Robustness in the Estimation of BRDF Model Parameters Using Limited Number of Observations

Junichi Susaki
Asian Institute of Technology
P.O. Box 4, Klong Luang, Pathumthani, 12120, Thailand

Insitute Industrial Science, University of Tokyo
4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan
susaki@ait.ac.th, susaki@iis.u-tokyo.ac.jp

Koji Kajiwara, Yoshiaki Honda
Center for Environmental Remote Sensing, Chiba University
1-33 Yayoi, Inage-ku, Chiba, 263-8522, Japan

Yoshihumi Yasuoka
Insitute Industrial Science, University of Tokyo
4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan

Abstract: Bidirectional Reflectance Distribution Function (BRDF) is reported to represent a characteristics of reflectance's angular dependency, and each land cover has different type of BRDF. BRDF products are operationally produced from Moderate Resolution Imaging Spectroradiometer (MODIS) data, and the estimated BRDF parameters are used to produce MODIS albedo products. Albedo is one of the most important parameters for heat and water budge analysis. However, observed data are often contaminated by errors caused by imperfect cloud mask and atmospheric correction. And, rainy season also limits available observations. Therefore, robust estimation of BRDF model parameters is required. Operationally, albedo is estimated from remotely sensed data through the production of Bidirectional Reflectance Distribution Function (BRDF). However, a limited number of observations is one of the most severe problems for the estimation of the BRDF. In the present paper, experimental results are reported that examine the robustness with respect to the scarcity of the number of observations. In the present research, the LSM was examined in terms of robustness with respect to the scarcity of the number of observations. In the experiments, BRDFs were estimated by the LSM using MODIS reflectance data on paddy fields in Japan in March, June and August, 2002 were used. The results revealed that the degree of the robustness depends on the condition of the land cover, even if the land cover is classified as the same category.
Keywords: BRDF, Robust Estimation, Limited Number of Observations

1. Introduction

Moderate Resolution Imaging Spectroradiometer (MODIS) instruments were launched on Terra in December of 1999 and on Aqua in May of 2002. The algorithms of various products derived from MODIS data are openly available to the remote sensing community as Algorithm Theoretical Basis Documents (ATBDs). These data products have been accumulated up to the present. Among the numerous products, the products related to the Bidirectional Reflectance Distribution Function (BRDF) are among the most valuable for use in remote sensing research. The data observed by wide-swath sensors, such as the MODIS or the Advanced Very High Resolution Radiometer (AVHRR), are affected by the sun-target-sensor geometry, and such an effect is expressed as the BRDF. Normalization is essential for temporal analysis using the data observed at different geometries, and the normalization must remove BRDF effects from the data observed by wide-swath sensors [1] [2].

The directional dependency of reflectance has been widely recognized since the 1980's [3]. The BRDF has potential for use in other applications of remotely sensed data. Albedo, one of the most important physical parameters for land remote sensing, can be estimated using the BRDF. Albedo is a physical parameter that describes the optical reflectance of the land surface. Albedo is commonly defined as the reflectance of a surface integrated with respect to both wavelength (usually between 0.3 μm and 3.0 μm) and angle (i.e. for all directions within the hemisphere above the surface). Albedo (black-sky albedo) and bihemispherical albedo (white-sky albedo) are formulated and calculated using parameters of the estimated BRDF [4].

BRDF is reported to represent characteristics of reflectance's angular dependency, and each land cover has different type of BRDF. However, observed data are often contaminated by errors caused by imperfect cloud mask and atmospheric correction. And, rainy season also limits available observations. Therefore, robust estimation of BRDF model parameters is required under the condition that limited numbers of observations are available. In the present paper, we examined the robustness of the BRDF estimation by reducing the number of observations used in estimation. In Chapter 2, the difficulty in the estimation of BRDF is described. In Chapter 3, the experimental results of examining robustness of BRDF estimation are reported. Finally, discussions and conclusions are described.

