GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 17, PAGES 3277-3278, SEPTEMBER 1, 2001

Reply to comment on "Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter"

Brian Cairns[1], Michael Mishchenko, Larry Travis and Jacek Chowdhary[1]

1. Introduction

In a recent paper [*Chowdhary et al.*, 2001; hereafter CCM&T], we showed that the inclusion of polarimetric information provides superior results in the retrieval of aerosol properties to those obtained using only the intensity. Having previously shown detailed theoretical analyses of the superiority of well calibrated polarimetric remote sensing to intensity only remote sensing of aerosols [*Mishchenko and Travis* 1997a, b], the purpose of CCM&T was to demonstrate that such analyses carry over to actual measurements. The excellent agreement between upward looking sunphotometer measurements of spectral optical depth and those inferred from the Research Scanning Polarimeter (RSP) measurements (Fig. 2 of CCM&T) provides a first demonstration of the validity of the previous theoretical analyses in a natural setting. In their commentary [this issue] Martonchik, Kahn, Diner and West (hereafter MKD&W) discuss the complementarity of polarimetric remote sensing and the type of measurements made by MISR. We would concur with MKD&W that it is "essential to validate retrieved spectral refractive indices and particle size distributions" that are possible with polarimetric measurements, just as it is essential to evaluate and validate the true capabilities of MISR. We look forward to such evaluation and analysis of RSP measurements in future co-ordinated field campaigns. In the following we discuss why we believe the set of measurements and the analysis presented in CCM&T provides a fair, although not perfect, representation of the capabilities of MISR and discuss the other issues raised by MKD&W.

2. Review of CCM&T analysis

MKD&W state that our "conclusion differs in part because CCM&T's analysis was restricted to view zenith angles less than 40° from nadir. Only three of the nine MISR cameras have view zenith angles in this limited range". The view angle range used in CCM&T is a limitation of the aircraft and instrument mount that we used to obtain the data, which limited viewing angles to less than ±45° from nadir because of vignetting by the aircraft skin. The full range of view angles available from the RSP is ±60° and we hope to be able to use this full range in future experiments. We attempted to compensate for the current limitations by choosing a time of day and aircraft orientation that maximized the available scattering angle range. These principal plane measurements, used by us in CCM&T, provide a larger range of scattering angle (i.e., angle between the direction of sun and viewing angle) than is usually encountered by the MISR instrument on the TERRA platform. We believe, based on our analyses, that the principal angular metric determining the quality and accuracy of aerosol retrievals is the scattering angle range. In Figure 1 we show a sample of the scattering angle range observed by MISR, aggregated over the course of a year, with the solid line representing observations equatorward of 60° and the dashed line representing observations poleward of 60° in latitude. The observed scattering angle range available from the measurements used in CCM&T is shown by the arrow, which lies well within the set of scattering angle ranges observed by MISR. Thus, although the measurements we used do not have the same geometry as MISR, we would contend that the viewing geometries available from CCM&T provide a useful, although less than ideal, comparison of the relative capabilities of multi-angle intensity and polarization measurements.

MKD&W emphasize that the actual MISR retrievals use metrics additional to the ones presented in CCM&T, such as normalization by the nadir viewing reflectance or by the reflectance obtained at 672 nm (*Kahn et al.* 1998). The use of such metrics is in large part driven by the fact that the relative spectral and angular calibration of MISR is expected to be much better than the absolute calibration and such ratios make proper use of this property of the instrument calibration approach. However, the use of the spectral ratio is not valid for the data presented in CCM&T since this metric assumes the water-leaving radiances to be negligible at 672 nm, which is not true for turbid ocean waters such as in our case-study (*Toole et al.*, 2000, *Gordon*, 1997). As regards ratioing the reflectances by the nadir viewing reflectance, our analysis of the RSP data makes implicit use of the fact that although the radiometric uncertainty of the intensity measurements is relatively high (3.5%) the angle-to-angle uncertainty is negligible.

