AEROSAT – a space-borne sensor for continental aerosols: evaluation of the conceptual model

S. K. Satheesh and K. Krishna Moorthy

Even though satellite observations are the most effective means to gather global information in a short span of time, the challenges in this field still remain over continental landmass, despite most of the aerosol sources being land-based. This is a hurdle in global and regional aerosol climate forcing assessment. Retrieval of aerosol properties over land is complicated due to irregular terrain characteristics and the high and largely uncertain surface reflection which acts as 'noise' to the much smaller amount of radiation scattered by aerosols, which is the 'signal'. In this paper, we describe a satellite sensor – the 'Aerosol Satellite (AEROSAT)', which is capable of retrieving aerosols over land with much more accuracy and reduced dependence on models. The sensor, utilizing a set of multi-spectral and multi-angle measurements of polarized components of radiation reflected from the Earth's surface, along with measurements of thermal infrared broadband radiance, results in a large reduction of the 'noise' component (compared to the 'signal'). A conceptual engineering model of AEROSAT has been designed, developed and used to measure the land-surface features in the visible spectral band. Analysing the received signals using a polarization radiative transfer approach, we demonstrate the superiority of this method. It is expected that satellites carrying sensors following the AEROSAT concept would be 'self-sufficient', to obtain all the relevant information required for aerosol retrieval from its own measurements.

On a global scale, satellite remote sensing is the only option to gather information on aerosols with high resolution within a short time span for using as input into climate models[1,2]. During the last decade, a large number of satellites have been realized with different types of sensors to obtain data on several aerosol parameters[3,4]. Data from polar orbiting instruments such as Advanced Very High Resolution Radiometer (AVHRR) and Total Ozone Monitoring Spectrometer (TOMS) have been widely used for decades to study aerosols over the oceans[5]. Recently, sensors like Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectro-Radiometer (MISR) and Polarization and Directionality of Earth's Reflectance (POLDER) are being used specifically to improve the aerosol retrievals[1,3,6,7]. However, the retrieval algorithms used in these sensors for continental regions involve uncertainties in the retrieved parameters due to the high reflectance effect. Because most of the aerosol sources are located over the land, satellite retrieval of aerosols over land assumes immense importance. However, the retrieval of aerosol properties over land is complicated due to irregular terrain characteristics and the high and largely uncertain surface reflection which act as 'noise' to the much smaller amount of radiation scattered by aerosols, which is the 'signal'. Despite the

increased proficiency and use of improved models in the aerosol retrieval algorithms, several studies have shown that satellite retrieval of aerosols over land remains sufficiently uncertain and is a hurdle in global and regional aerosol climate forcing assessment. Another aspect is the information on aerosol chemical composition, which is important for climate and radiation budget modellers[8]. Even though complete description of aerosol chemistry is not needed to estimate radiative forcing, at least information on single scattering albedo (ratio of scattering to extinction) is essential[9,10]. Some of the major issues which are needed by the climate science community at large are: (a) spatial and temporal heterogeneity in aerosol radiative forcing over land, (b) anthropogenic aerosol fraction and (c) absorbing versus non-absorbing aerosols. Keeping these objectives in mind, we describe a satellite sensor namely – the 'Aerosol Satellite (AEROSAT)', which is capable of retrieving aerosols over land with much more accuracy and reduced dependence on models. The sensor, utilizing a set of multi-spectral and multi-angle measurements of polarized components of radiation reflected from the Earth's surface, along with measurements of thermal infrared broadband radiance, results in a large reduction of the 'noise' component (compared to the 'signal'). A conceptual

engineering model of AEROSAT has been designed, developed and used to measure the land-surface features in the visible spectral band.

The AEROSAT instrument

The AEROSAT sensor is an improvement of the basic principle presented earlier[11], in which we have demonstrated using a radiative transfer model with polarization, the large advantage of polarized radiance measurements for the retrieval of aerosols over land. The proposed sensor has been conceptualized taking the advantages of different earlier sensors (such as MODIS, MISR and POLDER) and combining them in a way to reduce the ground reflectance-induced 'noise'. The main characteristics of AEROSAT are multi-spectral and multi-angle measurements of polarized components of reflected radiation from the Earth. It is known that accurate aerosol retrieval from the satellite is possible only if the background is dark. Over bright surfaces atmospheric signal is much weaker than the signal from the surface. Satheesh and Moorthy[11] have shown that the polarized light reflected by land surface is quite low and comparable or lower than that reflected by aerosols. This enables the detection of aerosols even over deserts. It may be

noted that the signal received by earlier satellites without polarization (and nadir-looking) was contributed significantly by reflection from the land surface. In the case of AEROSAT, the scattered component from the atmosphere dominates the signal reflected from land (see ref. 11, for detailed radiative transfer simulations).