2. Difficulties in Estimating BRDF

BRDF estimation requires robustness because it is strongly affected by noises contained in data. The robustness of BRDF model parameter estimation [5] [6] is very important for correcting remotely sensed data and thereby obtaining meaningful physical parameters from the data. Li et al. have discussed the importance of a priori knowledge accumulation and its application to linear BRDF model inversion [6]. Normally, unknown parameters of kernel-driven BRDF models are solved by minimizing the sum of the squared fitting error. After a successful inversion of the three parameters from kernel-driven BRDF models, the results are used to obtain albedos of the pixel, i.e. the white-sky albedo and the black-sky albedo. However, noise and poor sampling reduce the accuracy of the BRDF model inversion, and a failed inversion may result from either poor sampling or poor directional range, and noisy sample(s), or both. A priori knowledge can indicate when retrieved kernel weights or albedos are outside the expected bounds. On the other hand, Gao et al. has reported a multikernel least-variance approach to retrieve and evaluate the albedos from limited bidirectional measurements in order to avoid a biased estimation [5]. The parameters of the linear kernel-driven models are usually easily retrieved using a least squares method (LSM). In our previous studies, parameter estimation robustness was examined using Bidirectional Reflectance Factor (BRF) data measured for paddy fields in Japan. We compare both the M-estimator and the least median of squares (LMedS) methods for robust parameter estimation to the ordinary least squares method. The experimental results demonstrate that the LMedS method can be adopted for the robust estimation of a BRDF model parameter [7].

Among several factors causing non-robust estimation of BRDF parameters, scarcity of the number of observations is one of the most severe. In MODIS BRDF products, i.e. MOD43, the normal BRDF estimation procedure requires more than six cloud-free observations of the surface during a period of sixteen days. In such cases, a full model inversion, or a normal inversion, is attempted. The available data are first evaluated in order to discard outliers, and additional checks are performed in order to assure that the kernel weights are positive. If the data pass these evaluations, a full inversion is performed in order to establish the BRDF parameter weights that provide the best RMSE fit. For those cases with insufficient or poor sampling, or a poor fit, a magnitude inversion is performed, which exploits a priori knowledge [8]. However, such a criterion for the BRDF estimation is too strict for application in many areas, including Japan. Table 1 shows the number of available Terra/MODIS data for paddy fields at Yohkaichiba in Chiba, Japan from April, 2002 to March, 2003, where we conducted ground measurements in 2002. Clear-sky data were selected not only by visually checking MOD09 images, atmospherically corrected reflectance MODIS products, but also by checking “1 km Reflectance Data State QA” MOD09 data. The “1 km Reflectance Data State QA” data include various quality assurance data. Cloud state data, one type of quality assurance data, are classified into four categories: “clear”, “cloudy”, “mixed” and “not set, assumed clear”. In the present study, data are determined to be clear-sky data if cloud state data is “clear”.

As a result, the number of clear-sky data was found on occasion to be insufficient, even for a monthly period. In particular, during the rainy season in Asian countries, there are insufficient data to meet the requirement for BRDF products. For example, from June to July, we can have only a few clear-sky observations. The preliminary experiments revealed that even though the LMedS method is robust in the case of sufficient data, this method does not work effectively when the number of observations is limited, e.g. six or seven observations. However, there is a need to produce BRDF products even if there are a limited number of observations.

Table 1. Number of available MODIS data for paddy fields at Yohkaichiba in Chiba, Japan from April of 2002 to March of 2003. The data were collected from TERRA/MODIS

Year	Month	Number of available observations
2002	Apr	8
	May	5
	Jun	6
	Jul	7
	Aug	8
	Sep	5
	Oct	10
	Nov	12
	Dev	10
2003	Jan	18
	Feb	8
	Mar	14

3. BRDF Estimation Using Limited Number of Observations

We conducted ground measurements at the site located at E 140 34' 05", N 35 44' 02" in 2002. The MODIS data used for the experiments were received from and produced at Tokyo University of Information Sciences (TUIS), Chiba, Japan. The ground station at TUIS has a 2.9-m-diameter receiving antenna, and received data have been produced to higher-level products operationally. NASA processing algorithms were used for the processing. The MODIS data received from and produced at TUIS have been produced to higher-level products operationally. The MOD09 data, atmospherically corrected reflectance MODIS products, were examined with respect to being clear-sky data for three periods. The periods were 16-day periods, including the days when ground measurements were conducted. Clear-sky data were selected not only by visually checking MOD09 images, but also by checking “1 km Reflectance Data State QA” data of MOD09. In the present study, clear-sky data are determined by checking whether cloud state data are “clear”. The MOD09 data shown in Table 2 were selected as “clear-sky” data and used for the experiments.

