Multi-angle polarization imager: A satellite sensor for studies of continental aerosols

S. K. Satheesh and K. Krishna Moorthy

Knowledge of aerosol radiative forcing over land is essential to answer crucial questions related to climate change. Retrieval of aerosol properties over land is complicated due to irregular terrain characteristics and high surface reflection. The retrieval of algorithms used in conventional satellite sensors for continental regions is not completely free from the high reflectance effect and hence leads to large uncertainties in the retrieved parameters. We propose a dedicated satellite sensor namely multi-angle polarization imager (MAPI). The main characteristic of MAPI is multi-spectral and multi-angle measurements of polarized components of reflected radiation from the Earth. The proposed sensor has capability of aerosol retrieval over land. The sensor also has the ability to discriminate dust aerosols (which is the major natural aerosol over land) from other aerosols (using infrared radiance). This is the first step towards separating natural and anthropogenic aerosols, which is needed for the scientific community at large.

Aerosols are suspended particulates in the atmosphere and have implications to climate through different mechanisms[1]. Several studies have suggested that aerosols may be mitigating global warming because of backscattering by sulphate aerosols, which cool the planet. Recent studies have shown that absorption due to black carbon aerosols leads to warming of the lower atmosphere[2,3]. Due to these complex issues, magnitude and sign of the aerosol radiative forcing are still uncertain as outlined in the Intergovernmental Panel of Climate Change (IPCC) reports. Compounding the complexity of this problem is the interaction of aerosols with clouds. Aerosols change cloud properties, alter precipitation patterns and have serious consequences on the hydrological balance of the earth–atmosphere system. Given this background, it is imperative that simultaneous measurements of aerosols and clouds from space are performed carefully to answer crucial questions related to climate change.

Measurement of aerosols can be *in situ* or remote. *In situ* measurements, however, are point measurements and cannot provide information over large regions. Satellite remote sensing is best suited for obtaining information over vast area (either regional or global). Global and continuous coverage are the two main advantages of space-based platforms, while low accuracy is their major shortcoming. Since these measurements are taken from several hundreds of kilometres above the ground, their intelligent retrieval is important for these measurements to be accurate[4,5].

The simplest case of remote sensing is that over a black surface (e.g. ocean for near infrared), where the satellite-observed radiance at the top of the atmosphere is only due to photons backscattered by the atmosphere[5,6].

Atmospheric reflectance,

$$R_{\text{atmos}} = \frac{\pi L^{\text{TOA}}(\mu, \phi, \mu_0, \phi_0)}{\mu_0 F}, \qquad (1)$$

where μ_0 is the solar zenith angle, ϕ_0 is the solar azimuth angle, μ is the satellite view angle, ϕ is the satellite azimuth angle, F is the solar constant, and L^{TOA} is the satellite-observed radiance. If the surface is not black (such as continents), then top of the atmosphere radiance is due to reflection from the surface (L_s) as well as due to molecular ($L_{\text{molecules}}$) and aerosol backscatter (L_{aerosols}).
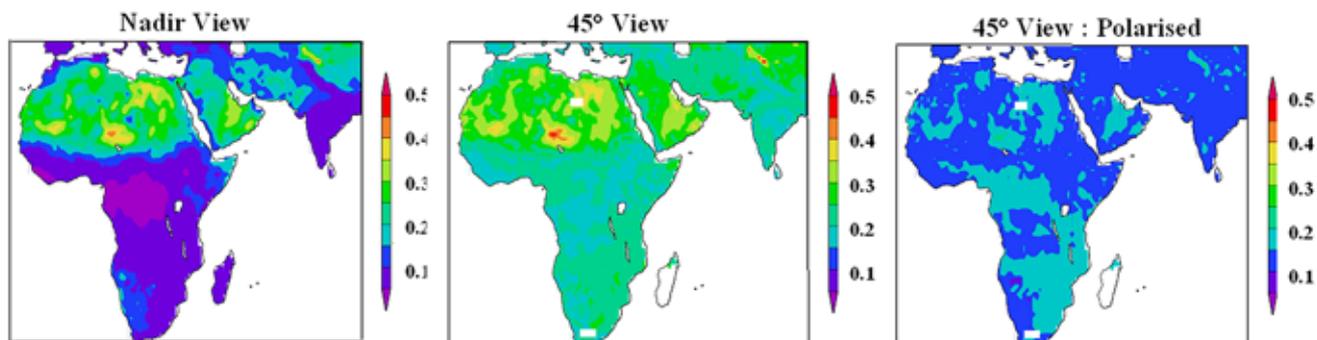
$$L^{\text{TOA}} = L_S + L_{\text{molecules}} + L_{\text{aerosols}}. \qquad (2)$$

