements on aerosol retrievals. Aspects of the instrument's on-board calibrator design, including careful pre-flight handling of the Spectralon diffusers and the novel use of detector-based standards, have contributed to excellent long-term radiometric stability. In addition, multiple methodologies, including comparisons with other Terra sensors, in-flight and laboratory tests involving AirMISR (the airborne counterpart to MISR), lunar observations, camera-to-camera radiometric comparisons at specialized viewing geometries, and investigations using surface-based radiometer data over dark water sites have provided a detailed picture of radiometric performance at the low light levels typical of a large fraction of global aerosol observations. We examine the sensitivity of aerosol property retrievals to small band-to-band and camera-to-camera calibration adjustments, and demonstrate the importance of calibration in meeting climate-quality accuracy requirements. Because combining downward-looking (satellite-based) and upward-looking (surface-based) radiometers can constrain the optical properties of an aerosol column to a greater extent than possible from either vantage point by itself, achieving radiometric consistency, or “closure” between them is essential to establishing a long-term aerosol/climate observing system.

1. INTRODUCTION

Aerosols have profound effects on the Earth’s environment, climate, and on human health. Obtaining an accurate description of aerosol distributions and microphysical properties is essential for detecting long-term atmospheric trends, and for evaluating the performance of chemical transport and climate models. Satellites provide the most practical means to track long-range transport of aerosol-laden airmasses and to identify their spatial and temporal context on both regional and global scales. However, many parameters jointly influence the top-of-atmosphere radiances from which aerosol properties are inferred, and the effects of the underlying surface and clouds further complicate the retrievals. Ultimately, a comprehensive aerosol observing system must integrate surface, airborne, and satellite-based data[1]. Nonetheless, this integration can only be effective if the satellite measurement record is consistent over time so that instrument changes can be distinguished from true variability in the atmosphere.

A multi-agency climate workshop[2] has established an uncertainty requirement of ±0.01 in aerosol optical depth (AOD). This level of uncertainty is challenging, even for surface-based solar radiometer networks[3], and demands far greater consistency among satellite observations than currently exists[4]. Temporal averaging (e.g., over monthly intervals) can help reduce instantaneous retrieval noise, but averaging will not have any effect on systematic biases. AOD biases can arise from a variety of sources, including faulty assumptions in the retrieval algorithms, imperfect cloud screening, selection or prescription of inappropriate aerosol models, or errors in calibration. In a recent paper[5], the temporally averaged AOD values derived over ocean from the Advanced Very High Resolution Radiometer (AVHRR), the MODerate resolution Imaging Spectroradiometer (MODIS), and the Multi-angle Imaging SpectroRadiometer (MISR) were compared. The authors found an average difference of 0.03 between MODIS and AVHRR, and a difference of 0.03 between MISR and MODIS. Other comparisons between MISR and data from the AERosol RObotic NETwork (AERONET)[6] showed MISR results to be biased high by about 0.05 over ocean, with smaller biases over land[7-12]. Overall (including both land and ocean), two-thirds of the 558-nm MISR optical depth retrievals to fall within 0.05 or 20% of AERONET values, with about a third of the data within 0.03 or 10%[9]. The stringent demands of a potential climate observing system on aerosol accuracies led us to investigate in depth what appears to be a positive bias of ~0.05 between MISR and AERONET and the NASA Ames Airborne Tracking Sunphotometer (AATS-14) over ocean[12,13], for the purposes of understanding the cause and making improvements where warranted. The differences quoted above are based upon AODs derived using MISR radiances which have not had any band-to-band or camera-to-camera calibration adjustments or aerosol model improvements. As described below, these adjustments and improvements will significantly reduce the observed discrepancies. This understanding represents a major step toward achieving the capability to combine satellite, surface, and airborne data into an integrated climate observing system.

2. MISR INSTRUMENT

MISR was launched into polar orbit on December 18, 1999 aboard the NASA Earth Observing System (EOS) Terra spacecraft. MISR makes near-simultaneous measurements at nine view-angles spread out in the forward (f) and aft (a) directions along the flight path, using nine separate pushbroom cameras observing the Earth at 70° (cameras Df and Da), 60° (Cf and Ca), 46° (Bf and Ba), 26° (Af and Aa), and nadir (An), in each of four spectral bands centered at 446, 558, 672, and 866 nm. MISR obtains global coverage between ±82° latitude in nine days, with spatial sampling per pixel between 275 m and 1.1 km, depending on channel. The instrument systematically covers a range of airmass factors from 1-3, and in mid-latitudes, samples scattering angles extending from about 60-160°. The analog readout from the charge-coupled device (CCD) detectors in the camera focal planes are digitized to 14 bits. Thermoelectric coolers and focal plane heaters are used to maintain stable detector temperatures of -5.0±0.1°C.

