Top of atmosphere flux from the Megha-Tropiques ScaRaB

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One of the important payloads on-board the joint Indo-French Megha-Tropiques satellite is the Scanner for Radiation Budget (ScaRaB). It is dedicated for monitoring the Earth Radiation Budget (ERB) parameters at Top of Atmosphere (TOA). In this article, details of the algorithm used for computing two important ERB components, namely TOA reflected shortwave and emitted longwave fluxes from ScaRaB radiance measurements are presented along with preliminary cross-satellite validation results.

The ScaRaB flux computation algorithm is similar to the one used in the ERB Experiment. The maximum likelihood estimation algorithm is used for identification of different Earth scenes and cloud types. First, the raw radiances are corrected for spectral filtering effects followed by implementation of scene-type dependent angular correction to deduce shortwave and longwave fluxes. The instantaneous TOA flux data derived from ScaRaB radiance measurements are compared with similar data available from Clouds and Earth's Radiant Energy System (CERES) on-board Aqua and Terra satellites. Preliminary comparison confined to two months period (September–October 2012) using the two satellites suggests that the ScaRaB data are in good agreement with the CERES data. The bias-corrected root mean square difference in ScaRaB longwave flux is 4.7 and 5.3 Wm^{-2} with respect to CERES on-board Aqua and Terra satellites respectively. For ScaRaB shortwave flux, it is 25.9 Wm^{-2} and 25.5 Wm^{-2} with respect to CERES on-board Aqua and Terra satellites respectively. A detailed comparison of ScaRaB TOA flux data with more than one-year of CERES data is already initiated. Results from the preliminary comparison exercise suggest that the ScaRaB data can be used with confidence for ERB studies.

Keywords: Atmosphere, computation algorithm, Megha-Tropiques mission, ScaRaB instrument.

Introduction

THE Megha-Tropiques (MT), a joint Indo-French satellite, was launched from Sriharikota, India, in an inclined 20° orbit on 12 October 2011 using Indian Space Research Organisation's (ISRO) Polar Satellite Launch Vehicle (PSLV-C18). The main objective of the MT mission is to monitor the energy and water cycle components of the global tropics. MT has four sensors on-board, namely MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures), SAPHIR (Sondeur Atmosphérique du Profil d'Humidité Intertropical par Radiométrie), ScaRaB (Scanner for Radiation Budget) and ROSA (Radio Occultation Sensor for Atmosphere). Among these, ScaRaB is the only sensor fully dedicated to monitoring the radiation budget components of the Earth–Atmosphere system.

Earlier, two more ScaRaB instruments developed by France, were launched in January 1994 (ref. 1) and August 1998 (ref. 2) on-board Russian satellites to monitor the Earth's Radiation Budget (ERB) parameters. Besides ScaRaB, NASA missions, namely ERB Experiment (ERBE)[3], and Clouds and Earth's Radiant Energy System (CERES)[4] and European Space Agency mission – Geostationary Earth Radiation Budget (GERB)[5] also provide useful ERB data.

ERB at top of atmosphere (TOA) is the balance between (i) incoming solar radiation at shortwave lengths (0.2–4.0 μm), (ii) reflected solar radiation at the same shortwave lengths (0.2–4.0 μm) and (iii) radiation emitted by Earth at longwave lengths (4.0–100.0 μm). Net energy gain in the tropics and net energy loss at the poles is the force which drives meridional energy exchange and ultimately the Earth's weather and climate. Hence changes in the Earth's meridional energy budget may affect its weather and climate. With the launch of ScaRaB on-board MT, it will be possible to study the role of the tropics on the meridional exchange of radiation fluxes using ScaRaB data. Clouds are important modulators of ERB[6–8]. Different cloud types exert different forcing on radiation budget[9]. The cloud radiative forcing is an important parameter used to measure the effect of clouds on ERB. The high temporal coverage and non sun-synchronous orbit of ScaRaB are ideal for cloud radiative forcing studies over the tropics. They are also useful to study the evolution of cloud patterns/forcing. In addition, changes in ERB due to naturally occurring climate shocks such as volcanic eruption and climate anomalies like

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El Niño–Southern Oscillation, extreme monsoon conditions, etc. can be studied using ScaRaB TOA flux data.