The proposed spectral channels include nine narrow bands – 0.34, 0.38, 0.45, 0.55, 0.65, 0.75, 0.85, 0.935, 1.02 μm (both polarized and unpolarized) and 2.1 μm (unpolarized), 10.5–12.5 μm (unpolarized and broadband). A wide range of spectral coverage is essential to get wavelength dependence of aerosol opacity[11]. Four look-angles are suggested, 0° (nadir), 15°, 35° and 70°. A 1 km spatial resolution (or pixel size) is considered for a swath of 1000 km. This configuration also enables the estimation of aerosol size distribution. Large viewing angles (thereby looking through a larger amount of atmosphere) provide enhanced sensitivity to atmospheric effects. While visible and near-infrared channels are meant for optical depth retrievals over land, the UV channels enable retrieval of aerosol absorption. The 10.5–12.5 μm broadband window channel is meant for dust aerosol retrieval and for cloud retrieval.

Experiment and preliminary results

The instrument was operated from the roof of a 100 m tall building in Bangalore. Images (raw digital counts) of scenes consisting of various surface types such as buildings (with high reflectance) and vegetation (with low reflectance) have been acquired. Figure 1 shows examples of such images acquired without polarization. High reflectance from buildings and land is clearly visible in this image. Atmospheric retrievals are likely to be erroneous when surface reflectance is so high and varying. An image of the same region acquired with polarization is shown in Figure 2. Because of elimination of directly reflected light from buildings and land (due to the polarizer), the scene is observed more spatially homogeneous, analogous to that over ocean/large water bodies/dense dark vegetation, despite the fact that the radiance also is largely reduced. If we apply the spatial coherence method[12] (a method usually emplo-

yed for cloud removal from satellite images), the scene in Figure 1 appears like a cloudy scene, whereas the same scene in Figure 2 (with polarization) resembles a clear-sky scene. In this exercise, we have estimated the local mean and standard deviation of the surrounding 3×3 pixel window. Local mean versus local standard deviation (of the surrounding 3×3 pixel window) is shown in Figure 3 a in the case of the unpolarized image and in Figure 3 b in case of the polarized image. In the former case, the plot takes the shape of an arch diagram with areas of high coher-

ence showing low standard deviation and areas of low coherence showing high standard deviation. Arch-shaped plot indicates low spatial coherence between pixels. In contrast, Figure 3 b (corresponding to the polarized image) clearly indicates high coherence between pixels. If we apply spatial coherence technique and mask regions of low coherence, we can see that a large fraction of pixels (63% of total pixels) is masked in case of the unpolarized image (Figure 4), whereas only a small fraction (6% of total pixels) is masked in case of the polarized image (Figure 5). Using radiative
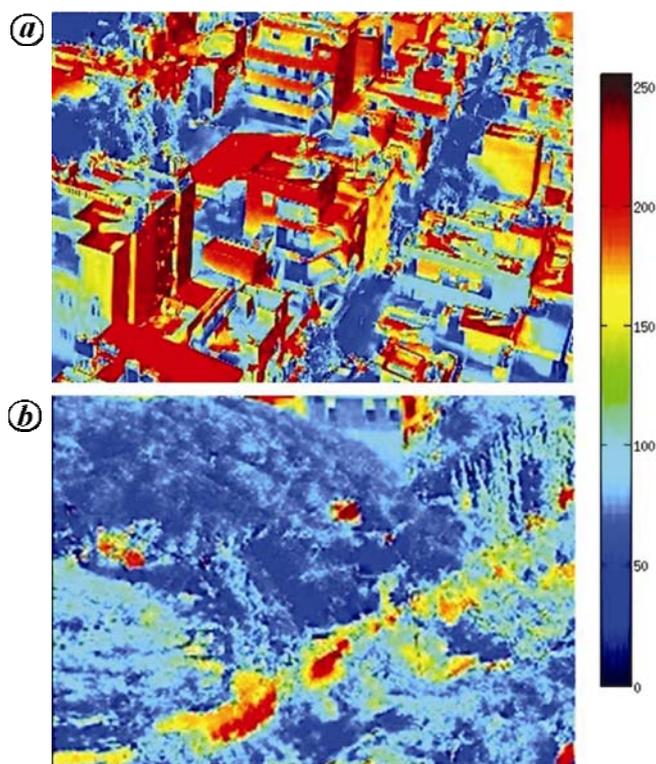

Figure 1. Raw counts from AEROSAT. Example of scenes consists of (**a**) buildings and (**b**) vegetated areas.