MISR contains an on-board calibrator (OBC), consisting of two deployable Spectralon diffuse panels, and six sets of photodiode detectors. The panels are deployed for several minutes every two months, and one panel calibrates the forward-viewing cameras and the other calibrates the backward-viewing cameras, by diffusely reflecting sunlight into the full camera fields of view. The nadir camera views both panels. During panel deployments, the diodes also observe the reflected sunlight, in order to measure camera-incident radiances. These measurements are regressed against the camera digital output to provide the radiometric response for each of the CCD detector elements. One such photodiode set is on a goniometric arm, and allows the angular shape of the panel bidirectional reflectance factors (BRFs) to be monitored, which is important because the cameras observe the panels at different view angles. Photodiodes are either of a light-trapped high quantum efficiency (HQE) design, or p-intrinsic-n doped (PIN) radiation resistant devices. To maximize system stability, the Spectralon panels were vacuum-baked prior to launch to remove hydrocarbon contaminants that are known to darken upon exposure to ultraviolet light[15,16]. In addition, prior to launch the panels used during instrument integration and test were removed and replaced with ones that had been vacuum baked and stored in a nitrogen-purged container.

3. MISR AEROSOL ALGORITHMS

MISR aerosol retrievals make use of a prescribed set of aerosol models considered to be representative of the types to be found over the globe. The algorithms determine for which models, and at what optical depth for each model, a set of “goodness of fit” criteria are satisfied. The aerosol models are mixtures of individual “component” aerosols, where each component is defined by a size distribution (typically log-normal), particle shape, spectral complex index of refraction, and vertical distribution within the atmosphere. Radiative properties, such as atmospheric path radiance as a function of wavelength and illumination and viewing geometry for each component aerosol, are contained in a look-up table known as the Simulated MISR Ancillary Radiative Transfer (SMART) dataset. For MISR aerosol products versioned 0007 and later, a set of 24 prescribed mixtures has been used, consisting of combinations of dispersions of nonabsorbing particles, black carbon, and dust[9]. Beginning with version 0016, the number of mixtures is increased to 74, with two main changes incorporated relative to the smaller set: (1) a finer gradation in accumulation-to-coarse mode optical depth ratio, and (2) new dust models that are less absorbing than the ones previously used[17]. The algorithmic search for those aerosol mixtures that give satisfactory fits to the MISR observations involves establishing a two-dimensional grid in “mixture”, a categorical variable ranging from 1 to 24 (or 1 to 74 with the new mixture set), and optical depth, a numerical variable ranging from 0.0 to 3.0 (at 558 nm). The radiative properties of the aerosol corresponding to each location on this grid are tested to see if the fit criteria established by the retrieval algorithm are satisfied.

Over deep water bodies, the MISR aerosol retrieval algorithm uses the 672 and 866 nm bands, similar to other sensors that take advantage of the very low surface reflectance at these wavelengths. At high optical depths, data from the 446 and 558 nm bands are also incorporated. An advantage of multiangle observations is that aerosol retrievals over water are possible even when some cameras are affected by sunglint. Over land, aerosol retrievals are complicated by the large variability in surface bidirectional reflectance, and for much of the Earth the ground reflectance is high, e.g., desert and urban areas, which are major aerosol source regions. The MISR land aerosol algorithm models the shape of the surface bidirectional reflectance as a linear sum of angular empirical orthogonal functions derived directly from the image data, making use of spatial contrasts to separate the surface and atmospheric signals[18]. Aerosols are detected by virtue of their effect on the angular variation in the observed spectral radiance, rather than by their effect on absolute brightness (as in the dark water algorithm). The retrievals over water appear to be more sensitive to subtleties of instrument calibration.