ScaRaB instrument

ScaRaB measures two important components of the ERB, namely reflected shortwave flux and emitted longwave flux at TOA. ScaRaB is a four-channel cross-track scanning radiometer. The four channels consist of two broadband channels, viz. channel-2 (0.2–4 μm) and channel-3 (0.2–100 μm) and two narrowband channels, viz. channel-1 (0.55–0.65 μm) and channel-4 (10.5–12.5 μm). The Earth scan angle coverage is 48.9° on both sides of the nadir. The number of pixels per scan is 51 and footprint size at the nadir is about 40 km^2. Of all the sensors on-board MT, ScaRaB has the widest swath of 2240 km. MT has a precession cycle of 51 days, which helps in the study of diurnal variability of radiation fluxes. A detailed description of radiometric and spectral characteristics of ScaRaB instrument, and its comparison with ERBE, CERES and GERB instruments can be found in Viollier and Raberanto[10].

The two broadband channels of ScaRaB, namely channel-2 and channel-3 are used to measure filtered shortwave ($L^{\mathrm{f}}_{\mathrm{SW}}$) and filtered total ($L^{\mathrm{f}}_{\mathrm{Total}}$) radiances respectively. The difference between these two channel radiances provides the filtered longwave radiance or synthetic longwave radiance ($L^{\mathrm{f}}_{\mathrm{SW}}$) in the range 4–100 μm.

$$L^{\mathrm{f}}_{\mathrm{SW}} = L^{\mathrm{f}}_{\mathrm{Total}} - A' L^{\mathrm{f}}_{\mathrm{SW}}. \tag{1}$$

Here the superscript f refers to 'filtered' and A' is a coefficient related to the equilibrium of channel-2 and channel-3 responses in the shortwave portion. The radiances measured by channel-2 and channel-3 are filtered radiances ($L^{\mathrm{f}}_{\mathrm{SW}}$ and $L^{\mathrm{f}}_{\mathrm{Total}}$), which are generally different from the unfiltered or real radiances L_{SW} and L_{Total}. According to Viollier and Raberanto[10], A' for ScaRaB on-board MT is 0.91. However, the calibration expert group from CNES updated the value of A' to 0.9159.

Top of atmosphere flux computation from ScaRaB radiance measurements

Each radiance measurement $L(\theta_0, \theta, \phi)$ by ScaRaB corresponds to one specific space direction characterized by solar zenith angle (θ_0), view zenith angle (θ) and relative azimuth (ϕ). The TOA flux is the integration of the radiances in the hemisphere

$$F(\theta_0) = \int_0^{\pi/2} \int_0^{2\pi} L(\theta_0, \theta, \phi) \cos\theta \sin\theta \,\mathrm{d}\theta\, \mathrm{d}\phi. \tag{2}$$

The computation of TOA flux from radiance is based on the angular dependence model (ADM) which depends on the Earth scene J. The ADM (R_J) is the ratio between the isotropic flux and the actual flux, which is given by

$$R_J(\theta_0, \theta, \phi) = \frac{\pi L_J(\theta_0, \theta, \phi)}{\int_0^{\pi/2} \int_0^{2\pi} L(\theta_0, \theta, \phi) \cos\theta \sin\theta \,\mathrm{d}\theta\, \mathrm{d}\phi}. \tag{3}$$

R_J is equal to 1 for the isotropic reflection or emission.

The flux computation from radiance thus becomes

$$F_J(\theta_0) = \frac{\pi L(\theta_0, \theta, \phi)}{R_J(\theta_0, \theta, \phi)}. \tag{4}$$

For longwave flux computation, the above formulae are simpler because they do not depend on θ_0 and ϕ.

$$F_J = \frac{\pi L(\theta)}{R_J(\theta)}. \tag{5}$$

TOA flux computation algorithm of ScaRaB is similar to the ERBE algorithm. It is a well-proven algorithm used in earlier two ScaRaB missions and also in the current CERES missions. Major steps involved in flux computation from radiance are: (i) spectral correction, (ii) scene identification and (iii) flux computation. These steps are shown in Figure 1.