Figure 2. Raw counts from AEROSAT. Example of a scene consists of buildings, bare land and vegetated areas with polarization.

transfer simulations, the accuracy of aerosol optical depth (AOD) retrieval using AEROSAT has been estimated as 0.03 compared to 0.1 in the case of conventional satellites available at present.

The AEROSAT: a 'self-sufficient' sensor

Conventional satellite remote sensing algorithms require an aerosol model to retrieve aerosols. Though zeroth-order assumption of an aerosol model in satellite retrieval algorithms may not affect the final retrieval, various aerosol components chosen by different workers can cause discrepancies in the final retrievals. We propose that future satellites should be 'self-sufficient', which means that all relevant information required for aerosol retrieval should be derived from the same satellite data. The AEROSAT is conceived to be a self-sufficient sensor and its retrieval algorithm is independent of aerosol models, but depend only on AEROSAT data. In the following paragraphs we provide preliminary information about the retrieval algorithm.

Most of the aerosol absorption is contributed by aerosol black carbon (BC). A less dominant aerosol, which contributes to aerosol absorption is dust. Once we retrieve composite aerosol absorption and contribution from dust, we can estimate absorption due to BC. Presently, composite aerosol absorption is poorly quantified because aerosols vary widely depending on their composition and origin. Retrieval of aerosol absorption using satellite remote sensing is an important but difficult problem[13]. The relative importance of scattering and absorption in satellite remote sensing has been addressed[13,14] since the 1980s. However, only very few satellite sensors currently make operational retrievals of aerosol absorption, even though most of these retrievals are validated[15]. The Ozone Monitoring Instrument (OMI) provides a retrieval of aerosol absorption with its aerosol product[5,16,17]. Still retrieving aerosol absorption from satellite remote sensing remains a challenge, especially when using a single sensor. Hence, multi-sensor retrievals become increasingly relevant[4,15]. Recently, several workers have shown improvements in the assessment of aerosol absorption using multiple satellite data, a combination of OMI and MODIS[15]. Such approaches use MODIS-

retrieved AOD to constrain the OMI retrieval, freeing OMI from making a priori estimate of aerosol height and allowing a more direct retrieval of aerosol absorption. As AEROSAT channels cover the range from UV to near-IR, while exploiting the advantages of such multi-sensor approaches to estimate

Figure 3. Spatial coherence in images. Local mean versus local standard deviation for images obtained (**a**) without polarization and (**b**) with polarization.

Figure 4. *a*, Original image obtained without polarization. *b*, The same image after applying spatial coherence technique to mask regions of low coherence.

composite aerosol absorption, one needs to avoid disadvantages such as collocating data, different time of overpass, etc.

