Concept of a new multiangular satellite mission for improved bi-directional sampling of surface and atmosphere properties

A. P. Trishchenko[*a]
[a]Canada Centre for Remote Sensing, Natural Resources Canada, 588 Booth St., Ottawa, Ont., Canada, K1A 0Y7

ABSTRACT

While existing satellite Earth Observing (EO) systems provide many baseline observations, they are lacking an important combination of capabilities in terms of angular sampling, spectral coverage, and spatial resolution. This has an impact on the accuracy of retrievals and the capability to provide accurate regular operational monitoring of surface and atmospheric properties on a large scale (global or continental).
The concept of Advanced Multiangular MEdium Resolution System (AMMERS), that addresses the above issues and provides unique capability presently unavailable from other space observing systems, is proposed here. The mission's unique feature is a combination of medium resolution (400m), multi-spectral observations (13 spectral bands in visible, NIR, SWIR, IR, SW and LW), and multi-angular capabilities (7 angles). AMMERS's multiangular features and swath width allow bi-directional angular sampling close to the solar principal plane and in the perpendicular plane. These capabilities are critically important for accurate estimation of surface albedo, vegetation structure, and forest parameters. AMMERS will also be superior to many other missions in retrieving SST, aerosol, clouds parameters, snow, and wild fire mapping.

Keywords: AMMERS, satellite, multiangular observations, albedo, BRDF retrievals, global monitoring

1. INTRODUCTION

The atmospheric radiation in the Earth's environment is essentially anisotropic. Aerosols, clouds, and air molecules, that all have an anisotropic scattering phase function, affect the radiation field in the atmosphere, leading to different intensities, depending on the direction of propagation[1, 2]. Another source of anisotropy in the radiation field comes from the anisotropic properties of the surface elements that reflect and absorb solar radiation and emit thermal radiation depending on the relative direction of incoming and outgoing photons. This property of the surface is characterized by the bi-directional reflectance (emission) distribution function (BRDF)[3]. Therefore, the measuring of the radiation field along a single line of sight (satellite detector viewing direction) provides incomplete information about the entire radiation field and the properties of the atmosphere, such as aerosols and clouds.

Except for a few cases, as discussed below, so far the single view observing paradigm has prevailed in the development and exploitation of remote sensing observing systems. The EO scientific research and application community has matured to the point where the multiangular approach needs to be employed on a broader scale, leading eventually to the transition to a systematic operational multiangular strategy. There are a significant number of success stories, like the POLDER, MISR and ATSR missions, which prove the fruitfulness of this approach. However, the existing plans for major future satellite systems, like NPOESS, still employ the advantages of multiangular observations very little, if at all.

Generally speaking, one can identify three major dimensions in the "observational space" of remote sensing applications: ***spectral***, ***spatial*** and ***angular*** (we did not consider the polarization information at this time). From the spectral point of view, the information in several spectral intervals within the atmospheric transparency windows would satisfy the vast majority of an optical and thermal remote sensing application. The spatial requirements must be a compromise between the scale of monitoring the area, the repeat time of observations, and the size of the features to be resolved. The third dimension is the angular one, which so far seems to be somewhat underutilized, but it delivers, in

[*] trichtch@ccrs.nrcan.gc.ca; phone 1-613-995 57 87; fax 1-613- 947 13 85

many aspects, critically important information about surface and atmospheric properties that cannot be obtained from the information contents pertinent to the first 2 dimensions.

2. MULTIANGULAR OBSERVATIONS DELIVER CRITICAL INFORMATION ABOUT SURFACE AND ATMOSPHERE

Most natural surfaces and satellite-observed scenes exhibit anisotropic reflective and emissive properties in the solar spectral domain and thermal region, as revealed by many in-situ[4-6] and remote sensing observations[7-9]. Knowledge of these properties is essential for adequate characterization of the physical processes and parameters of the Earth's system. For example, in climate studies[10], it is important to correct for the angular effects in long-term satellite data series. These effects appear as systematic trends, artifacts, or noise in the data series due to compositing satellite observations collected under variable observational conditions: solar zenith angle (SZA), viewing zenith angle (VZA) and relative azimuth angle (RAA). Drift in the satellite orbit may lead to systematic changes in the observational conditions and has to be accounted for properly[11]. Surface BRDF properties, apart from being used for the correction and normalization of satellite data series as described above, are also used to determine the vegetation 3D geometrical structure, properties of the vegetation elements, and understorey[12]. Important features of the surface BRDF are the width and amplitude of hot and dark spots. A hot spot is usually quite narrow and can be reliably observed only from the observations close to the principal plane. Accurate information about hot spots is crucial for determining an accurate BRDF shape, which is employed to produce albedo, leaf area index, fraction of photosynthetically active radiation (fPAR), clumping index, crown closure, and some other parameters.

The concept of angular distribution models (ADM) analogous to the BRDF is a central issue in the Earth radiation budget research[13-14]. The ADMs are employed in a radiance-to-flux conversion procedure, i.e., for converting unidirectional observations into the hemispherically-integrated energy flux. The ADM concept employed in the radiation budget research is an attempt to develop statistical models for the angular distribution of radiation for various states of atmosphere over a set of surface classes (ocean, land, snow, desert etc). The state of the atmosphere is described by type, amount of cloudiness and, possibly, some other parameters, such as aerosol and water vapor, for example[14]. One can think about ADM as the Top-Of-the-Atmosphere (TOA) BRDF for the surface-atmosphere-cloud system. Having BRDF models for separate components (surface, cloudiness), one can link them into ADM by means of radiative transfer modeling, provided that other properties of the atmosphere such as aerosol, vertical profiles, and gases, are known.