The kernel-driven model reported by Wanner et al.[9] and Lucht et al. [2] was adopted for the BRDF/albedo standard product, i.e. MOD43, of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the Terra satellite, launched in December of 1999[10]. This model adopts RossThick and LiSparse kernels as volume and geometric scattering kernels, respectively [8]. The parameters required in the model were set as h/b = 2.0 and b/r = 1.0, based on MOD43 products. Band 1 (620-670 nm) and band 2 (841-876 nm) reflectance data were used in the present experiments, and results of band 2 reflectances are reported in the present paper.

Initially, BRDF model parameters were estimated by the LSM using all eight observations in March, from May to June, and in August, respectively. Then, the nadir-reflectances were calculated based on the estimated BRDFs. Next, robustness of the estimation by LSM was examined by reducing the number of observation for these three periods. For these experiments, we assume that the results estimated using all eight observations are robust estimation results and that robustness related to the number of observations can be evaluated by the difference between the results estimated using eight observations and the results estimated using fewer observations. Seven observations were selected from among the eight observations, and in each selection, nadir-reflectance was estimated. In the selection, ${}_8C_7 = 8$ combinations were examined, and the mean and standard deviation of the nadir-reflectance were then calculated. In the same way, several cases were examined in which six, five, or four observations were selected from among the eight observations, which means that ${}_8C_6 = 28$, ${}_8C_5 = 56$, and ${}_8C_4 = 70$ cases were examined, respectively. In these cases, the mean and the standard deviation of the nadir-reflectance were calculated.

The reflectances adjusted at nadir and +60 and -60 degree view zenith angles were obtained based on the estimated BRDFs. As a result, the mean and standard deviation of reflectances at nadir μ_{nadir}, σ_{nadir}, at +60 degrees μ_{+60}, σ_{+60}, and at -60 degrees μ_{-60}, σ_{-60} were calculated. Using these results, a parameter set (μ_{+60}- σ_{+60}, μ_{nadir}-σ_{nadir}, μ_{-60}-σ_{-60}) was applied for BRDF estimation. In the same manner, a parameter set (μ_{+60}+ σ_{+60}, μ_{nadir}+σ_{nadir}, μ_{-60}+σ_{-60}) was applied for BRDF estimation. These estimated BRDFs are shown in Figs. 1 to 3. In the horizontal axis, positive values indicate backward viewing zenith angles. The estimated BRDFs from a parameter set (μ_{+60}, μ_{nadir}, μ_{-60}) are also shown in the same figures.

These figures give a visual representation of the magnitude on the fluctuation due to limited observations compared to the results obtained from normal BRDF estimation.

Table 2. Observed reflectances and geometrical parameters for three experimental sites. Reflectances were obtained from bands 1 and 2 of MOD09, atmospherically corrected reflectance products. Geometrical parameters obtained from MOD03, geolocation products, are expressed in degrees. All data have a 1-km resolution.

March, 2002

Observed date (yyyymmdd)	Reflectance (b2)	Sensor zenith	Sensor azimuth	Solar zenith	Solar azimuth
(1) 20020307	0.1949	38.95	96.93	47.20	145.55
(2) 20020308	0.1682	36.13	-77.54	42.78	159.40
(3) 20020309	0.2198	52.73	95.58	47.95	141.55
(4) 20020310	0.1533	16.07	-79.89	42.97	154.95
(5) 20020312	0.1788	8.18	103.82	43.34	150.53
(6) 20020313	0.1623	55.61	-74.23	39.69	165.78
(7) 20020314	0.2072	30.37	97.51	43.89	146.18
(8) 20020319	0.1766	4.33	-86.49	40.00	151.71

May to June, 2002

Observed date (yyyymmdd)	Reflectance (b2)	Sensor zenith	Sensor azimuth	Solar zenith	Solar azimuth
(1) 20020525	0.1757	50.60	-75.11	16.15	154.93
(2) 20020526	0.1310	38.57	97.86	23.50	122.98
(3) 20020528	0.2261	52.52	94.96	25.49	117.70
(4) 20020602	0.2310	29.54	98.65	21.88	123.08
(5) 20020604	0.2642	46.24	95.94	23.94	117.64
(6) 20020606	0.2347	57.74	94.70	26.12	113.06
(7) 20020607	0.1435	4.85	-81.42	18.62	130.17
(8) 20020609	0.1794	19.23	98.88	20.56	123.60