Here the observed quantity is top of the atmosphere radiance (L^{TOA}) measured by the satellite. The parameter to be retrieved is the aerosol characteristics. This is a more complex inverse problem. Over continents, reflection from the surface is much larger compared to aerosol backscatter and hence a small error in the surface reflectance used in retrieval algorithm can cause large uncertainties in the inferred aerosol properties.
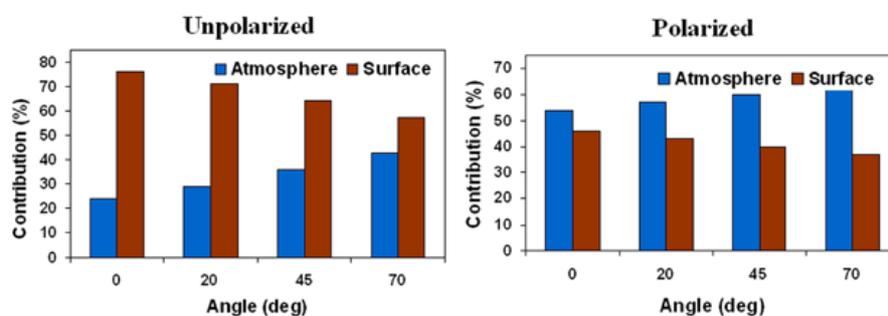
Several satellites have been launched with different types of sensors to obtain data on several parameters. Data from polar orbiting instruments such as National Oceanic and Atmospheric Administration (NOAA)'s Advanced Very High Resolution Radiometer (AVHRR) have been widely used for studies of aerosols over the oceans[7]. Now due to greater understanding of the importance of aerosols, sensors like moderate resolution imaging spectroradiometer (MODIS), multi-angle imaging spectroradiometer (MISR) and polarization and directionality of earth's reflectances (POLDER) are designed specifically to obtain aerosol data[5,8,9]. However, the retrieval algorithms used in these sensors for continental regions is not completely free from the high reflectance effect and hence leads to large uncertainties in the retrieved parameters.

Information on aerosols over land is of importance to climate-change studies. Another aspect is the information on aerosol chemical composition, which is important for climate and radiation budget modellers. Even though complete description of aerosol chemistry is not needed, at least information on single scattering albedo (ratio of scattering to extinction) is essential. Major issues which are of interest to climate change community are: (a) spatial heterogeneity and temporal variations in aerosol radiative forcing over land, (b) natural versus anthropogenic aerosols, (c) absorbing versus non-absorbing aerosols, and (d) contributions from various source regions. Keeping these objectives in mind, we propose a dedicated satellite sensor, namely multi-angle polarization imager (MAPI) for aerosol retrieval over land. The proposed sensor (MAPI) has been

Figure 1. *a*, Simulated radiance image for a nadir-looking satellite sensor at typical atmospheric conditions. *b*, Simulated radiance image for the same sensor looking at angle of 45° with respect to local normal. *c*, Simulated radiance image for the same sensor looking at angle of 45° and receiving polarized signal.

Figure 2. Quantitative assessment of the contribution of surface and atmospheric contributions to satellite radiance shown as a function of view angle.

designed utilizing a combination of features used in earlier satellites such as MODIS[5], MISR[8] and POLDER[9]. The main characteristics of MAPI are multi-spectral and multi-angle measurements of polarized components of reflected radiation from the earth. This sensor is capable of measuring polarized components of reflected signals from the earth's surface at several angles.
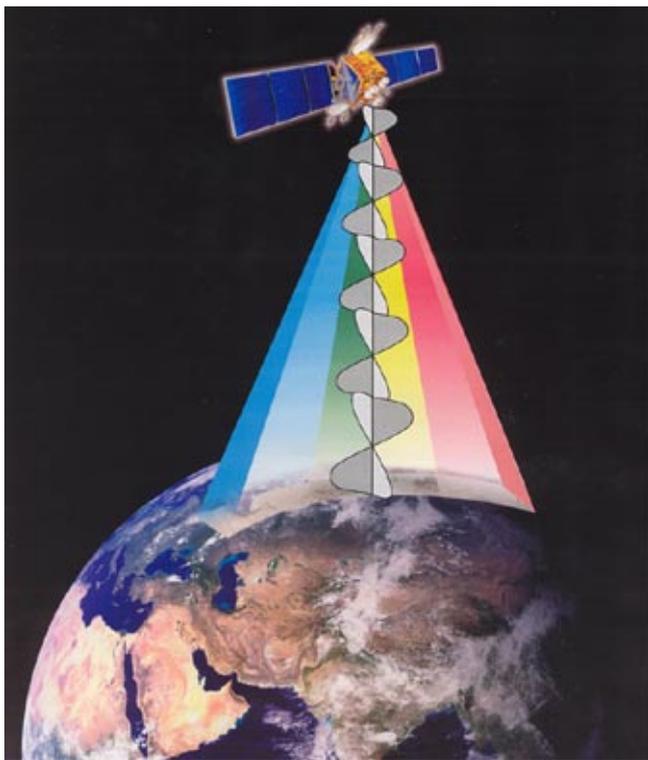
A wide range of spectral coverage is essential to get wavelength dependence of aerosol opacity. This enables the estimation of aerosol size distribution. Large viewing angles (thereby looking through a larger amount of atmosphere) provide enhanced sensitivity to atmospheric effects. Accurate aerosol 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. 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 MAPI, the scattered component from the atmosphere dominates the signal reflected from land. The accuracy of aerosol optical depth retrieval using MAPI has been estimated as 0.03 compared to 0.1 in the case of conventional satellites available at present.