4. FACTORS AFFECTING AEROSOL OPTICAL DEPTH RETRIEVALS OVER WATER

Because of our interest in establishing whether the systematic difference between MISR and sunphotometer AODs over water imply the need for some improvements in the MISR approach, the remaining discussion concentrates primarily on the dark water retrievals. Imperfect cloud screening, violations of the surface reflectance assumptions, overestimation in the amount of absorption in the dust models used in the retrievals, and calibration errors are each likely to play contributing roles. After briefly touching upon non-calibration related factors, we spend the majority of the discussion on refinement of the instrument calibration, as radiometric accuracy impacts the most fundamental instrument data products.

4.1 Non-calibration related factors

Because of their high brightness and ubiquity, clouds must be effectively screened in order to isolate the more subtle aerosol signal in top-of-atmosphere radiance imagery. Several cloud masks are derived during MISR data processing. The first, the Radiometric Camera-by-camera Cloud Mask (RCCM)[19], uses thresholds on reflectance and reflectance standard deviation to detect clouds. The second, the Stereoscopically Derived Cloud Mask (SDCM), uses automated pattern recognition to retrieve the heights of observed features in the MISR imagery; those features which have altitudes higher than a certain distance above the surface terrain are classified as cloud. The third, the Angular Signature Cloud Mask (ASCM)[20], calculates a metric known as the band-differenced angular signature (BDAS), which takes the difference between 446 and 866 nm reflectance, then differences this quantity between the two most oblique cameras viewing forward-scattered light. The ASCM is particularly effective at detecting clouds over snow and ice, but also works well over ocean and land. To date, however, the ASCM has not been incorporated into the aerosol retrieval logic. Furthermore, the current logic requires that the RCCM and SDCM agree that a particular pixel should be classified as cloud. This approach was adopted due to the presence of certain deficiencies in earlier versions of the RCCM thresholds and geometric calibration of the input radiance products, which affects the quality of the SDCM. As these are now or about to be improved significantly, the cloud screening logic will also be revised. Improved cloud screening will likely have some impact on temporally and spatially averaged AOD comparisons. However, since MISR-sunphotometer matchups are instantaneous, and retrievals over many dark water sites have been visually examined to ensure that they are cloud-free, the effect of cloud screening improvements will most probably have only a small effect on those results.

MISR algorithms do not prescribe any geographic stratification as to which aerosol models are used in the retrievals; that is, all 24 (or 74) mixtures are used everywhere. This places stringent demands on the retrieval itself to distinguish absorbing from non-absorbing particles. For example, we find that absorbing particles are necessary to achieve AOD agreement with sunphotometers over highly polluted areas; however, over mid-ocean, where conditions are more pristine, we generally want the highly absorbing models to be rejected, otherwise the mean optical depth over all successful models will be biased high. In addition, it is important to prescribe the optical properties of the underlying models as accurately as possible. The new dust models in the 74 mixture set reduce the hematite content of the mineral grains from 10% to 1%, leading to significantly brighter particles. Both the earlier (24-mixture) and later set model the dust grains as nonspherical, though the particle shapes were modified in the more recent set after a study showed that MISR is sensitive not only to the difference between spherical and nonspherical particles, but also to the form of the nonsphericity[17].

Figure 1 shows an area near the Cape Verde Islands where a large amount of dust is present in the atmosphere. In Fig. 2, the retrieved AODs using the 74-mixture set are regressed against the values obtained using the 24-mixtures. The results confirm that the new, brighter dust particles lead to an overall reduction in AOD.