Spectral correction

The spectral response functions of the ScaRaB broadband channels are not perfectly flat-topped, which may lead to errors when the ScaRaB instrument looks at the Earth scene with different spectral signature than that of the calibration source. It is to be mentioned that ScaRaB on-board MT has better calibration module when compared

Figure 1. Major steps involved in ScaRaB top of atmosphere flux retrieval.

to earlier two ScaRaBs[10]. The shortwave filter on channel-2 is removable so that it can be calibrated by viewing an on-board blackbody. Three different in-flight calibration modes (calibration mode, total mode and solar mode) are possible with the help of on-board blackbody and a filter wheel.

ScaRaB measures the filtered radiance L_J^{f} associated with the Earth scene J, which is generally different from the unfiltered radiance L_J.

$$L_J = \int L_J(\lambda)\mathrm{d}\lambda, \tag{6}$$

$$L_J^{\mathrm{f}} = \int r(\lambda)L_f(\lambda)\mathrm{d}\lambda, \tag{7}$$

where $r(\lambda)$ is the spectral response for shortwave ($r_{\mathrm{SW}}(\lambda)$) and longwave ($r_{\mathrm{LW}}(\lambda)$) channels.

The filtered radiances may be slightly different from the unfiltered radiance when the spectra of the Earth scene and of the calibration source differ. Though it is a minor correction, it is done after identifying the Earth scenes.

Spectral correction for shortwave and longwave channels is defined as

$$L_J = \frac{L_J^{\mathrm{f}}}{F}, \tag{8}$$

where F is the filtering factor to be found out for different Earth scenes.

$$F = \frac{\int r(\lambda)L_J(\lambda)\mathrm{d}\lambda}{\int L_J(\lambda)\mathrm{d}\lambda}. \tag{9}$$

Radiative transfer model simulations by Viollier and Raberanto[10] suggest that spectral corrections for both the longwave and shortwave channels of ScaRaB on-board MT are minimal and may be ignored. In future, spectral filtering effects will be further examined by performing rigorous radiative transfer simulations.

Scene identification

Maximum likelihood estimation (MLE) algorithm of Wielicki and Green[11] is used for identifying different Earth scenes and cloud types. The 12-scene classification of MLE uses five geo-types [land, ocean, desert, snow-ice and coast] and four cloud types [clear (0–5%), partly cloudy (5–50%), mostly cloudy (50–95%) and overcast (95–100%)]. In this method, for each shortwave and longwave radiance measurement, probability of being the four-cloud category is computed using the procedure given by Wielicki and Green[11] using the ADM tables of Suttles *et al.*[12,13]. The cloud type with maximum probability is assigned to that scene.

Flux computation

By selecting appropriate ADMs provided by Suttles *et al.*[12,13] corresponding to the identified scene, observed Sun–Earth–satellite geometry and using eq. (4), shortwave fluxes are computed. The longwave ADMs are functions of scene, view zenith angle, latitude and season. By selecting appropriate ADM corresponding to the identified scene, satellite view angle, latitude and season and using eq. (5), longwave fluxes are computed.

Level-1 and level-2 ScaRaB data

ScaRaB was switched on about 3 weeks after the launch of MT. The ScaRaB data were available from 4 November 2011. The level-1 and level-2 ScaRaB data were released to the users from 24 January 2013. The level-1 data files contain date, time, geo-location, filtered radiance for all the four channels along with synthetic longwave channel computed using eq. (1), angles, quality flags, etc. The level-2 file contains the TOA reflected shortwave flux and emitted longwave flux, unfiltered radiances, and scene identified using MLE. All these files contain pixel data and are in hdf-5 file format. These data are available for the research community upon registration at ISRO's data portal – Meteorological and Oceanographic Satellite Data Archival Centre at http://www.mosdac.gov.in.