The proposed spectral channels are 0.4, 0.5, 0.65, 0.75, 0.85, 0.935, 1.02 (both polarized and unpolarized), 2.0, 10.5, 11.5 and 12.5 μm. Look angles are between 0 and 70°. The exact look angles shall be decided after detailed sensitivity studies at the implementation stage. The spatial resolution (or pixel size) of MAPI is 5 km with a swath width of 1000 km. While visible and near infrared channels are meant for optical depth retrievals over land, 10.5–12.5 μm window channels are meant for dust aerosol retrieval as well as for cloud retrieval. Detection of dust using infrared radiance has been described by Legrand *et al.*[10]. It may be noted that bands in the thermal infrared region require separate sensor technology which hitherto has not

been tried in India. Calibration of space-borne observations of infrared signals is required for converting digital count to radiance. On-board blackbody calibration mechanism (in which a blackbody with known temperature can be viewed) is best suited for this type of sensor. Thus, development of infrared sensor technology should be considered as a new initiative in India. The sensor needs to be in sun-synchronous orbit at an inclination of 98° from the equator in the case of global coverage and 20° from the equator in the case of tropical coverage. The equatorial crossing time is important because the earth's surface is hottest at around 14 : 30 local time and infrared radiation emitted by the earth's surface is maximum at around 14 : 30. This is a suitable condition for retrieval of dust aerosols using infrared radiance[10].

Simulations are carried out on how satellites see the earth and atmosphere at various spectral, angular and polarization channels at different sun–satellite geometry. These simulations were carried out using a radiative transfer model with polarization. An example is shown in Figure

Figure 3. A conceptual sketch of operation of the proposed sensor.

1. Three cases are shown. Figure 1 a shows simulated radiance image for a nadir-looking sensor at typical atmospheric conditions. Here, an aerosol image (for January 2001) has been superposed over the continent with known surface reflectance. The large radiance value over Sahara is due to high reflectance of the desert. This is a conventional case where radiance signal from the surface is much larger compared to aerosol backscattered signal. In this case, it is difficult to retrieve aerosol information. In Figure 1 b, we show the same sensor looking at angle of 45° with respect to local normal. It can be seen that surface reflection effect is less compared to the nadir case. This is because of larger atmospheric path length in this case. In Figure 1 c, we show the same sensor looking at angle of 45° and receiving polarized signal. Here, surface reflection effects are minimum. The features visible are mainly due to atmosphere and not due to surface reflection. This case is

similar to that over the ocean and hence retrieval of aerosol information is possible without sacrificing the accuracy. A quantitative assessment of the contribution of surface and atmospheric contributions to satellite radiance is shown in Figure 2 as a function of view angle. The main point to note is that as view angle increases, contribution from the earth's surface relative to that of atmosphere comes down. Similarly, for the case of channel with polarization, even nadir-looking sensor receives larger contribution from the atmosphere, which is a favourable condition for atmospheric remote sensing over land. As the angle increases, percentage contribution of the atmosphere becomes stronger. A conceptual sketch of the operation of the proposed sensor is shown in Figure 3. The sensor measures radiance at various spectral channels and at various angles. For a subset of channels and angles, polarized signal also will be measured. The proposed sensor has the capability of aerosol retrieval over land.

The sensor also has the ability of discriminating dust aerosol (which is the only natural aerosol component over land) from other aerosols (using infrared radiance) simultaneously with composite aerosol measurements. This is the first step towards separating natural and anthropogenic aerosols, which is much needed for the scientific community at large.

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