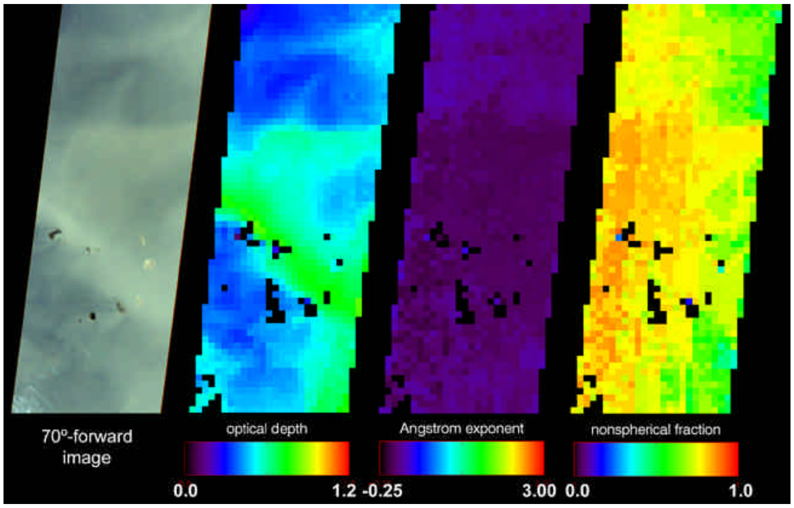

Figure 1. MISR oblique-camera image and aerosol retrievals near the Cape Verde islands, west of Africa and the Sahara desert (Feb. 6, 2004). A large amount of dust is present in the atmosphere. The results make use of the new 74-mixture aerosol set. The retrieved Angstrom exponent is representative of particles with little spectral variation in extinction over the MISR wavelength range, and the retrieved nonspherical fraction (in optical depth) is very high, as expected for aerosols comprised mostly of desert dust.

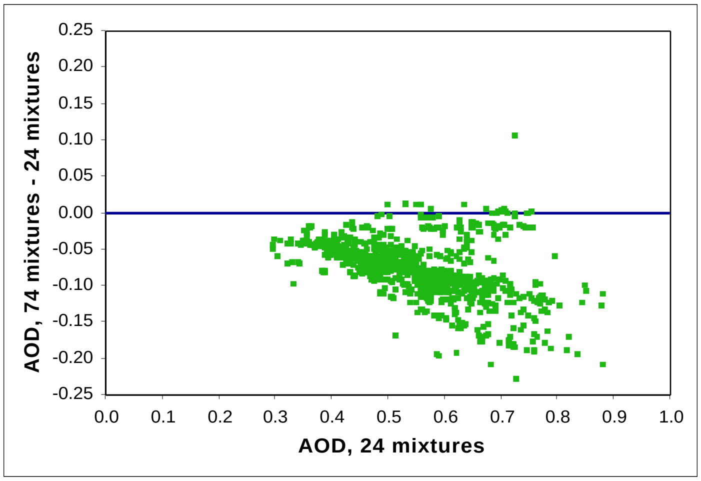

Figure 2. Comparison of aerosol optical depth retrieved using the new 74 mixture set containing less absorbing dust models, with the previous 24 mixture set. The results are for retrievals over water only, for the scene shown in Fig. 1. For this dust-laden scene, the average reduction in aerosol optical depth with the new dust models is -0.07. Due to the global prevalence of dust, this is expected to translate into a globally-averaged AOD decrease whose magnitude will be calculated once global aerosol products using the new mixture set are generated, beginning in late 2004.

4.2 Calibration-related factors: relative radiometry

Several updates to the MISR radiometric calibration process have been summarized in earlier paper[21]. We showed that following these refinements, a consistent band-to-band (BTB) relative calibration discrepancy existed between the MISR radiometric scale and that established by desert playa vicarious calibration (VC) experiments and lunar calibration data. acquired during the Terra pitchover maneuver[21] conducted on 14 April 2003. This led to the application of 3% and 1.5% adjustment factors to the gain coefficients in the MISR red and near-infrared bands, respectively[21]. MISR aerosol products having version number 0015 and later have had these BTB correction factors applied.

More recently, we have studied camera-to-camera (CTC) calibration in detail. CTC calibration makes use of the Spectralon panel BRF to transfer the radiances determined from the OBC diodes to the cameras. Independent data sets were used to validate this process. The first, referred to as the "symmetry" experiment, makes use of those points on the Earth where symmetric camera pairs (e.g., Bf/Ba) view the same location with nearly identical view zenith angles and nearly identical azimuth differences with respect to the Sun. Because most targets should have the same BRF under such conditions, a statistical accumulation of data at such locations provides a check on the relative calibration between forward and aft camera pairs. Filters were applied to screen the data for clouds and to test for scene homogeneity over a 17.6-km area. Averaged results, summarized over a wide range of land scenes observed during different seasons, are shown in the left-hand plot of Fig. 3. This figure shows a residual asymmetry, which probably arises from uncorrected differences in the BRFs of the two OBC Spectralon panels. A set of channel-by-channel correction factors was derived based on these results, and their application leads to the plot shown on the right-hand side of Fig. 3. One drawback of this technique is that it cannot tell whether a fore-aft asymmetry is due to one camera being too bright, the other being too dark, or something in between. Consequently, we also looked at the CTC variation observed during the April 2003 lunar calibration experiment. All nine cameras swept past the lunar disk at the same face-on observation angle during the “reverse somersault” which the Terra spacecraft performed during this maneuver. CTC residuals relative to the mean value in each spectral band are shown in the left-hand plot of Fig. 4. Application of the gain correction factors derived to make the adjustments shown in Fig. 3 results in the right-hand plot of Fig. 4. Overall, a slight improvement in the channel-by-channel residuals is observed. We also found that the same adjustment factors reduced the off-nadir BTB differences in MISR/AirMISR radiance ratios. The CTC correction factors were typically small, usually 1% or less. The largest adjustment was applied to the Bf camera, particularly in the near-infrared band, where a 2.5% reduction in radiance was applied (this is in addition to the 1.5% BTB correction derived earlier).