The second largest contributor to composite aerosol absorption is dust aerosols. Remote sensing of dust over land in visible wavelengths is difficult because dust is nonspherical and Mie scattering theory
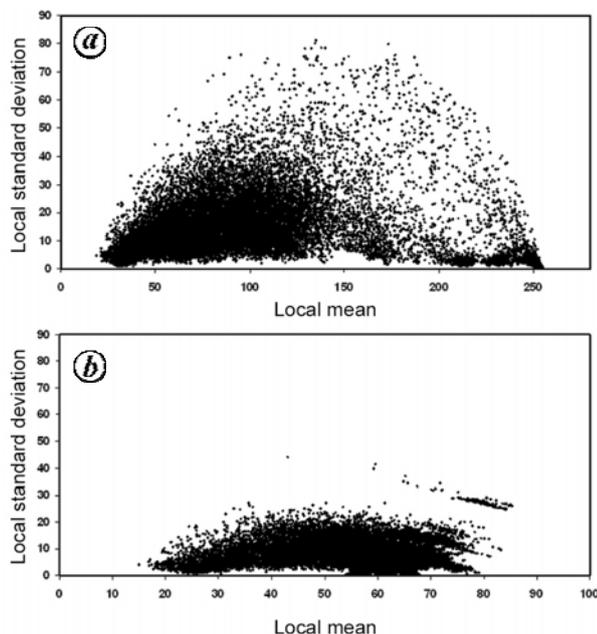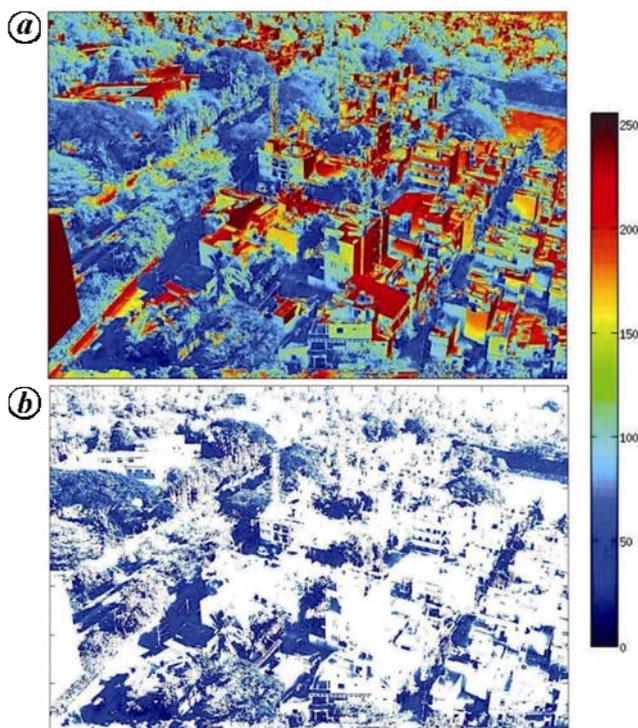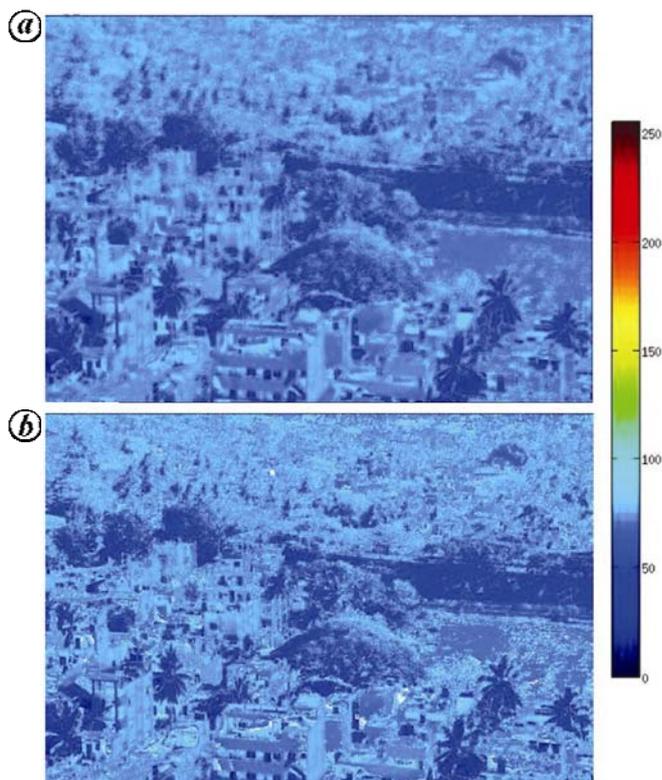
Figure 5. *a*, Original image obtained with polarization. *b*, The same image after applying spatial coherence technique to mask regions of low coherence.

is not fully applicable. Hence, infrared remote sensing is a better option for continuous retrieval of dust aerosols. The infrared radiance depression resulting from the presence of dust in the atmosphere has been used as an index (infrared difference dust index (IDDI)) of dust load in the atmosphere. The IDDI has been used extensively as an index of dust load[18–20] and can be derived using satellite measurements of infrared radiance in the 10.5–12.5 µm wavelength band. Deepshikha *et al.*[19] and Moorthy *et al.*[21] have demonstrated a method to estimate dust absorption efficiency using a combination of IDDI and AOD. Once we retrieve composite aerosol absorption (using UV and visible channels) and contribution from dust (using thermal IR channels), it is possible to estimate absorption due to BC. Using values of absorption cross-section of BC, it is possible to gather information on the regional distribution of BC mass concentration. The widespread aerosol network (ARFINET) existing over India could be used as a strong means for validating the product.

