6.4

EVALUATION OF RADIOMETRIC MEASUREMENTS FROM THE NASA MULTI-ANGLE SPECTRO-RADIOMETER FROM AN INHOMOGENEOUS CLOUD USING A COMBINATION OF 2D AND 3D RADIATIVE TRANSFER MODELING AND AIRBORNE MEASUREMENTS

Roger Marchand* and Thomas Ackerman
Pacific Northwest National Laboratory

1. INTRODUCTION

In December 1999, NASA launched the EOS AM1 satellite. This platform carries five instruments whose purpose is to measure important properties of the Earth climate system. One of these instruments is MISR, the Multi-Angle Spectro-Radiometer. This instrument measures the light reflected from the Earth at high spatial resolution (275 to 1100 m) at four wavelengths (three in the visible and one in the near IR) and at nine different viewing angles that vary from +70 to –70 degrees along the direction of flight of the satellite. This multi-angle data has the potential to provide information on aerosols, surface and cloud characteristics that compliments traditional single-view-direction satellite measurements. Before this potential can be realized, the accuracy of the satellite radiance measurements must be carefully assessed and the implications of the radiometric accuracy on the remote sensing algorithms evaluated.

In this article, we show a comparison of the MISR multi-angle measurements and 2D radiative transfer simulations from an inhomogeneous cloud scene. The inputs to the radiative transfer code are based entirely on independently gathered data (ground-based radar, lidar, microwave radiometer, in situ aircraft data, etc.). It is found that the 2D radiative transfer solution compares favorably in the forward scattering directions, but is off by as much as 10% in the backscattering directions. Using 3D radiative transfer modeling, we show that this difference is due to the 3D structure of the cloud, which is not resolved in the 2D simulations. Comparison of the simulations to the MISR measurements, after accounting for 3D effects, show residual differences which are less than 4% at all angles.

2. BACKGROUND

On March 3, 2000 EOS AM1 passed over the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site. The ARM program operates an array of cloud remote sensing equipment including a millimeter wavelength cloud radar, a passive microwave radiometer, broadband solar radiometers, and several lidars. At the time of this overpass, the ARM program was conducting an experiment to measure cloud absorption. As part of this experiment, in situ measurements of the cloud microphysics where made from the University of North Dakota citation using an FSSP and 1DC probes.

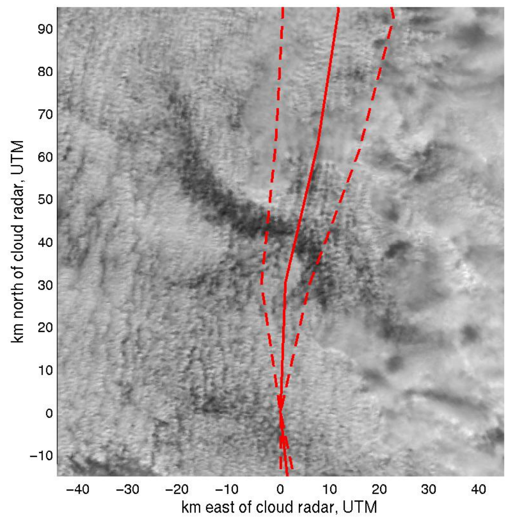

Figure 1 – MISR Nadir view at 866 um.

Figure 1, shows the MISR nadir view image of the cloud field at 866 um (NIR band). Superimposed on this image are the three lines. The solid line represents the path of clouds that are likely to have advected over the ARM SGP site, based on radar wind-profiler measurements. The dashed lines represent one standard deviation in the wind direction measurement.

In the next section, we show the result of 2D simulations based on the time series data measured by the instruments at the ARM SGP site (located at the intersection of the lines in figure 1) and we compare this with the MISR radiance measurements along the advection paths shown in figure 1. Cloud particle size information as measured by the in situ probes is also used in the simulations.