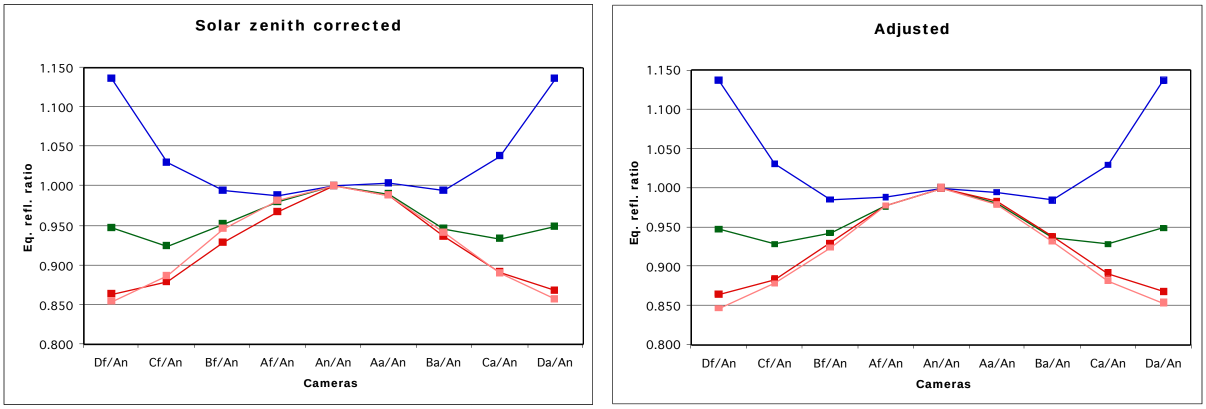

Figure 3. Left: Plot of “symmetry” data acquired over land. The curves are expected to be symmetric fore-aft. Due to the 7-minute time interval between the Df and Da views of a particular scene, a correction for solar zenith angle was applied. Right: Effect of including CTC correction factors.

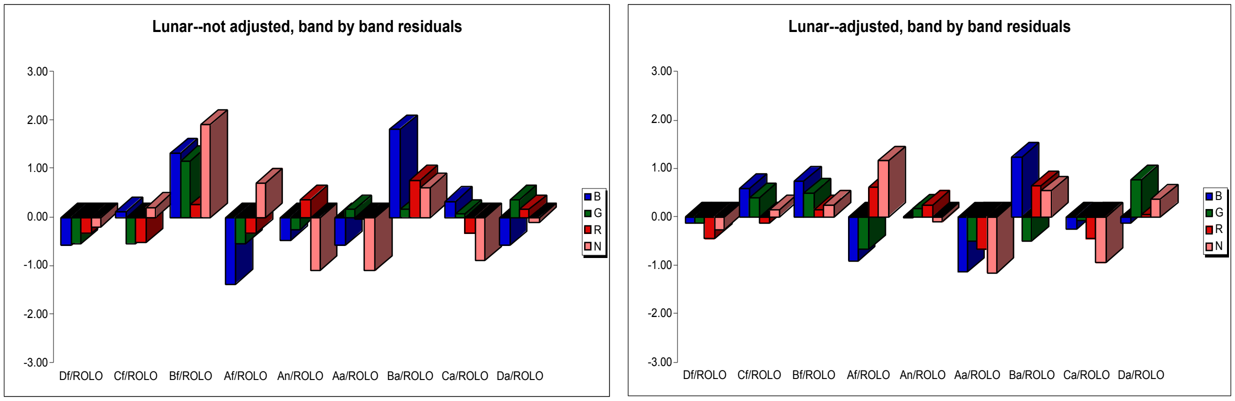

Figure 4. Left: Band-by-band residuals between MISR radiances and values obtained from the RObotic Lunar Observatory (ROLO) model (H. Kieffer, personal communication). The absolute offset between the MISR radiometric scale and the ROLO model of about 5% has been subtracted out, so that this plot shows the camera-by-camera residuals about this offset for each spectral band. Right: Residuals obtained after application of the CTC correction factors. Slight reduction in the overall residuals is obtained. Adjustment factors were not permitted to lead to zero residuals, because this would have worsened the “symmetry” data results, which are deemed more accurate because they come from a large statistical database and involve fewer assumptions.