The most suitable approach to determine the BRDF for a particular location would be to acquire observational reflectance data for this spot under various VZA, RAA and sun conditions. This is feasible to a certain extent for ground observations, although in most cases, observations under variable observing geometries are made for different pixels from a fixed platform, located over a uniform area. The shadowing effects may cause some contamination of the measurements in the hot spot area if the detector is placed too close to the observed spot. For the vast majority of cases in remote sensing, however, the BRDF information is collected from single-view cross-track scanners. Angular coverage is achieved by accumulating data from different orbits over a period of time [9,15]. Although this approach was proven to be useful, it has some limitations, such as separating the temporal phenological changes of the surface elements and the BRDF signatures, extra noise due to uncertainties in the atmospheric correction for pixels observed at different times, and a narrow range of angular variables. Although extremely useful for extending the overall angular range, the rotating azimuth mode of operations, such as the one employed in the CERES experiment[16], for example, does not provide systematic, truly multiangular observations for the same spot.

It is also important that observations used for deriving the BRDF shape provide a good coverage of the entire angular domain for all three variables: SZA, VZA and RAA. If this condition is not satisfied, then retrievals made on the basis of limited sampling may provide biased results when extrapolated outside of the fitting domain. This may happen despite the fitting of the model parameters being quite perfect within an observed set of points. An example is shown in Fig. 1, where two widely used analytical models, the modified Rahman model, employed in the MISR project, and the Ross-Li model, employed in MODIS BRDF/Albedo processing, produce good fitting results for the angular area outside of the principle plane. They show quite substantial differences when the results are extrapolated in the principle plane, however. The difference can be as much as 40-50% (relative). Analysis of the SZA, VZA and RAA angle distribution shows that achieving good coverage of the range of parameters is very challenging task. Most sensors cannot satisfy this requirement even with multiangular observing capabilities. Thus, special attention has to be paid to provide an adequate sampling of an angular range.

One key application of the multiangular EO information is aerosol retrieval from space. This area has attracted significant interest in recent years[17-18]. The physical basis for aerosol retrievals can be explained using the single scattering approximation for aerosol contribution to the TOA scattered radiation over a dark surface:

$$L_{aer} = \omega_0^{aer} \tau_{aer} \gamma_{aer}(\xi) / 4\mu_0 \mu \qquad (1)$$

where L_{aer} is the single scattering contribution to the TOA radiance field due to aerosol, ω_0^{aer} is the aerosol albedo of single scattering, τ_{aer} is the aerosol total optical depth, $\gamma_{aer}(\xi)$ is the aerosol scattering phase function that depends on the scattering angle ξ, and μ_0, μ are the cosines of the SZA and VZA. Aerosol signal in the TOA reflectance, L_{aer}, is proportional to the aerosol optical depth. However, other factors, such as the aerosol phase function and single scattering albedo, are also important. The retrievals over non-black surfaces require the knowledge of surface reflectance. Therefore, to retrieve three aerosol parameters from a single-view geometry observation, one needs to make an assumption about the type of aerosol model and surface reflectance. This introduces uncertainties in the retrieval results, which are significantly reduced when simultaneous multiangular information is available. In this latter case, there are n (number of angles) pieces of independent information that can be used to better constrain the input parameters.

Multiangular observations provide a superior quality of atmospheric correction, which is important for Sea Surface Temperature (SST) retrievals. Stereoscopic capabilities from multiple views deliver important information about cloud vertical distribution and the anisotropy of the radiance field at the TOA.

3. EXISTING GAPS IN EO MULTIANGULAR OBSERVATIONS

There are a number of sensors that provide direct multiangular observations, such as POLDER[19], MISR[20], ATSR[21], or were planned for development, such as the SPECTRA[22] mission. These instruments have the capability to observe a particular pixel from different viewing directions almost instantaneously, as the satellite moves along the orbit. However, ***none of these missions has the optimal combination of parameters*** to satisfy simultaneously the following four basic requirements:

i) Large swath to provide the capability for large-scale regional and global operational monitoring on a daily basis;
ii) Small enough pixel size to resolve the essential spatial features of the terrestrial ecosystems;
iii) Spectral coverage in the entire solar spectrum range to satisfy most land and ocean applications;
iv) Multiangular observations that cover the entire angular domain of VZA and RAA.

Table 1 summarizes briefly the parameters of the above four missions and ASTER, which has some stereoscopic capabilities. Table 1 also includes the basic parameters for the newly proposed mission, AMMERS. Table 1 shows that indeed, so far there is no mission that satisfies requirements i)-iv). The POLDER instrument satisfies two out of the four requirements: operational capabilities for regular monitoring due to large swath and good angular sampling. However, POLDER has a very coarse spatial resolution (6x7km^2). POLDER does not provide observations in SWIR and thermal regions, although these spectral intervals deliver very rich information content and are important for many applications. The MISR instrument demonstrates excellent potential as a source of medium resolution information. It also acquires observations at large oblique viewing zenith angles. However, MISR provides limited capabilities for operational applications due to its narrow swath width. The narrow swath width also limits observational capabilities in the vicinity of the principal plane, since MISR is launched on sun-synchronous morning orbit. The distribution of VZA and RAA angles for MISR and several other missions is presented in Fig.2. Another MISR limitation is the absence of SWIR and thermal bands, similar to POLDER. ASTER and the proposed SPECTRA mission are designed for high-spatial resolution observations; as such, they are not suitable to address issues of global operational daily monitoring. AATSR is an interesting concept that was successfully utilized for global Sea Surface Temperature (SST) retrievals and some other applications. AATSR acquires multiangular observations using a conical scanner, which observes nadir and forward directions during one scan. It is therefore possible to obtain directional data for each pixel from two viewing directions. Although very useful in SST applications, the application of AATSR data is somewhat limited for land and atmosphere research, however.