3. TWO-DIMENSIONAL SIMULATIONS

Unfortunately the uncertainty in the radiance simulations due to the uncertainty in the particle effective radius and cloud liquid water path (from the ARM microwave radiometer) is large. To reduce this uncertainty we further constrained the simulations to match the measurements of the solar broadband surface flux as shown below in figure 2.

* *Corresponding author address*: Dr. Roger Marchand, Pacific Northwest National Laboratory, P.O. Box 999, Richland WA 99352.

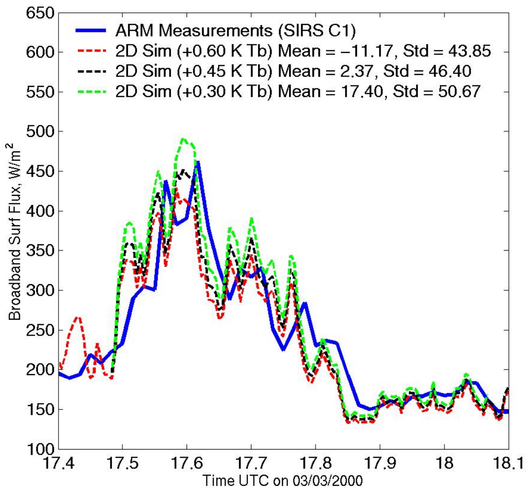

Figure 2 –Broadband surface flux

The broadband surface flux measurement is good to approximately 10 W/m^2 and the three simulations in figure 2 span this range. These simulations differ only in the amount of liquid water placed in the cloud; expressed here as an equivalent increase in the 31.4 GHz brightness temperature measured by the ARM passive microwave radiometer. While all three simulations require increasing the brightness temperature from the measured value, these increases are all within the expected uncertainty in the measurement and underlying microwave absorption model used in retrieving the liquid water path.

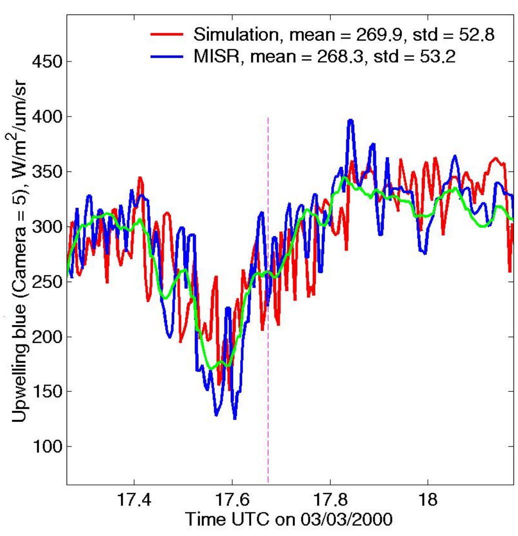

Figure 3 – Comparison of MISR measurement and 2D simulation (+0.6 K) for the MISR nadir camera at 0.446 um.

Figure 3 compares the MISR nadir radiance measurement at 0.466 um (blue band) along the cloud advection path with one of the simulations for this same quantity. As the figure shows, when averaged over a half hour period, centered on the overpass time, excellent agreement is observed between the two. The simulations are conducted at a temporal resolution of 20 seconds and the wind speed was approximately 13 m/s, with the result that the simulations have a horizontal resolution of about 260 m. This resolution is close to that of the MISR measurements, which is 275 m. The simulations do not match the measurements at the highest spatial frequencies and given the uncertainty in the advection path, one would not expect such. We note, however, that the magnitude of the variations are similar.