The net effect of the BTB and CTC corrections on aerosol optical depth was estimated by randomly selecting a few orbits containing dark water retrievals and regressing the results obtained with and without the corrections. The results are shown in Fig. 5. An overall reduction averaging -0.02 in AOD is obtained, implying that these corrections account for about one-third of the difference between MISR and AERONET results.

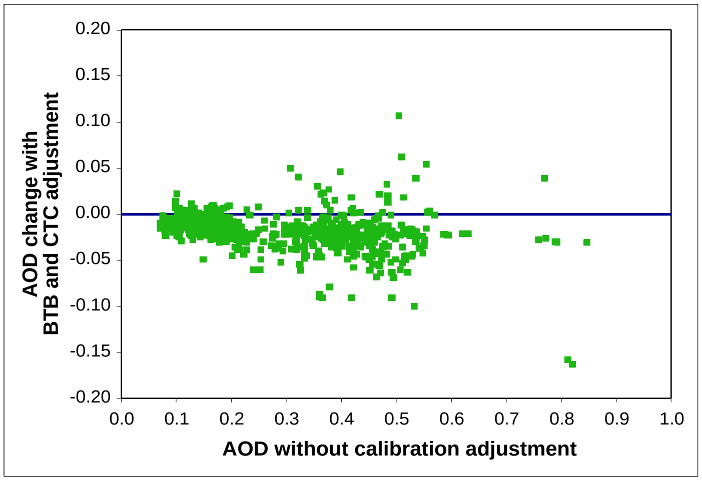

Figure 5. Difference between dark water 558-nm AODs obtained after BTB and CTC calibration adjustments and AODs without the adjustments, plotted against AOD without the adjustments. Data are from randomly selected orbits in March 2002. The BTB correction accounts for most of the difference. On average, AOD decreases, with the mean reduction for this set of test cases amounting to about -0.02. Larger differences are seen for some cases, owing to the radiometric adjustments resulting in a different set of successful aerosol mixtures being chosen by the aerosol retrieval algorithm.

4.3 Calibration-related factors: absolute radiometry

Early in the Terra mission, we discovered that the absolute radiometric response of the OBC photodiodes did not conform to preflight expectations. The likely cause was traced to inadequate characterization of the diode out-of-band spectral response. Nevertheless, the OBC has proven to be an excellent stability monitor. Analysis indicates that flight Spectralon panels and that the blue-filtered HQE diode have each remained stable to better than 0.5% throughout the mission[22]. The blue HQE diode is used as the primary calibration standard, and all other photodiodes are recalibrated against it during the bi-monthly OBC activations. The absolute scale is determined by annual vicarious calibration (VC) experiments over desert playa in Nevada, namely Railroad Valley (RRV), Lunar Lake (LL), Black Rock Desert (BRD), and Ivanpah (Ivan). Vicarious calibration entails making accurate measurements of surface reflectance and atmospheric transmittance, then using a radiative transfer code to predict top-of-atmosphere (TOA) radiances. Results from five year's worth of VC desert deployments are shown in Fig. 6. As described above and in earlier papers[12,21], a systematic analysis of MISR radiance products in comparison to both VC and lunar data acquired during the Terra pitchover maneuver[21] have led us to apply a band-to-band adjustment to MISR's radiometric scale. This BTB correction is included in the results shown in Fig. 6.