August, 2002

Observed date (yyyymmdd)	Reflectance (b2)	Sensor zenith	Sensor azimuth	Solar zenith	Solar azimuth
(1) 20020807	0.4287	46.44	96.28	29.28	124.54
(2) 20020808	0.3877	26.97	-77.52	23.21	143.56
(3) 20020809	0.4304	57.95	94.01	31.74	121.29
(4) 20020810	0.3899	4.49	-78.42	25.21	138.38
(5) 20020811	0.3270	60.34	-73.33	21.16	162.75
(6) 20020814	0.4153	38.85	96.95	29.64	129.96
(7) 20020820	0.3320	55.93	-73.94	24.15	162.04
(8) 20020821	0.4066	29.72	97.72	30.26	135.68

4. Discussions

We examined cases in which less than eight observations were available, and the results are shown in Figs. 1 to 3. The robustness in estimating BRDF parameters depends on the band, and to a greater extent on the period, March, May to June, and August, 2002. For example, in both March and August, the estimations were quite stable, even using four or five observations. However, the estimations in May to June are not robust and are meaningless. Around the site where ground measurements were conducted, paddies are growing from May to June. On the other hand, the water depth in paddy fields is approximately five to ten centimeters. The reflective characteristics change gradually even during the sixteen-day period from late May to June. In March, the paddy fields have no water or vegetation. In August, paddies have a vegetation layer of approximately one meter in height. The conditions during both March and August are more stable than the conditions during the period from May to June. This difference may affect the robustness of the estimation of BRDF parameters. In most of areas in Japan, there is a rainy season from late May to June. Therefore, clear-sky data are very limited during this period and then there is a need that BRDF can be estimated using a limited number of observations. However, the experimental results of the present study reveal that the BRDFs obtained using four or five observations are not useful.

Therefore, robustness of the estimation of BRDF parameters is subject to land cover and its conditions. For the case of four or five observations for the estimation of three BRDF parameters, the LSM can be implemented. During the rainy season in Japan, the condition of paddy fields change significantly and the number of clear-sky data are very limited. One possible method by which to estimate the BRDF during the rainy season may be to utilize both Terra/MODIS data and Aqua/MODIS data. Aqua/MODIS data were not available for the three measurement dates in the experiments of the present study because Aqua was launched in May, 2002. Another reasonable solution may be to accumulate more than seven clear-sky data through several years under the assumption that the conditions of the land cover have changed little. The first solution is quite significant because the possibility of obtaining clear-sky data for a certain period, i.e. a sixteen-day period, is increased. Although the latter solution cannot guarantee reliability of the estimated results, the results can be useful.

Finally, the effect of angular sampling on the robustness of BRDF estimation was examined. In the experiments using four or five observations for three periods, the LSM was applied for the estimation, and the mean and standard deviation of the reflectance at nadir, μ_{nadir}- and σ_{nadir} , were calculated. Then, the reflectances outside the range $[\mu_{nadir}-\sigma_{nadir}, \mu_{nadir}+\sigma_{nadir}]$ were considered as the non-robust estimation results, and the tendency for the angular sampling in non-robust estimation was examined. No tendency for angular sampling could be found. Even when applying the same angular sampling, it sometimes happened that while robust estimation was performed for one band (e.g., band 1), non-robust results were obtained for the other band (e.g., band 2). These experimental results indicate that non-robustness is not caused by angular sampling.

5. Conclusions

A limited number of observations is one of the most severe problems for the estimation of the BRDF. In particular, in Asian countries that have a rainy season, the solution to the non-robustness due to scarcity of the number of observations is desirable. In the present paper, experimental results are reported that examine the robustness with respect to the scarcity of the number of observations. In the present research, the LSM was examined in terms of robustness with respect to the scarcity of the number of observations. In the experiments, BRDFs were estimated by the LSM using MODIS reflectance data on paddy fields in Japan in March, June and August, 2002 were used. The estimation was conducted by reducing the number of observations, and the mean and standard deviation of the reflectance at nadir were examined. The results revealed that the degree of the robustness depends on the condition of the land cover, even if the land cover is classified as the same category.

References

[1] Verstraete, M. M., Pinty, B., and Myneni, R. B. (1996). Potential and limitations of information extraction on the terrestrial biosphere from satellite remote sensing. *Remote Sensing of Environment*, vol.58, pp.201-214.