Figure 2 shows TOA reflected shortwave and emitted longwave fluxes (L2A-GP data) during a typical MT orbit (orbit number 6755-6756, 1 February 2013). Since it is a segment data, one full orbit and a part of the next orbit are seen in the plot. As the solar radiation is restricted to the sunlit portion of the globe, reflected shortwave flux is available for half of the orbit only. But the longwave flux is available for the entire orbit since longwave radiation is emitted by the Earth during day and night. The reflected shortwave flux ranges from 0 to 1000 Wm^{-2}, whereas the longwave flux ranges from 50 to 400 Wm^{-2}. Shortwave flux is highest over the deep convective clouds which reflect most of the incoming shortwave solar radiation to space. The tropical cyclone Felleng is seen between Reunion Island and Madagasar in this image. The reflected shortwave is high over the central dense overcast region of this cyclone. The cyclone is clearly seen in the longwave flux image also. Since the cyclone is tall, nearing the tropopause, less longwave radiation is emitted from the colder cloud tops. Hence the longwave flux over Felleng cyclone is less compared to the surrounding areas. The hot oceanic surfaces and deserts which are free of clouds emit more longwave radiation than the cloudy regions.

Preliminary comparison of ScaRaB top of atmosphere flux data with CERES data

Since there is no *in situ* measurement of radiative flux available at TOA, comparison of satellite-estimated

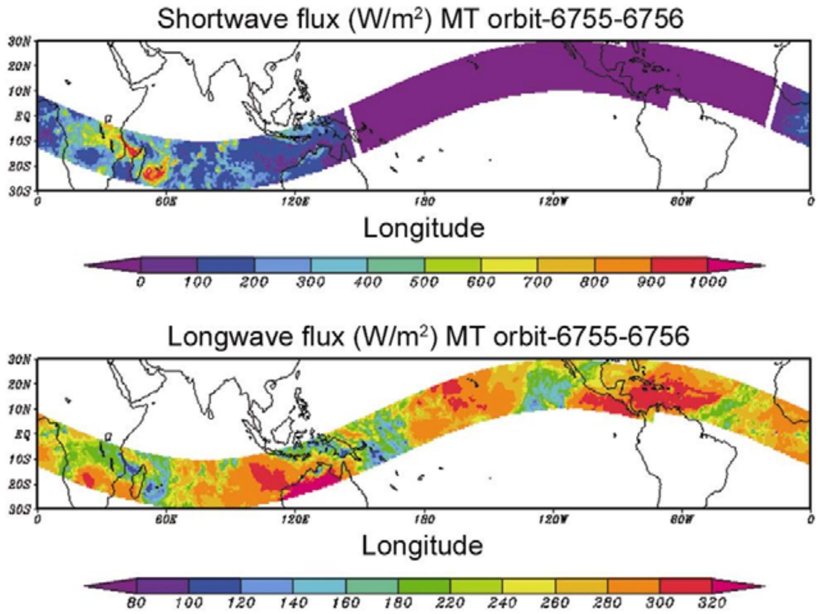

Figure 2. TOA reflected shortwave flux (Wm^{-2}; top) and emitted longwave flux (Wm^{-2}; bottom) computed from ScaRaB radiances for the Megha-Tropiques orbit 6755-6756 of 1 February 2013.