Table 1. Basic parameters of various multiangular satellite missions

Parameter	**POLDER**	**MISR**	**AATSR**	**ASTER***	**SPECTRA**	**AMMERS**
# Spectral bands, range	9 443-910 nm	4 443-865 nm	7 0.550-12 μm	14 VNIR, SWIR, TIR	60 chs (10nm) in VIS, NIR, SWIR and 2 chs in TIR	13 0.44-12 μm; SW, LW
Pixel size	6x7km^2	275m/ 1.1km	1-2 km	15-90m	50m	400m
# Angles	14	9	2	2	7	7
Swath/Max angle Crosstrack	2400 km/ 51^0	360km	512km/23.5^0	60x60km^2 scenes	50x50km^2 scenes	1600km/ 42^0
Max angle Along track	43^0	70.5^O	47^O	27.6^O	up to 70^O	48^0
Principal plane	YES	NO	NO	NO	YES	YES
Encoding, bits	12	12	12	8-12	-	12
Global coverage, days	1	8	3-4	NO, Selected scenes	NO, selected scenes	1-2
Data rate, Mbit/sec	0.86	9 (peak) 3.3 (average)	0.63	69 (day) 4.2 (night)	8.5 GBit/orbit	Upper limit 33 (day) 12 (night) 23 (average)

* - limited stereoscopic capabilities

4. NEW MISSION SPECIFICATIONS

4.1 Spectral characteristics.

The location and width of potential spectral channels for the AMMERS instrument are listed in Table 2. Spectral bands are also graphically shown in Fig.3, where examples of atmospheric transmittance and the spectrum of green vegetation are plotted for reference purpose. Channels are selected in the atmospheric transparency windows to maximize their potential for surface observations, aerosol and cloud retrievals. There are three exceptions. Channel 5 (IR2, 936μm) is located within a strong water vapor absorption band. It will be utilized for retrieving water vapor columnar amounts using the difference in atmospheric absorption between channels 4 and 5. Channels 12 (broadband SW) and 13 (broadband LW) are designed for Earth radiation budget observations. The proposed set of spectral channels covers a vast majority of land and ocean remote sensing applications and enables an accurate atmospheric correction.

Table 2. Location and width of spectral channels for AMMERS instrument

Channel	Location	Width [nm]
1 Blue	455 nm	30 nm
2 Green	555 nm	30 nm
3 Red	660 nm	30 nm
4 IR1	870 nm	30 nm
5 IR2*	936 nm	10 nm
6 IR3	1.040 μm	40 nm
7 SWIR1	1.245 μm	30 nm
8 SWIR2	1.650 μm	60 nm
9 SWIR3	3.75 μm	100 nm
10 TIR1	11 μm	100 μm
11 TIR2	12 μm	100 μm
12 SW	0.2-4.5 μm	4.3 μm

13 LW	4.5 –100 μm	95 μm

* - water vapor absorption band channel for retrieval atmospheric water vapor

4.2 Spatial resolution

AMMERS's spatial resolution of 400m is a compromise between large scale monitoring capabilities, the volume of information and spatial resolving power. To be useful for operational crop monitoring, pixel size must be of the order of magnitude of typical agricultural spatial scale or smaller. Figures 4 and 5 provide some information to support the choice of spatial resolution of 400m for AMMERS's instrument. Figures 4a)-4d) show an area of 15x15km^2 with a spatial resolution of 30m, 300m, 500m and 1000m. This is a typical agricultural scene in the Southern Great Planes (SGP) area (northern Oklahoma). Figures 4 e), 4f) show larger area (~150x150km^2) in the SGP region. The typical spatial scale in the farming area is in the order of several hundred meters. For the scene shown in Fig.4, this size is in the range of 0.8-1.6 km (1/2-1 mile). The results of a spatial Fourier analysis, presented in Fig.5 for large SGP area, confirm the above conclusion. The power spectrum in Fig.5 demonstrates several maxima and peaks. For the spatial sizes below 2 km, the maximum corresponds to spatial scales <100m, which describes small scale spatial heterogeneity. Maxima at the 200-300m and 400-700m scales describe the typical size of various landcover types. Peaks at larger scales correspond to regularities and the structure of the farm field and regional variability at mesoscales. Both Figures 4 and 5 confirm that a pixel size of the order of 400m provides useful information and enables monitoring of relatively homogeneous landcover types.

A spatial scale ~400m will be also useful for the monitoring of forest cover, mixed scenes, inland water bodies, forest fires, snow cover and many other applications. This pixel size also provides good opportunity for cloud and aerosol retrievals. For observations of the ocean surface color and temperature, the spatial resolution can be degraded to 2x2 pixels (800x800m), which still provides very good spatial resolution for ocean surface retrievals, aerosol, and cloud studies. A degraded spatial resolution reduces the volume of data to be stored on board over the ocean by a factor of four. The overall data volume reduction will be approximately (2/3*1/4 +1/3)=0.5, i.e. by factor of two.