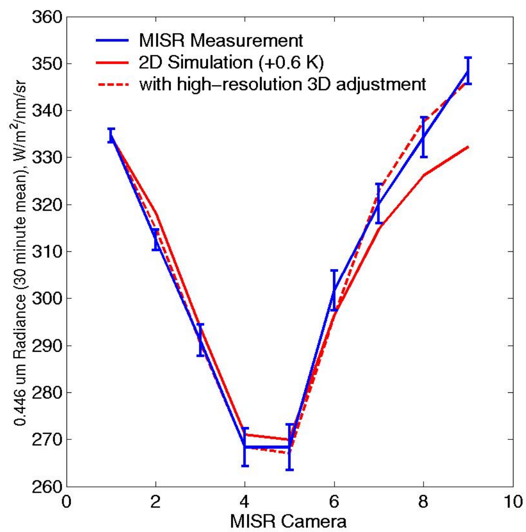

Figure 4 – Comparison of mean MISR measurements to simulations for all 9 MISR view angles in the MISR blue band (0.446 um).

Figure 4 shows the mean value of the MISR radiance (solid line with error bars) along the advection path over a distance equivalent to 30 minutes for all 9 MISR view angles in the blue band. As a rough measure of the uncertainty in this value, the error bars show the minimum and maximum value obtained from the MISR measurements using 5 different advection paths (best guess – solid line figure 1, plus one standard deviation in wind direction, minus one standard deviation in wind direction, plus one standard deviation in wind speed, and minus one standard deviation in wind speed). This figure indicates the 2D simulations (solid line) agree with the MISR measurements in the MISR forward cameras (cameras 1-4) and at nadir (camera 5), but diverge from the simulation in the backscattering direction. The largest difference is about 6%, in camera 9 which views the cloud field at a view zenith angle of 70.5 degrees.

The figure also hints that the difference in these backscattering angles is a result of fluctuations in the cloud structure at resolutions less than 260 meters and 3D effects. The details of this correction are discussed in the next section. However, before discussing the high resolution/3D effects, let us first examine the influence of the uncertainties in the 2D simulation.

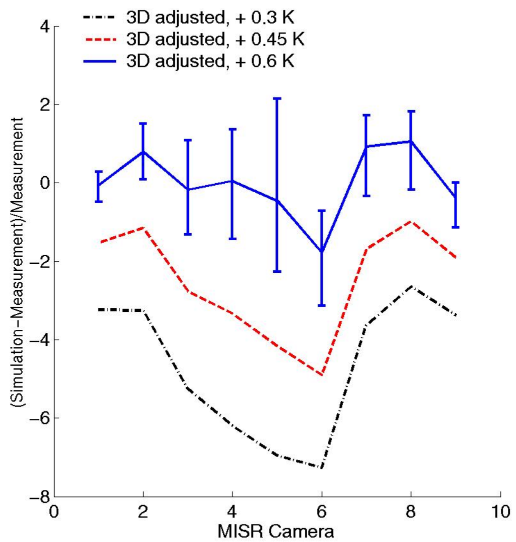

Figure 5 – Relative difference between all the 2D simulations and the MISR measurements at 0.446 um.

Figure 5 shows the relative difference between the 2D simulations (after correcting for the 3D effects) for the three simulations that gave reasonable agreement with the surface broadband flux. As in the previous figure, the error bars show the uncertainty due to the advection path. In summary we can say that the MISR measurements are in very good agreement with the +0.6 K simulation and are thus entirely consistent with the independently gathered data. However, the uncertainty in the simulation inputs limits our ability to confirm the MISR absolute calibration to approximately 7% at nadir and to 3.5% at the most oblique views (70.5 degrees fore and aft).

4. 3D SIMULATIONS

Our initial 1D simulations (not shown here) produced results that are very close to the those of the 2D simulations. Like the 2D results, the 1D results disagreed with the MISR measurements in the backscattering direction. An analysis of the 1D simulation inputs showed that no uncertainty in the input could explain this trend. Inclusion of roughness in cloud top height with scales less than 260 meters did move 2D simulations in the needed direction, but such scales are not observed by the ground-based instruments. To examine the impact of cloud roughness and 3D effects on the scattered field we looked to AirMISR.