[2] Lucht, W., Schaaf C. B., and Strahler, A. H., 2000. An algorithm for the retrieval of albedo from space using semiempirical BRDF models, *IEEE Transactions on Geoscience and Remote Sensing*, vol.38, pp.977-998

[3] Kimes, D.S., Newcombe, W.W., Tucker, C.J., Zonnefeld, I.W., van Vijingaarden, W., de Leeuw, J., and Epema, G. F., 1985. Directional reflectance factor distributions for cover types of Northern Africa, *Remote Sensing of Environment*, vol.18, pp.1-19

[4] d'Entremont, R. E., Schaaf, C. L., Lucht, W., and Strahler, A. H., 1999. Retrieval of red spectral albedo and bidirectional reflectance using AVHRR HRPT and GOES satellite observations of the New England region, *Journal of Geophysical Researches*, vol.104, pp.6,229-6,240

[5] Gao, F., Schaaf, C.B., Strahler, A.H. and Lucht, W., 2001. Using a multikernel least-variance approach to retrieve and evaluate albedo from limited bidirectional measurements, *Remote Sensing of Environment*, vol.76, pp.57-66

[6] Li, X., Gao, F. and Strahler, A. H., 2001. A priori knowledge accumulation and its application to linear BRDF model inversion, *Journal of Geophysical Researches*, vol.106, pp.11,925-11,935

[7] Susaki, J., Hara, K., Kajiwara, K., and Honda, Y., 2004. Robust Estimation of BRDF Model Parameters, *Remote Sensing of Environment*, vol.89, pp.63-71

[8] Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., Strungnell, N. C., Zhang, X., Jin, Y., Muller, J. P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d`Entremont, R.P., Hu, B., Liang, S., Privette, J.L. and Roy, D., 2003. First operational BRDF, albedo nadir reflectance products from MODIS, *Remote Sensing of Environment*, vol.83, pp.135-148

[9] Wanner, W., and Strahler, A. H., 1995. On the derivation of kernels for kernel-driven models of bidirectional reflectance, *Journal of Geophysical Researches*, vol.100, pp.21,077-21,089

[10] Strahler, A.H., Muller, J.P. and MODIS Science Team Members, 1999. MODIS BRDF/Albedo product: Algorithm theoretical basis document, NASA EOS MODIS Doc., version 5.0, (available at http://modis.gsfc.nasa.gov/data/atbd/atbd_ mod09.pdf)