4.3 Angular sampling and orbit

AMMERS will provide observations at seven viewing angles along the satellite track: one at nadir, three forward and three backward directions with 16° steps. The maximum forward-backward viewing zenith angle is 48°. The number of pixels across the track is 4000, which corresponds to the swath width of 1600km and maximum scan angle 42°. With this swath, AMMERS launched at the polar orbit can provide complete global daily coverage (at least one observation – day or night), and, therefore, at least 2 observations per day at the latitude 60°. Sampling in the VZA-RAA plane is similar to POLDER. Observations in the principal plane and perpendicular plane can be obtained from the views in forward-backward directions. Fig.6 shows an example of such a distribution for a sun-synchronous orbit at 11am with altitude 840km for four latitude zones. The single cross track observation approach enables observational geometry for a relatively narrow sector. However, seven such sectors, observed from each multiangular direction, cover the entire VZA-RAA plane quite satisfactory. The distribution of the solar zenith angle from a polar orbiting platform is a narrow-range function of latitude. The SZA at each location varies within a small range and slowly in time. Therefore, to cover larger SZA interval, one needs to have more than one AMMERS instrument on the orbit or else use a precessing orbit, although the precessing orbit still cannot provide significant variation in the SZA range for a short period of time (less than one week).

4.4 Data storage/transmission requirement

One of the critical parameters for the proposed AMMERS mission is a data storage and data transmission requirement. Continuous data collection at fine (400m) resolution over land and coarse (800m) resolution over the ocean areas will generate a data stream at a rate of 33 Mbits s^{-1} (daytime) and 12 Mbits s^{-1} (nighttime). On average, this corresponds to 23 Mbits s^{-1}. To store 1 orbit of data will require 17.5Gbytes, so one day of data will require 240Gbytes. These numbers do not include redundancy coding for error correction and engineering telemetry. Once implemented, this may increase data volume by approximately 10%.

Although quite substantial, data volume numbers are comparable to MERIS/ENVISAT, which has data rate around 25 Mbits s^{-1}. The Advanced Synthetic Aperture Radar (ASAR) and ASTER have even larger numbers: 100 Mbits s^{-1} and 69 Mbits s^{-1}, correspondingly.

4.5 Potential applications and capabilities

The range of potential applications of the proposed AMMERS mission is very wide. It can be used for all essential applications planned for the MODIS, MISR, CERES, and VIIRS instruments with better potential accuracy due to advanced multiangular, spectral, and observing geometry capabilities. Among potential applications, one can mention

1) Daily operational multiangular monitoring of land, ocean and atmosphere on global scale;
2) Monitoring of the state and 3D structure of crop, forest and other vegetation types; vegetation productivity
3) Earth radiation budget measurements;
4) Surface albedo/BRDF retrievals,
5) Cloud cover, microphysics and 3D structure retrievals by combining multispectral and multiangular data;
6) Forest fire monitoring;
7) Aerosol retrievals;
8) Snow cover mapping;
9) SST monitoring with improved spatial resolution and accuracy;
10) Improved landcover mapping, and emergency disturbance mapping.

Listed above are a few general applications where AMMERS can provide superior performance over existing and planned missions in terms of accuracy and temporal and spatial resolution. This list is incomplete and can be expanded.

5. ACKNOWLEDGEMENT

This work was partially supported by the Canadian Space Agency (CSA) through the Government Research Initiative Program (GRIP) and the US Department of Energy Atmospheric Radiation (ARM) Program grant No. DE-FG02-02ER63351 to the Canada Centre for Remote Sensing

REFERENCES

1. V.V. Sobolev. *Ligh scattering in planetary atmospheres.* Pergamon Press. 1975.
2. M.I.Mishchenko, L.D.Travis, A.A.Lacis. *Scattering, absorption, and emission of light by small particles*. Cambridge University Press. 2002.
3. F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I. Ginsberg, and T. Limperis. *Geometric considerations and nomenclature for reflectance*. U.S. Dept. of Commerce, NBS Monograph. 1977.
4. A. Kuusk A.. Determination of vegetation canopy parameters from optical measurements, *Rem. Sen. Env.*, 37, 207-218, 1991.
5. D.S. Kimes. Dynamics of directional reflectance factor distributions for vegetation. canopies », *App. Opt.*, 22, 1364-1373, 1983.
6. A.P.Trishchenko, Y.Luo, M.Cribb, Z.Li. Surface spectral albedo IOP at the ARM SGP site in August 2002: Results, analysis, and future plans. *Proceedings of the 13th ARM Science Team Meeting*. Broomfield. CO. March 31-April 3, 2003. 8pp. Document available from the ARM Program web site at http://www.arm.gov/publications/proceedings/conf13/extended_abs/trishchenko-ap.pdf. 2003.
7. P. Bicheron, and M. Leroy. Bidirectional reflectance distribution function signatures of major biomes observed from space, *Journal of Geophysical Research, 105, 21, 26,669-26,681,* 2000.
8. F-L.Chang, Z. Li and A. P. Trishchenko: The dependence of TOA reflectance anisotropy on cloud properties inferred from ScaRaB satellite data. *Journal of Applied Meteorology*. 39, 2480-2493. 2000.
9. Y.Luo, A.P. Trishchenko, R.Latifovic, Z.Li. Surface bidirectional reflectance and albedo properties derived by a landcover based approach from the MODIS observations. *Journal of Geophysical Research (submitted).* 2004.
10. J.Cihlar, R. Latifovic, J. Chen, A. P. Trishchenko, Y. Du, G. Fedosejevs, and B. Guindon. Systematic corrections of AVHRR image composites for temporal studies. *Remote Sensing of Environment*. 89, 217-23. 2004.
11. A.Ignatov, I.Laszlo, E.Harrod, K.Kidwell, and G.Goodrum. Equator Crossing Times for NOAA, ERS and EOS Sun-Synchronous Satellites. *Int.J.Rem.Sens.* in press. 2004