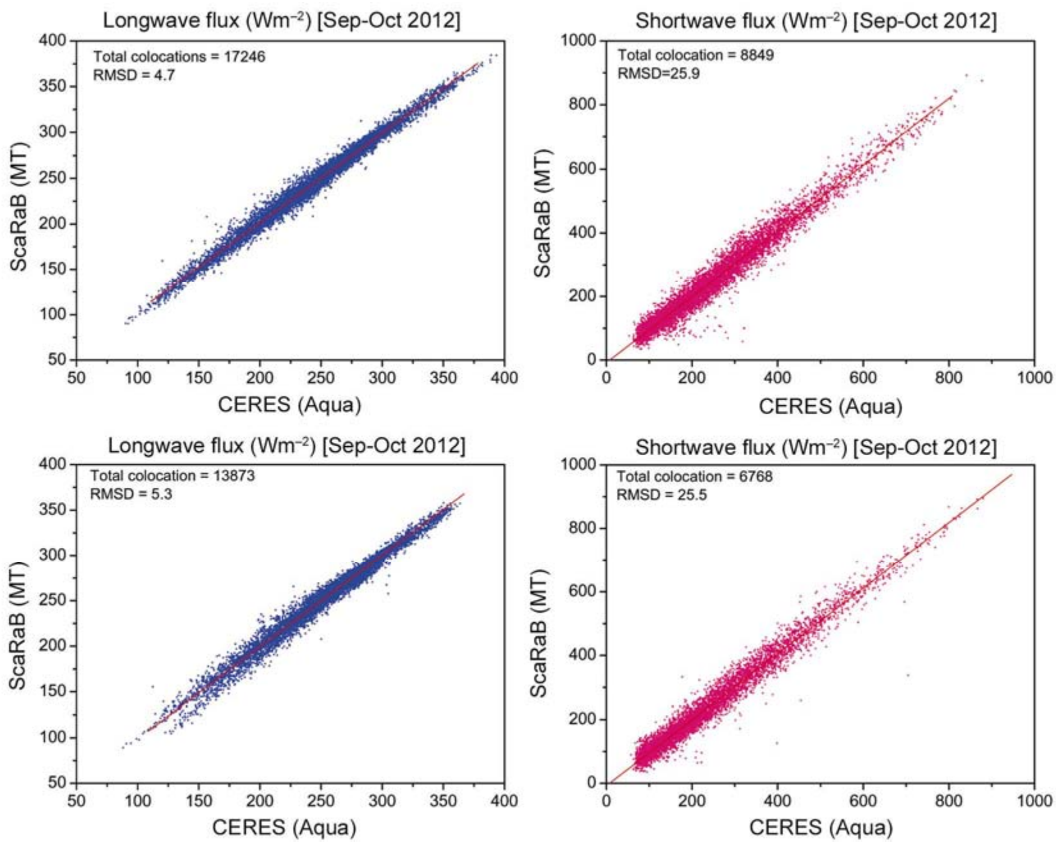

Figure 3. Scatter plots between (top left) ScaRaB longwave flux (Wm^{-2}) and CERES/Aqua-FM3 longwave flux (Wm^{-2}), (bottom left) ScaRaB longwave flux (Wm^{-2}) and CERES/Terra-FM2 longwave flux (Wm^{-2}), [top right] ScaRaB shortwave flux (Wm^{-2}) and CERES/Aqua-FM3 shortwave flux (Wm^{-2}) and (bottom right) ScaRaB shortwave flux (Wm^{-2}) and CERES/Terra-FM2 shortwave flux (Wm^{-2}). The comparison is done for September–October 2012 with bias-corrected ScaRaB data. Statistics of the comparison is provided in individual plots. Straight lines in these plots are the linear-fit lines.

Table 1. Statistics of the preliminary validation of ScaRaB instantaneous top of atmosphere fluxes with CERES TOA fluxes on-board Aqua and Terra satellites for September–October 2012

Satellite	Parameter	RMSD (Wm^{-2})	Bias (Wm^{-2})	RMSD (bias-corrected; Wm^{-2})
Aqua	Longwave flux	5.3	–2.4	4.7
	Shortwave flux	30.5	16.1	25.9
Terra	Longwave flux	6.7	–4.2	5.3
	Shortwave flux	31.1	17.8	25.5

radiative flux is generally done with flux data from similar sensors on-board other satellites. In cross-satellite comparison, collocated and concurrent observations of both the satellites will be considered for comparison. Presently, CERES instruments on-board Terra and Aqua satellites measure TOA radiation fluxes using similar broadband sensors. Both Terra and Aqua are sun-synchronous polar-orbiting satellites having local time of equatorial crossing at 1030 and 1330 h respectively. The CERES instrument has a footprint size of approximately 20 km at the nadir, which is four times finer than ScaRaB footprint size.