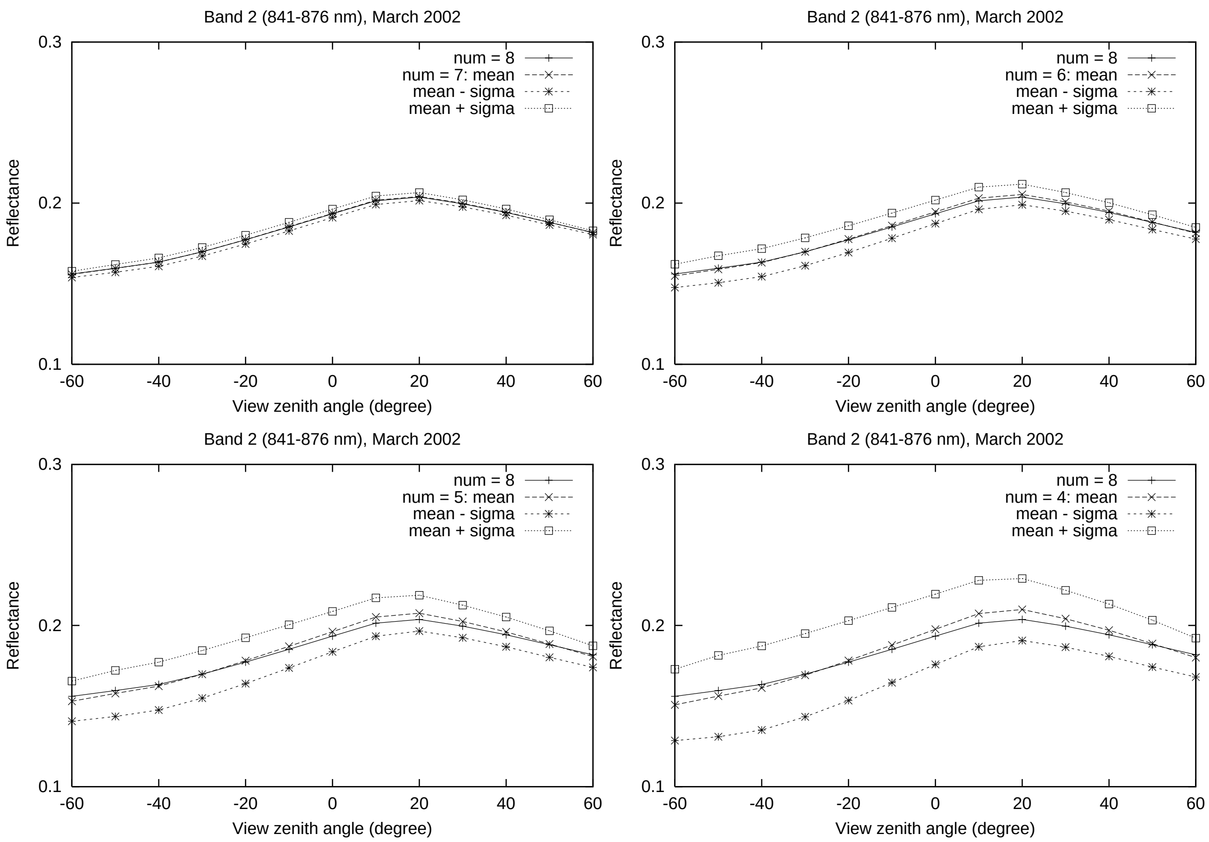

Figure 1: BRDFs in the principal plane estimated using MODIS band 2 (841-876 nm) reflectances in March, 2002. The BRDFs were estimated by applying different number of observations.