12. Leblanc S. G. , Bicheron P. , Chen J. M., Leroy M. , Cihlar J. Investigation of directional reflectance in boreal forests with an improved four-scale model and airborne POLDER data. *IEEE Transactions on Geoscience & Remote Sensing* , 37, 1396-1414. 1999.
13. B.R. Barkstrom, and G.L. Smith, The earth radiation budget experiment: Science and implementation. *Rev.* Geophys., 24, 379-390. 1986.
14. N.G. Loeb, N. Manalo-Smith, S. Kato, W.F. Miller, S. Gupta, P. Minnis, and B. Wielicki. Angular distribution models for Top-of-Atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System Instrument on the Tropical Rainfall Measuring Mission Satellite, Part I: Methodology. *J. Appl. Meteo*r., 42, 240-265. 2003.
15. C.B.Schaaf, F. Gao, A.H. Strahler, W. Lucht, X. Li, T. Tsang, N.C. Strugnell, X. Zhang, Y. Jin, J.-P. Muller, P. Lewis, M. Barnsley, P. Hobson, M. Disney, G. Roberts, M. Dunderdale, C. Doll, R. d'Entremont, B. Hu, S. Liang, and J.L. Privette (2002), First operational BRDF, albedo and nadir reflectance products from MODIS, *Remote Sens. Environ.*, *83*, 135-148.
16. B.A.Wielicki, B.R. Barkstrom, E.F. Harrison, R.B. Lee III, G.L, Smith, and J.E. Cooper. Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment. *Bull. Amer. Meteor. Soc.*, 77, 853-868. 1996.
17. King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima, Remote sensing of tropospheric aerosols from space: Past, present, and future. *Bulletin of the American Meteorological Society*, 80, 2229–2259. 1999.
18. R.A.Kahn, B.J. Gaitley, J.V. Martonchik, D.J. Diner, K.A. Crean, and B. Holben. MISR global aerosol optical depth validation based on two years of coincident AERONET observations, *J. Geophys. Res., in press.* 2004.
19. P.Y. Deschamps, F.M. Breon, M. Leroy, A. Podaire, A. Bricaud, J.C. Buriez, and G. Seze. The POLDER Mission: Instrument Characteristics and Scientific Objectives. IEEE Trans. Geosc. Rem. Sens. 32, 598-615. 1994
20. D.J.Diner, J.C., Beckert, T. H. Reilly, C. J. Bruegge, J. E. Conel, R. A. Kahn, J. V. Martonchik, T.P. Ackerman, R. Davies, S. A. W. Gerstl, H. R. Gordon, J.-P. Muller, R. B. Myneni, P. J. Sellers, B. Pinty, M. M. Verstraete. Multi-angle Imaging SpectroRadiometer (MISR) Instrument Description and Experiment Overview. IEEE Trans. on Geosci and Remote Sensing. 36,. 1072-1087. 1998.
21. T.Edwards, *et al.*, The along track scanning radiometer measurement of sea surface temperature from ERS-1, *J. Br. Interplanet. Soc.*, 43, 160-180, 1990.
22. U.del Bello, J.L.Bezy, J.Fuchs, M.Rast. System definition of the ESA Earth Explorer SPECTRA mission. In Proc. of SPIE Vol. 4881 *Sensors, Systems, and Next-Generation Satellites, VI. Edited by H.Fujisada, J.B.Lurie, M.Aten, K.Weber (SPIE, Bellington, WA, 2003)* pp.1-11.

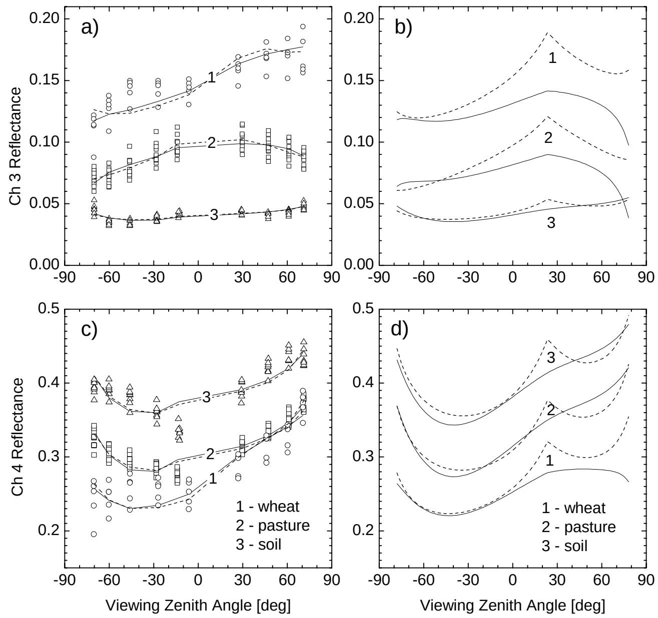
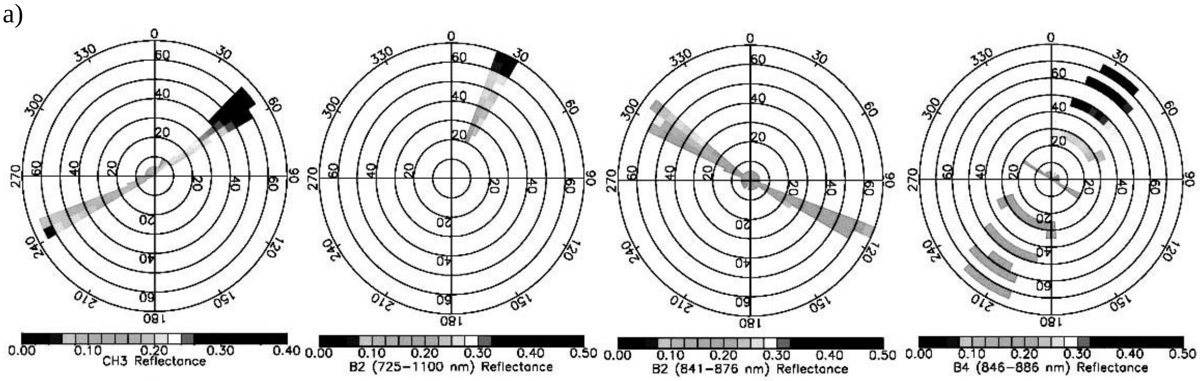