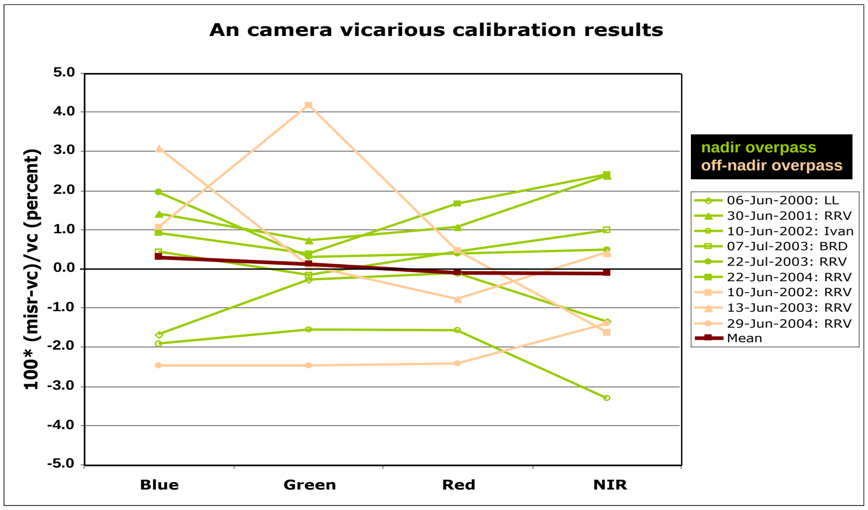

Figure 6. Average over 5 years' worth of desert playa vicarious calibrations, for the MISR nadir (An) camera. A "nadir overpass" means that the surface target is near the center of the camera's field of view (FOV), whereas an "off-nadir overpass" places the target closer to the edge of the field (the An camera has a cross-track FOV of ±15°. Most of the data fall within error bars of ±3%, and in the mean there is negligible bias. The band-to-band adjustment described in the text has been applied to these data.

The absolute radiometric scale established from the desert VC data have been verified independently using AirMISR, the airborne counterpart to MISR flown on the NASA ER-2 high-altitude aircraft. AirMISR is calibrated in the laboratory using a large integrating sphere and a set of high quantum efficiency photodiode standards. AirMISR calibrations performed between October 2002 and May 2004 have a standard deviation of 0.6% or less, depending on spectral band, so the sensor is very stable, and the AirMISR radiometric scale is entirely independent of the MISR scale. Nonetheless, Fig. 7 shows very good agreement between the MISR scale, the VC scale, and AirMISR. MISR is also in good agreement with MERIS in the red and near-infrared, which are the primary bands used in dark water aerosol retrievals. However, MISR is several percent brighter than MODIS and Landsat-7, whose scales are determined from their on-board calibrator (in the case of MODIS) or preflight data (in the case of Landsat). Independent VC data acquired by the University of Arizona (K. Thome, personal communication) also show a 3% discrepancy with MODIS, in the same sense as the results shown here.

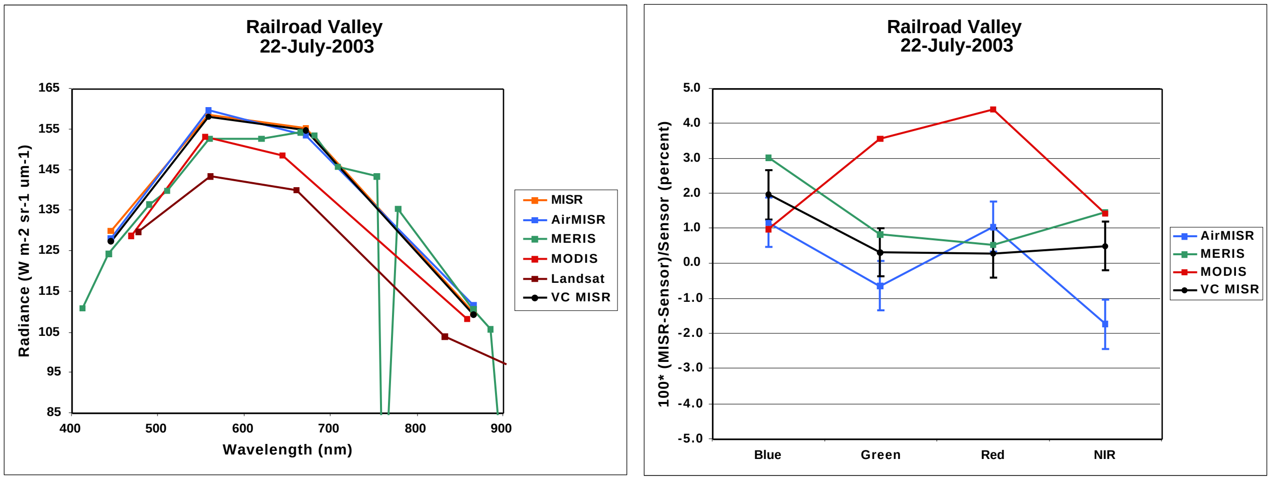

Figure 7. Left: Comparison of radiance vs. wavelength for various measurements over Railroad Valley, NV on 22 July 2003: MISR, AirMISR, MODIS, the Envisat MEdium Resolution Imaging Spectrometer (MERIS), Landsat-7, and the MISR vicarious calibration. Right: Differences between the MISR absolute radiometric scale and that from other measurements.