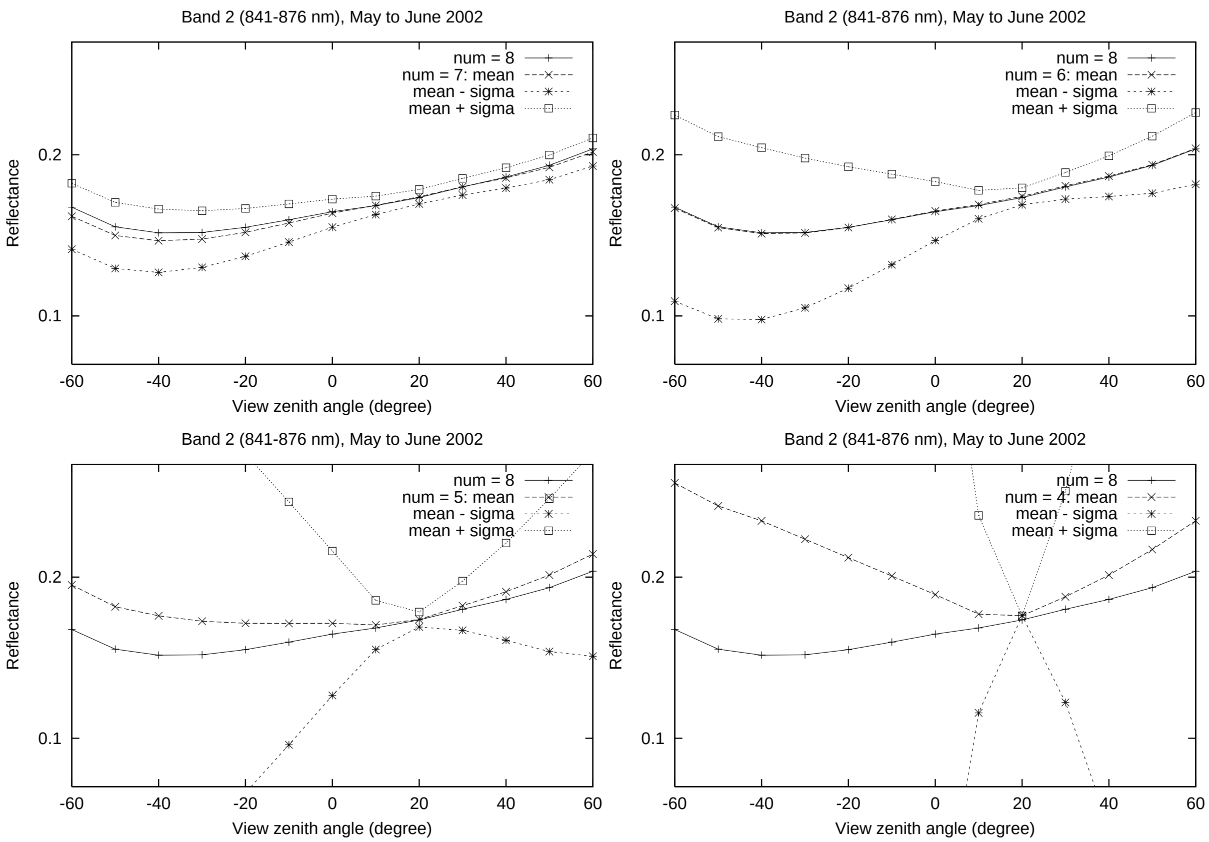

Figure 2: BRDFs in the principal plane estimated using MODIS band 2 reflectances in May to June, 2002. The BRDFs were estimated by applying different number of observations.

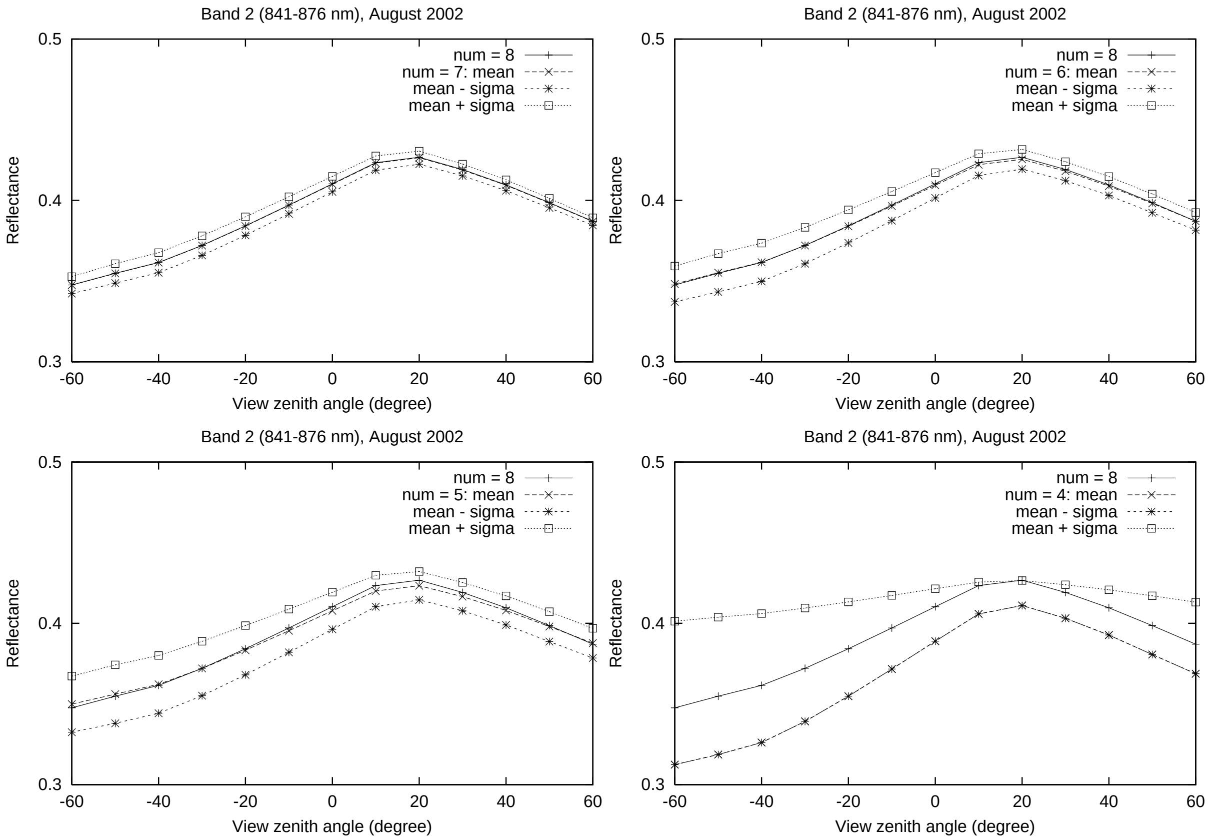

Figure 3: BRDFs in the principal plane estimated using MODIS band 2 reflectances in August 2002. The BRDFs were estimated by applying different number of observations.