Figure 1. Differences in the fitted BRDF shape due to limited angular sampling. The left panels (a, c) show fitting results for Ross-Li and modified Rahman's models for points located off the principal plane. The right panels (b, d) show the BRDF model results extrapolated to the principal plane. A significant difference is observed between two models (up to 40-50% or even more) in the direction of principal plane.

VGT AVHRR MODIS MISR

a)



b)

POLDER

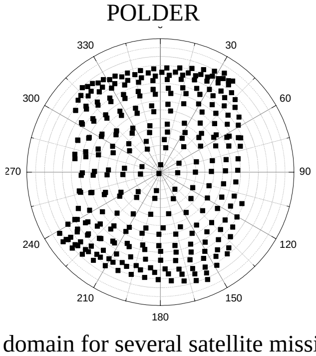


Figure 2. Angular sampling in the VZA-RAA domain for several satellite missions.

a) VGT, AVHRR, MODIS, MISR; b) POLDER.

RAA is shown as polar angle, VZA as radius. Data are presented for the ARM Program CART site area. Only POLDER provides reasonably complete angular sampling suitable for unbiased BRDF fitting.

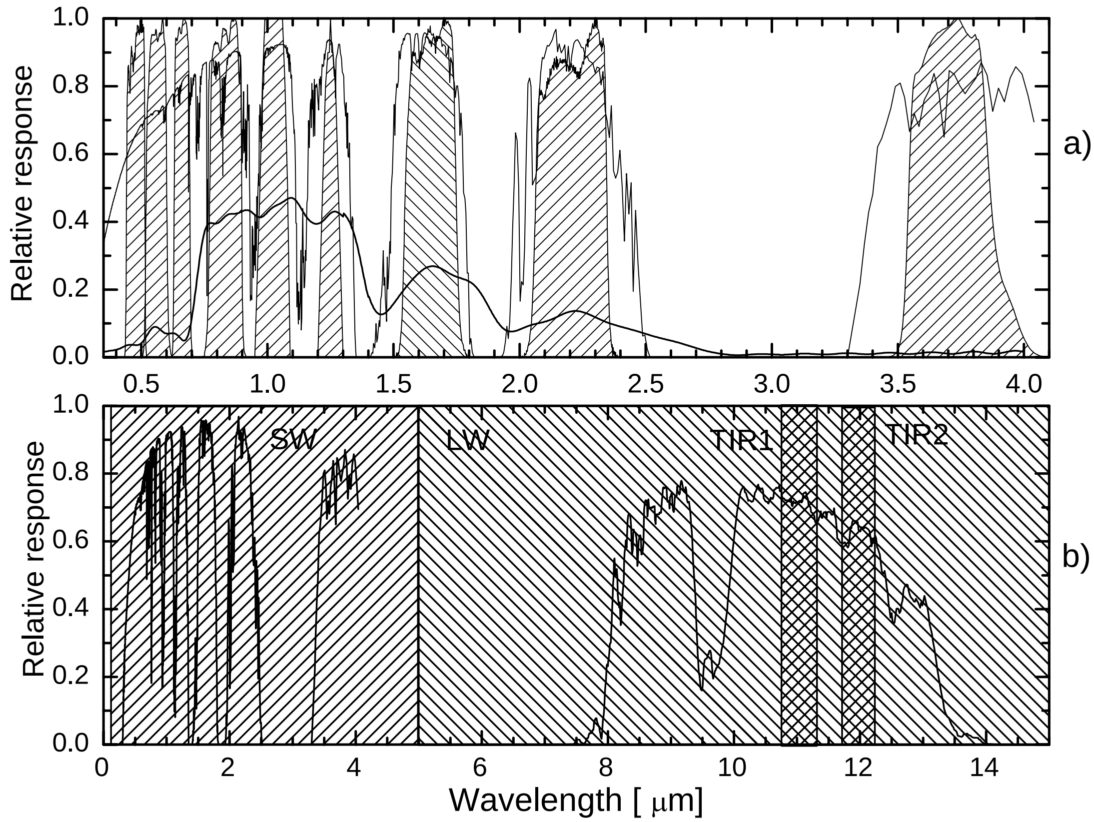


Figure 3. Location of spectral channels for proposed AMMERS multiangular observations.
a) Narrow band channels in solar domain.
b) Broadband channels in SW and LW domains and 2 narrowband channels in thermal IR region.
Typical total atmospheric transmittance and spectrum of green vegetation are plotted for reference.