Using water-leaving radiances constrained by nominal ocean color models and Marine Optical Buoy (MOBY) data, and aerosol data constrained by AERONET, vicarious calibration experiments were also performed using data near Lanai and Midway islands acquired on 10 February 2002 and 9 February 2001, respectively[12]. Relatively cloud-free data with excellent surface homogeneity were chosen for the analysis. The results, which are summarized in Fig. 8, are consistent with Fig. 7 in (a) validating the MISR absolute radiometric scale, and (b) suggesting that the MODIS land channel in the red may be too dark. Figure 8 shows in particular an apparent discrepancy between the radiometric scale of the MODIS land and ocean channels for nearby wavelengths, particularly in the red. This is significant because the land channels are used for MODIS aerosol retrievals, even over ocean.

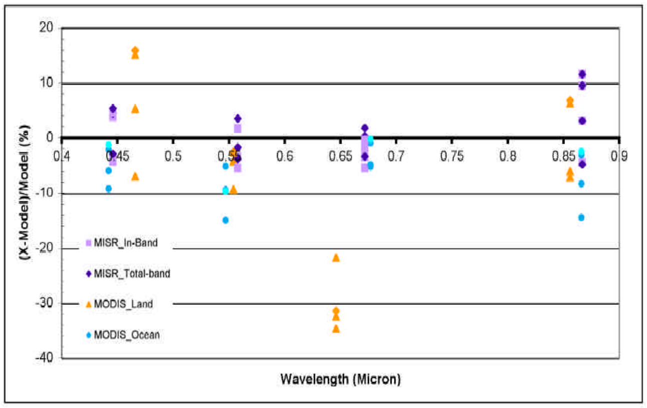

Figure 8. Comparison of MISR and MODIS radiances over dark water sites (different locations near Lanai and Midway islands) with VC results calculated using surface reflectance and AERONET data, as a function of wavelength. Good agreement is observed between the MISR and MODIS ocean measurements and the model. The MODIS red land band appears as an outlier.

Figures 7 and 8 show that MISR radiances are higher than MODIS', particularly in red, and this likely accounts for some of the discrepancy observed in MISR and MODIS retrieved AODs. We find that the bias corresponds to an optical depth difference of ~0.02 over dark water. Because the MODIS AOD values over ocean are closer in the mean to AERONET, as described above, it is tempting to conclude that the MISR absolute radiances are too high. In our view, the results shown in Figs. 7 and 8 strongly dispute this interpretation. Further complicating the issue is that the MISR/MODIS land band spectral ratio shows a dependence on whether land or ocean is observed[21]. The MISR cameras use Lyot depolarizers, and the instrument is insensitive to polarization effects. Whether MODIS polarization sensitivity is a factor, or some other phenomenon is involved, requires further study.

5. CONCLUSIONS

Several factors have been explored as potential contributors to an apparent bias between MISR and AERONET optical depths over dark water sites, and between temporally-averaged AODs among MISR and other satellite radiometers. Improved cloud screening will likely lead to better agreement in the temporally-averaged results, as will the incorporation of less absorbing dust models in the MISR retrieval database. Calibration has been extensively explored a potential contributor, and both relative and absolute radiometric accuracies have been examined. Several lines of evidence indicated the need for small band-to-band and camera-to-camera adjustments in the MISR calibration, which together can account for about one-third of the difference between MISR and AERONET over dark water. Although a darkening of the MISR absolute radiometric scale would bring MISR, MODIS, and AERONET optical depths over water into better agreement, independent lines of evidence argue against this particular adjustment to the MISR radiometry. Several unresolved issues associated with the MISR-MODIS calibration differences emphasize the need for further rigorous intercomparisons, and investment in research and technologies to improve sensor calibration and cross-calibration. Unless we develop better ways to reduce calibration uncertainties, and to understand the underlying causes of current discrepancies, these issues will continue to limit quantitative progress in understanding aerosol effects on climate.

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