MKD&W note that MISR measurements can distinguish between the monomodal and bimodal aerosol distributions described in CCM&T, although it is not clear if such a distinction requires use of the 672 nm measurements. Nonetheless, this is most encouraging since MISR is currently flying and this result indicates that its measurements may have the potential to substantially improve our existing knowledge of the distribution of aerosols. However, it should be emphasized that in generating the monomodal aerosol distributions in CCM&T, we required that the intensities simulated using the monomodal distributions match the intensities simulated using the bimodal distribution over both the available view angle range and for **both** 865 and 2250 nm measurements. Under the type of turbid ocean conditions which apply to CCM&T, only the measurements at 865 nm, with their full angular range, would be usable by MISR. A theoretical analysis that demonstrates the non-uniquenes of this MISR measurement set has already been performed [*Mishchenko and Travis*, 1997a, 1997b].

[1]Also at the Department of Applied Physics and Applied Mathematics, Columbia University, New York.

Copyright 2001 by the American Geophysical Union.

Paper number 2001GL013344.
0094-8276/01/2001GL013344$05.00

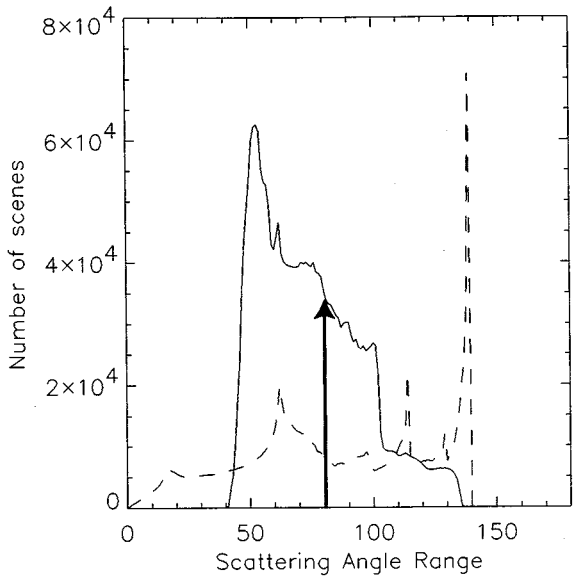

Figure 1. Scattering angle range used in CCM&T (arrow) compared to a sample of the scattering angle ranges observed (equatorward of ±60° - solid line, poleward of ±60° - dashed line) by MISR over the course of a year.

MKD&W indicate that the MISR operational aerosol retrieval algorithm uses the fact that "MISR is sensitive to the difference between monomodal and bimodal particle distributions, composed of a set of climatologically likely component particles [*Kahn et al.*, 2001]." As the INDOEX results demonstrate [*Meywork and Ramanathan*, 1999] there are significant dangers in such climatological assumptions and it is only with measurements such as those made by RSP, or the potential EOSP instrument, that one can restrict the amount of prior information required for an aerosol retrieval algorithm to a level where it does not prejudice the results.

3. Discussion

MISR complements the proposed EOSP measurements by virtue of being an imaging rather than a scanning instrument. That is, MISR is capable of viewing the earth with higher pixel resolution and of obtaining global coverage. MKD&W point out that MISR has 275 meter resolution, while the proposed EOSP instrument has a 10 km pixel size. This is true and subpixel cloud could be a problem for an EOSP instrument, which would be mitigated by operation in conjunction with a MISR-type instrument. It is also suggested in MKD&W that MISR observes over a larger angular range than EOSP. In fact EOSP would observe over a view angle range relative to the surface reference ellipsoid of ±74° (±60° nadir angles at the satellite), as compared to the ±70° of the highest view angle cameras on MISR. The implications of the absence of global coverage from instruments that only measure along the ground track for studies of climate forcing are less critical than is commonly believed. Sampling studies indicate that an adequate sample of aerosol radiative properties can be obtained with along-track scanning instruments and that, because of the time and space scales of synoptic systems, the climatological sampling noise is not reduced by cross-track coverage [*Hansen et al.* 1995]. In fact, to robustly monitor the radiative forcing of the climate it is necessary to have an observing system with more than one satellite [*Salby* 1989]. Finally MKD&W suggest that surface variability will represent a serious problem to the use of an EOSP instrument over land surfaces. However RSP measurements indicate [*Cairns et al.* 2001] that the approach pioneered by the POLDER team [*Herman et al.* 1997, *Nadal and Bréon* 1999] can be simplified and made more robust using EOSP. Detailed analyses of data taken over the ARM SGP site run by the Department of Energy site are in preparation.