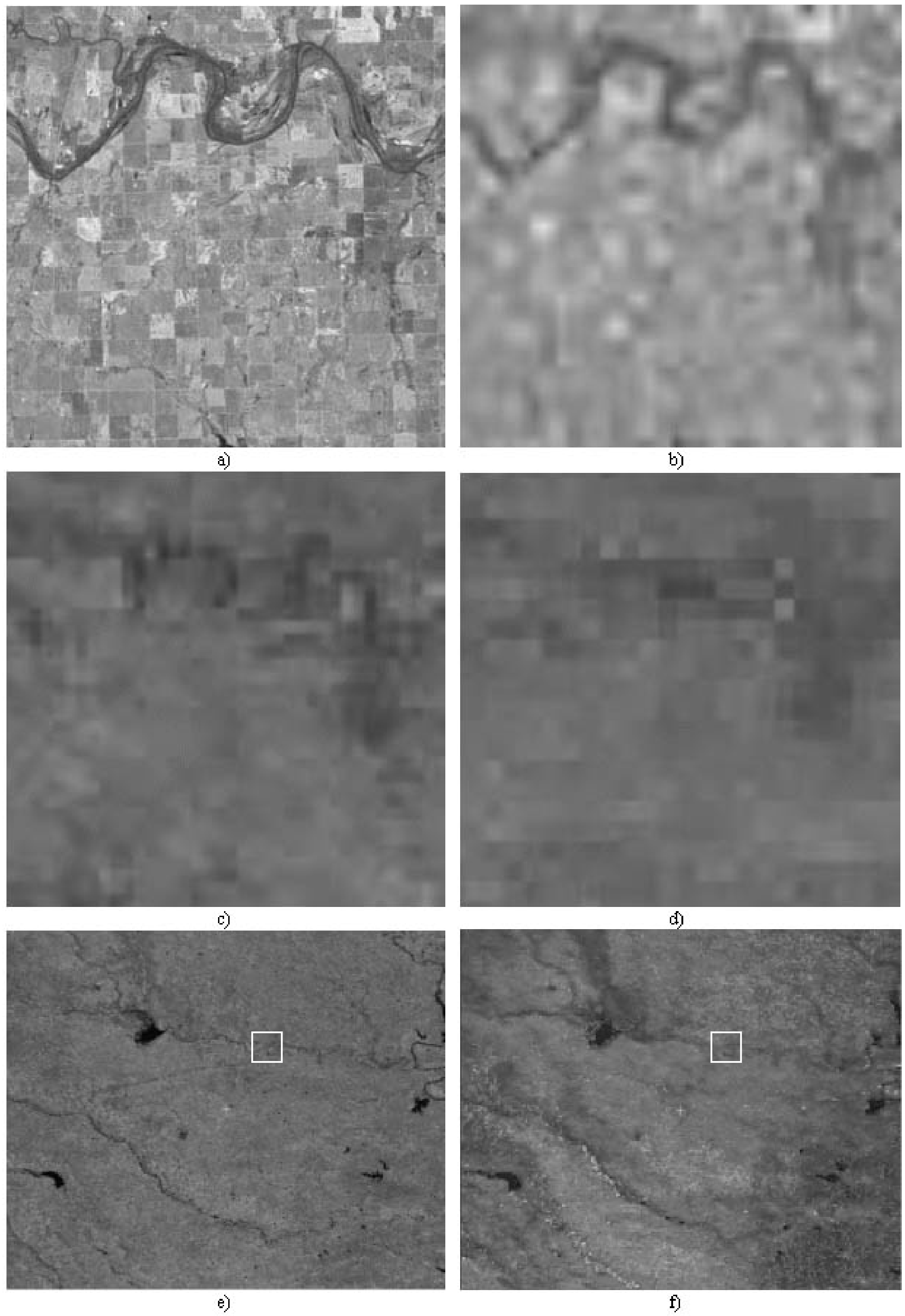


Figure 4. Southern Great Plains (SGP) area (Oklahoma and Kansas, USA)

a) Landsat image with pixel size 30m, area 15 x15 km^2;b) Landsat image aggregated to 300m resolution (10x10 pixels); c) same area observed at 500m spatial from MODIS; d) same area observed at 1000m spatial resolution from VGT/SPOT; e) larger SGP area 150x150km^2 observed at 500m resolution from MODIS; d) same as in e), observed at 1000m resolution from VGT/SPOT. The white square on panels e)-f) corresponds to the area shown in panels a)-d).