AirMISR is an airborne version of the MISR sensor that flies on the high altitude NASA ER-2 aircraft. However unlike the MISR instrument, AirMISR has only one camera. This camera can be programmed to move in flight to reproduce the MISR view angles. The AirMISR camera is of the same design as the MISR cameras, but since it flies much closer to the Earth, it produces images with much higher spatial resolution. Figure 6 shows the AirMISR nadir image of the cloud field captured less than 1 minute after the MISR overpass.

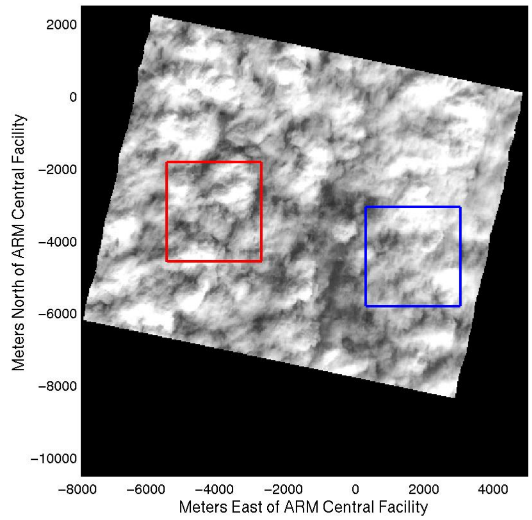

Figure 6 – AirMISR view of cloud field with 27.5 m resolution at 0.866 um. The boxes show regions of the cloud field used in the 3D analysis.

To evaluate the effect of high resolution (scales less than 260 m) and 3D effects, the scheme depicted in figure 7 was applied in order to obtain a three dimension description of the cloud liquid water. Once the three dimension liquid water field is specified, we can then calculate the radiances at all angles and at all other wavelengths of interest. This calculation can be conducted using full 3D radiative transfer and 1D (i.e. independent pixel) approaches to see if 3D effects are significant.

In our approach a subset of the AirMISR nadir imagery is selected. We opt to use the 0.446 um wavelength (blue band) because the surface reflectance is small at this wavelength and because there is no significant gas absorption. Also because we have multi-angle images of this same cloud scene, stereo-imaging techniques can be applied to determine the cloud top height, directly. Such algorithms are currently applied to MISR data on an operational basis to determine cloud top height. Using our best guess for the cloud particle size (from in situ aircraft) and cloud base height (from nearby lidar measurements), we estimate the liquid water path for each pixel in the AirMISR nadir scene from the measured nadir radiance. This estimate is based on the traditional 1D solution. Starting with this estimate, we then solve the full 3D radiative transfer problem. This was done using SHDOM code [Evans, 1998]. The solution of the 3D calculation is then compared with the measured value on a pixel by pixel basis. If the simulated value is too large for a given pixel then the liquid water path estimate is decreased for that pixel and if the simulated value is too small then the liquid water path is increased for that pixel. This process is repeated until the mean absolute deviation of the 3D simulation (summed over all pixels) is within 1 or 2 % of the mean measured value. Typically this required 6 to 10 iterations. The maximum liquid water path was capped at 1000 g/m^2 and a few pixels did reach this level. It turned out that this occurred in places where the stereo-derived cloud top height had erred and falsely set a cloud height too low, such that it was shadowed by adjacent cloud elements.

Figure 8 shows the result of this process. In this figure the solid lines are the AirMISR measurements (blue, green, red and NIR bands from top to bottom) with error bars that indicate the uncertainty in aligning the same scene in all 9 AirMISR views. The dashed curves, which are close to a given measurement, are the associated simulations.