Realization of AEROSAT is expected to be a step forward in satellite remote sensing of aerosols.

Conclusions

We have presented the preliminary results obtained from a laboratory model of a satellite sensor – the 'aerosol satellite (AEROSAT)' which is capable of retrieving aerosols over land with much more accuracy and reduced dependence on models. The sensor, utilizing a set of multi-spectral and multi-angle measurements of polarized components of radiation reflected from the Earth's surface, along with measurements of thermal infrared broadband radiance, results in a large reduction of the 'noise' component (compared to the 'signal'). A conceptual engineering model of AEROSAT has been designed, developed and used to measure the land-surface features in the visible spectral band. Analysing the received signals using a polarization radiative transfer approach, we demonstrated the superiority of this method over the conventional ones, which require an aerosol model to retrieve aerosols. The AEROSAT was conceived to use a 'self-sufficient' scheme so that all relevant information required for aerosol retrieval should be derived from the satellite data.

1. Remer, L. A. *et al.*, *J. Atmos. Sci.*, 2005, **62**, 947–973.
2. Levy, R. C. *et al.*, *J. Geophys. Res.*, 2007, **112**, D13211.
3. Kaufman, Y. J. *et al.*, *J. Geophys. Res.*, 1997, **102**, 16,815–16,830.
4. Anderson, T. L. *et al.*, *Bull. Am. Meteorol. Soc.*, 2005, **86**, 1795–1808, doi: 10.1175/BAMS-86-12-1795.
5. Torres, O. *et al.*, *J. Geophys. Res.*, 2007, **112**, D24S47, doi: 10.1029/2007JD008809.
6. Diner, D. J. *et al.*, *Remote Sensing Environ.*, 2005, **97**, 495–518, doi: 10.1016/j.rse.2005.06.006.
7. Kahn, R. A. *et al.*, *J. Geophys. Res.*, 2005, **110**, doi: 10.1029/2004JD004706.
8. Satheesh, S. K. and Moorthy, K. K., *Atmos. Environ.*, 2005, **39**, 2089–2110; doi: 10.1016/j.atmosenv.2004.12.029.
9. Satheesh, S. K. and Ramanathan, V., *Nature*, 2000, **405**, 60–63; doi: 10.1038/35011039.
10. Satheesh, S. K. and Srinivasan, J., *J. Atmos. Sci.*, 2006, **63**, 1082–1092; doi: 10.1175/JAS3663.1.
11. Satheesh, S. K. and Moorthy, K. K., *Curr. Sci.*, 2007, **92**, 174–176.
12. Coakley, J. A. and Bretherton, F. P., *J. Geophys. Res.*, 1982, **87**, 4917–4932.
13. Fraser, R. S. and Kaufman, Y. J., *IEEE Trans. Geosci. Remote Sensing*, 1985, **GE23**, 625–633.
14. Kaufman, Y. J. *et al.*, *Geophys. Res. Lett.*, 2001, **28**, 1479–1483.
15. Satheesh, S. K. *et al.*, *J. Geophys. Res.*, 2009, **114**, doi: 10.1029/2008JD011024.
16. Levelt, P. F. *et al.*, *IEEE Trans. Geosci. Remote Sensing*, 2006, **44**, 1093–1101; doi: 10.1109/TGRS.2006.872333.
17. Schoeberl, M. R. *et al.*, *J. Geophys. Res.*, 2006, **111**, doi: 10.1029/2006JD007134.
18. Legrand, M., Plana-Fattori, A. and N'doumé C., *J. Geophys. Res. D*, 2001, **106**, 18251–18274.
19. Deepshikha, S., Satheesh, S. K. and Srinivasan, J., *Geophys. Res. Lett.*, 2005, **32**, doi: 10.1029/2004GL022091.
20. Deepshikha, S., Satheesh, S. K. and Srinivasan, J., *Ann. Geophys.*, 2006, **24**, 37–61.
21. Moorthy, K. *et al.*, *J. Geophys. Res.*, 2007, **112**, doi: 10.1029/2006JD007690.

S. K. Satheesh* is in the Centre for Atmospheric and Oceanic Sciences, and Divecha Centre for Climate Change, Indian Institute of Science, Bangalore 560 012, India and K. Krishna Moorthy is in the Space Physics Laboratory, Thiruvananthapuram 695 022, India.
*e-mail: satheesh@caos.iisc.ernet.in