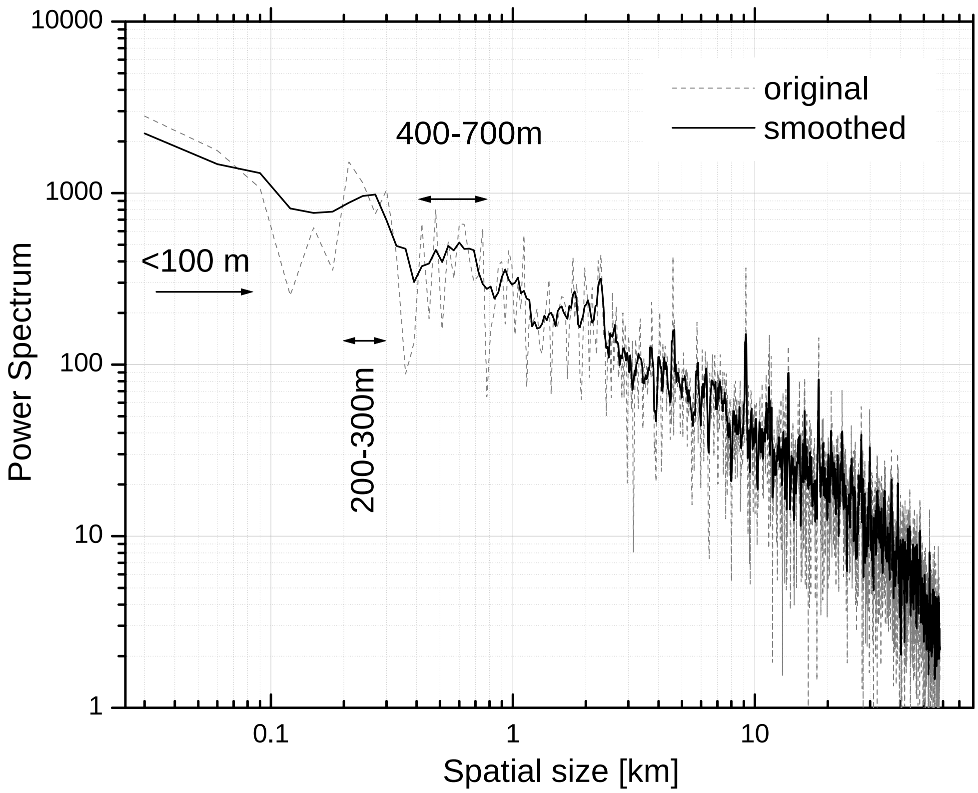


Figure 5. Power spectrum of the scenes shown in Figure 4e at 30m spatial resolution. Original (dash) and smoothed (4 point running average, solid) results are plotted.

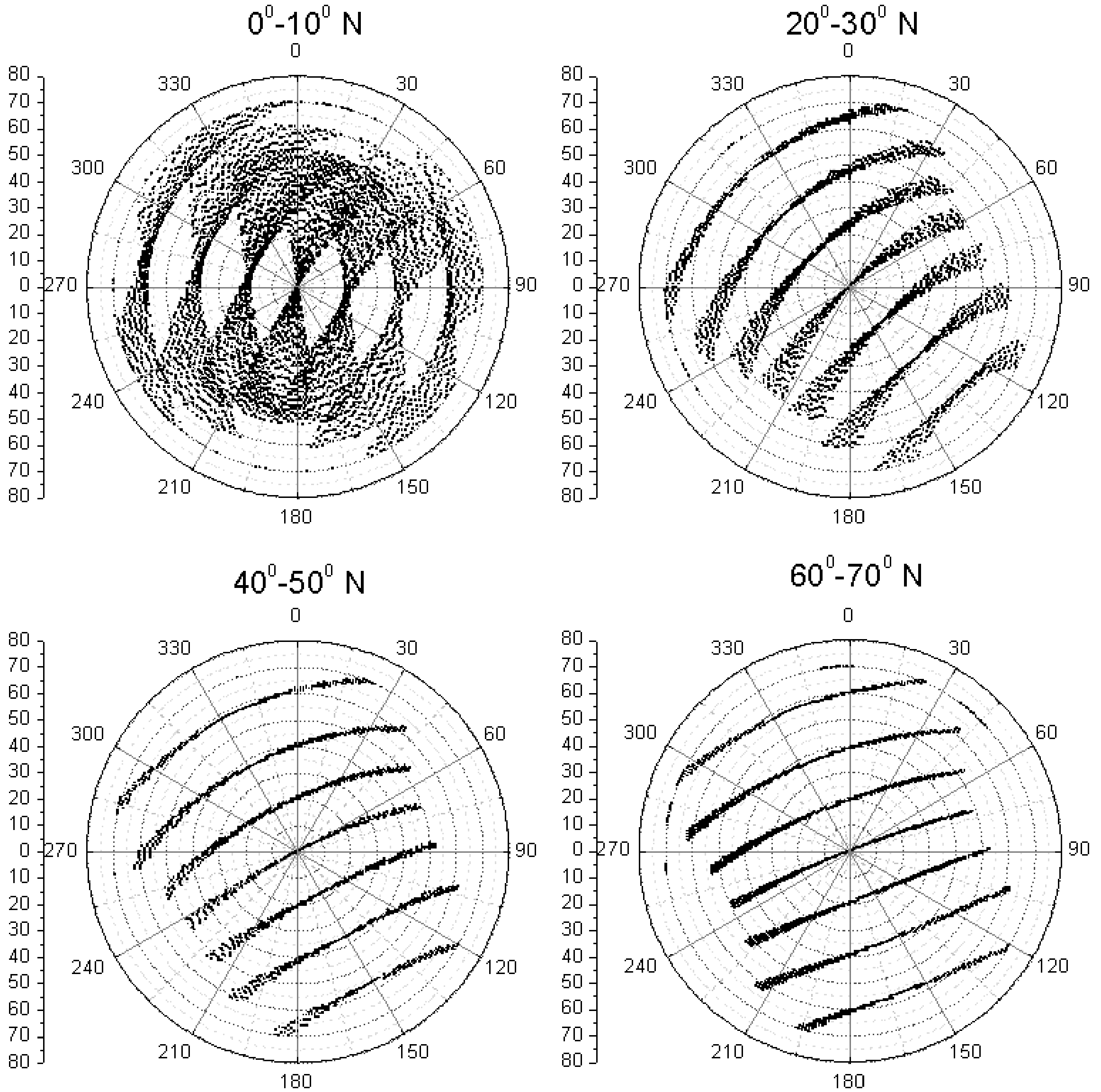


Figure 6. Distribution of observations from AMMERS within 10^0 latitude zone. Sun-synchronous orbit at 11 am with altitude 840km. VZA is shown as polar radius, RAA is shown as polar angle.
Latitude zones are 0°-10° N; 20°-30° N; 40°-50° N; 60°-70° N.