In conclusion, we believe that all the evidence shows that well calibrated, multi-angle, multi-spectral measurements of the intensity and polarization represent the best approach to the estimation of the aerosol burden and aerosol microphysical models from space. We would agree that the use of EOSP together with a lidar, MISR and MODIS represent a highly complementary instrument payload and recognise the continuing need for *in situ* and ground-based measurements against which to test and evaluate remote sensing methods.

References

Cairns, B., J. Chowdhary, Mishchenko, M.I. and L.D. Travis, "Aerosol retrievals over land surfaces (The advantages of polarization)," Proceedings of the American Meteorological Society, Albuquerque NM, 2001.

Chowdhary, J., B. Cairns, M. Mishchenko, and L. Travis, Retrieval of aerosol properties using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter, *Geophys. Res. Lett*, **28**, 243-246, 2001.

Gordon, H. R., Atmospheric correction of ocean color imagery in the Earth Observing era, *J. Geophys. Res.*, **102**, 17,081-17,106, 1997.

Hansen, J., W. Rossow, B. E. Carlson, A. A. Lacis, L. D. Travis, A. D. D. Genio, I. Fung, M. I. Mishchenko, B. Cairns, and M. Sato, "Long-term monitoring of global climate forcings and feedbacks," *Climatic Change*, **31**, pp. 247-271, 1995.

Herman, M., J. L. Deuzé, C. Devaux, P. Goloub, F. M. Bréon, and D. Tanré, "Remote sensing of aerosol over land surfaces including polarization measurements and application to POLDER measurements," *J. Geophys. Res.*, **102**, 17039-17049, 1997.

Kahn, R., P. Banerjee, D. McDonald, and D. Diner, Sensitivity of multiangle imaging to aerosol optical depth, and to pure-particle size distribution and composition over ocean, *J. Geophys. Res.*, **103**, 32195-32213, 1998.

Meywerk, J. and V. Ramanathan. Observations of the Spectral Clear-Sky Aerosol Forcing over the Tropical Indian Ocean. *J. Geophys.Res.*, **104**, 24,359-24,370, 1999.

Mishchenko, M. I. and L. D. Travis, "Satellite retrieval of aerosol properties over the ocean using polarization as well as intensity of reflected sunlight," *J. Geophys. Res.*, **102**, 16,989-17,013, 1997a.

Mishchenko, M. I. and L. D. Travis, "Satellite retrieval of aerosol properties over ocean using measurements of reflected sunlight: Effect of instrumental errors and aerosol absorption," *J. Geophys. Res.*, **102**, 13543-13553, 1997b.

Nadal, F. and F. M. Bréon, Parameterization of surface polarized reflectance derived from POLDER spaceborne measurements. IEEE Trans.*Geo. Rem. Sens.*, **37**, 1709-1718, 1999.

Salby, M. L., Climate monitoring from space: Asynoptic sampling considerations. *J. Climate*, **2**, 1091-1105.

Toole, D. A, D. A. Siegel, D. W. Menzies, M. J. Neumann and R. C. Smith, Remote-sensing reflectance determinations in the coastal ocean environment: impact of instrumental characteristics and environmental variability. *Appl. Opt.*, **39**, 456-469, 2000.

B. Cairns, J. Chowdhary, M. Mishchenko, and L. Travis, NASA GISS, 2880 Broadway, New York, NY 10025. (bcairns@giss.nasa. gov, jchowdhary@giss.nasa.gov, mmishchenko@giss.nasa.gov, ltravis@giss.nasa.gov)

(Received April 18, 2001; revised: June 18, 2001; accepted: June 21, 2001)