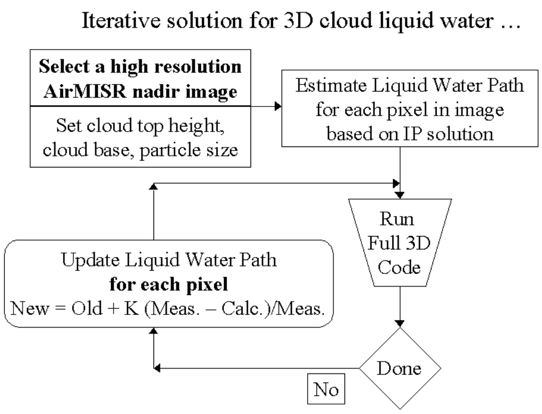

Figure 7 – Scheme to obtain 3D liquid water field.

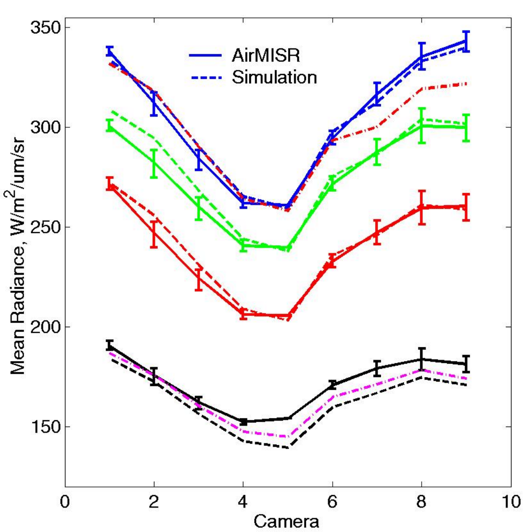

Figure 8 – comparison of measured and simulated

As a result of process shown in figure 7, the measurement and simulation in the nadir (camera 5) blue band (top curve) must agree. The agreement at all other points shows the consistency of the AirMISR measurements and simulations. The only place where there appears to be a problem is in the AirMISR NIR band (solid curve near bottom of figure 8), which appears about 5% brighter than the simulation. However, it should be mentioned that the surface is quite bright in this band and we do not know what the actual surface albedo was at the time of the MISR overpass. Figure 8, shows two NIR simulations. The simulation that is closer to the measurement uses an albedo of 0.4. It is possible that the underlying surface is brighter than this.

There are also two simulations shown in connection with the blue band. The simulation which is very close to the measurement is the 3D result. The simulation curve that drops below the blue band measurement in the backscattering directions (camera 6 to 9) is the 1D result. Therefore, we see that the 1D or independent pixel result does underestimate the radiances in the backscattering direction. The “correction” applied to the results in section 2, is simply the ratio of the 3D to the 1D result shown here.

5. CONCLUSIONS

A comparison of Independent Pixel (IP) and full 3D calculations for the same 3D cloud scene show that the IP results **underestimate** the radiances **in the MISR aft viewing directions**. In this case, the solar zenith angle is about 45 degrees and the measurements are about 12 degrees off the principle plane. Correcting our 2D simulations by the relative error between the IP and 3D solutions brings our 2D simulations into good agreement with the MISR measurements in the blue band.

Uncertainty in the overall comparison due to advection path uncertainty is approximately 2 to 3%. The uncertainty in the “ground-based” estimates of cloud liquid water and drop size effective radius are the largest source of uncertainty in comparing the simulation to measurements. Constraining the cloud liquid water such that good agreement between the simulated and measured broadband fluxes is achieved, suggest that MISR radiances may be correct and are at most 7% too high at Nadir to 3.5% too high at the 70.5 degree view angles. The MISR blue band radiances match our “+0.6 K” simulation (which is based entirely on independently gathered data) to better than 2% for all 9 MISR view angles.

The results shown here incorporate all updates to the MISR calibration through June of 2002. The MISR calibration team is continuing to adjust the sensor calibration, retroactively. Currently, the MISR team believes their absolute calibration (which applies equally to all cameras) maybe 1% to 3% too high (for bright targets such as clouds), which is consistent with the results of figure 5.