For comparison, concurrent (within ± 15 min) and collocated footprints of ScaRaB and CERES are considered. The collocated footprints of both the instruments having different footprint sizes are gridded onto coarser 2° lat. × 2° long. grids to reduce sampling noise (Norman Loeb, pers. commun.). Version 1.03 of the ScaRaB shortwave and longwave TOA flux data during September and October 2012 is considered for preliminary comparison. Because the CERES ES-8 data also uses ERBE-like algorithm of Suttles *et al.*[12,13] and MLE of Wielicki and Green[11], comparison is made with these data for the same two-month period. The comparison is made only when there are at least 25 and 100 pixels present in each 2° lat. × 2° long. grid for ScaRaB and CERES respectively, to avoid under-sampling related errors. Results of this preliminary comparison exercise with CERES on-board Terra (FM-2) and Aqua (FM-3) are shown in Figure 3. Both longwave and shortwave fluxes of ScaRaB show good agreement with the longwave and shortwave fluxes of CERES on-board Terra and Aqua satellites. The root mean square difference (RMSD) between bias-corrected ScaRaB longwave flux and CERES longwave flux is 4.7 and 5.3 Wm^{-2} with respect to Aqua and Terra satellites respectively. Similarly, the RMSD for bias-corrected ScaRaB shortwave flux is 25.9 and 25.5 Wm^{-2} with respect to Aqua and Terra satellites respectively. The value of bias is subtracted for each gridded ScaRaB observation and then bias-corrected RMSD is computed. Results of the preliminary cross-satellite comparison are summarized in Table 1. The RMSD of shortwave flux is more than longwave flux possibly due to the following reasons: (i) anisotropy of radiation field is more for shortwave than the longwave[12,13] and (ii) dynamic range of the shortwave flux is more (0–1000 Wm^{-2}) than the longwave flux (50–400 Wm^{-2}). Close agreement of TOA shortwave and longwave fluxes from ScaRaB with CERES on-board Aqua and Terra satellites suggests that the ScaRaB fluxes can be used with confidence for ERB studies. But caution must be exercised that the preliminary comparison results are restricted to 2 months only. In future, new versions of ScaRaB flux data (due to improvements in level-1 and level-2 processing) are expected. Hence further improvement in the quality of the ScaRaB TOA flux data is expected. A detailed comparison exercise using latest version of flux data for about a year has already been initiated. It is also to be remembered that if the fluxes are averaged on monthly scales as in the case of CERES ES-9 data, errors are expected to decrease further due to their averaging.

Conclusion

In this article, details about the recently launched broadband ScaRaB radiation budget instrument on-board MT are provided. Also, the algorithm used to compute TOA reflected shortwave flux and emitted longwave flux from ScaRaB measured radiances are described. The TOA fluxes are computed using an algorithm similar to that used in earlier successful ERB missions like ERBE, ScaRaB on-board Russian satellites and CERES on-board TRMM, Aqua and Terra satellites. This algorithm makes use of MLE algorithm of Wielicki and Green[11] for scene identification. The fluxes are computed by applying scene-type dependent angular dependence models of Suttles *et al.*[12,13].

The instantaneous ScaRaB TOA flux data were cross-validated with broadband TOA flux available from CERES on-board Aqua and Terra. The initial comparison results corresponding to September–October 2012 are presented. Both the longwave and shortwave fluxes of ScaRaB show a good agreement with CERES data. The RMSD in bias-corrected ScaRaB longwave flux is 4.7 and 5.3 Wm^{-2} with respect to CERES on-board Aqua and Terra satellites respectively. In case of shortwave flux, the RMSD after bias correction is 25.9 and 25.5 Wm^{-2} with respect to CERES on-board Aqua and Terra satellites respectively. Results from the preliminary comparison exercise suggest that the ScaRaB data can be used with confidence for ERB studies. It is to be noted that the preliminary comparison is confined to a period of two months only and hence care should be taken while using the data. A detailed comparison of ScaRaB data with more than one year of CERES data has already been initiated. Several climate studies such as cloud radiative forcing studies, climate monitoring, verification of climate model simulation, ERB studies, etc. can be made with these important data.

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