Derivation of Energy and Water Balance Parameters from ENVISAT AATSR Data across Savannah Volta Catchments in West Africa

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Abstract: This paper is an attempt to derive energy and water balance parameters from the ENVISAT Level 1B Advanced Along-Track Scanning Radiometer (AATSR) data across savannah Volta catchments in West Africa as one of the solutions for scarce spatial data sets needed for hydrological modelling. This was achieved through solution of the radiation and energy balance equations, which were computationally-driven by the Surface Energy Balance Algorithm for Land (SEBAL) algorithm. The results showed that the AATSR sensor is a potentially good source of key geophysical parameters (e.g. NDVI, net radiation [R_n], surface temperature [T_s] and evapotranspiration [ET]) needed as inputs to regional hydrological models. A multiple regression analysis showed quite strong correlations between these parameters (R^2=0.61; p<0.001), which also compared well with published results over other semi-arid regions. However, comparison of AATSR estimates of ET with Landsat ETM+ and ground-based observations showed a wide deviation of about 2.0 mm day^{-1}, which may be explained by differences in sensor calibration and spatial mismatch.

Keywords: Volta Savannah, Energy & Water Balance Parameters, AATSR, SEBAL

INTRODUCTION

In Africa, the scarcity of spatial data needed for hydrological modelling makes derivation of energy balance parameters such as vegetation cover (e.g. NDVI), surface temperature (T_s) and evapotranspiration (ET) from satellite sensors very important [1]. This is one of the principal objectives of the ESA TIGER Project (Space Applications for Water Management in Africa) which was initiated in 2002 as part of ESA's contribution to the UN goal on sustainable development of the continent (http://www.tiger.esa.int). In 2004, the ESA-Volta Project #2992 was started as part of the overall TIGER Initiative, one of the main objectives being assessment of the potential of ESA's Environmental Satellite (ENVISAT) Advanced Along-Track Scanning Radiometer (AATSR) Level 1B data as a potential source of spatially-derived energy balance parameters which may be used as inputs to new-generation hydrological models such as the modified Pitman model [2] across savannah catchments of the Volta basin. In the Volta basin (Fig 1), remote sensing data is important for two reasons: (1) spatially observed hydrometeorological data (needed for hydrological modelling) are very scarce because of the paucity of ground monitoring stations; and (2) the basin is very large (~400,000 km^2) with extreme heterogeneous land cover, which makes accessibility and ground data collection a very difficult issue. In this context, coarse-resolution sensors such as the AATSR and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) remain the most tangible option to obtain or model energy balance parameters at the regional scale [3-7]. Recently, a number of papers have demonstrated for instance, the potential of the MODIS sensor as an attractive source of land surface information [5-7]. However, the derivation of energy balance variables from the AATSR sensor remains a key research issue. Although [3, 8] have previously derived T_s from AATSR over Spanish and Australian landscapes, the potential of the sensor over extremely heterogeneous savannah catchments in West Africa is yet to be determined. Also, there are no published papers on validation of energy balance variables over tropical areas. For example, papers that show validation of the AATSR reflectance bands are quite difficult to find. These are some the gaps this paper is intended to address. Specifically, the paper seeks to derive key components of the energy balance equation, e.g. NDVI, T_s and ET over the Volta basin and examine their potential uses as inputs to hydrological models.

The paper is structured in the following way: the first part provides a description of the AATSR sensor data, followed by their application to the study area. The second part describes the study methods including a stepwise detail of image processing, derivation of key energy balance variables. This section also deals with data evaluation using a 30m resolution Landsat ETM+ image, ground data and published information. The third part discusses the results, which is followed by a summary of the key findings.

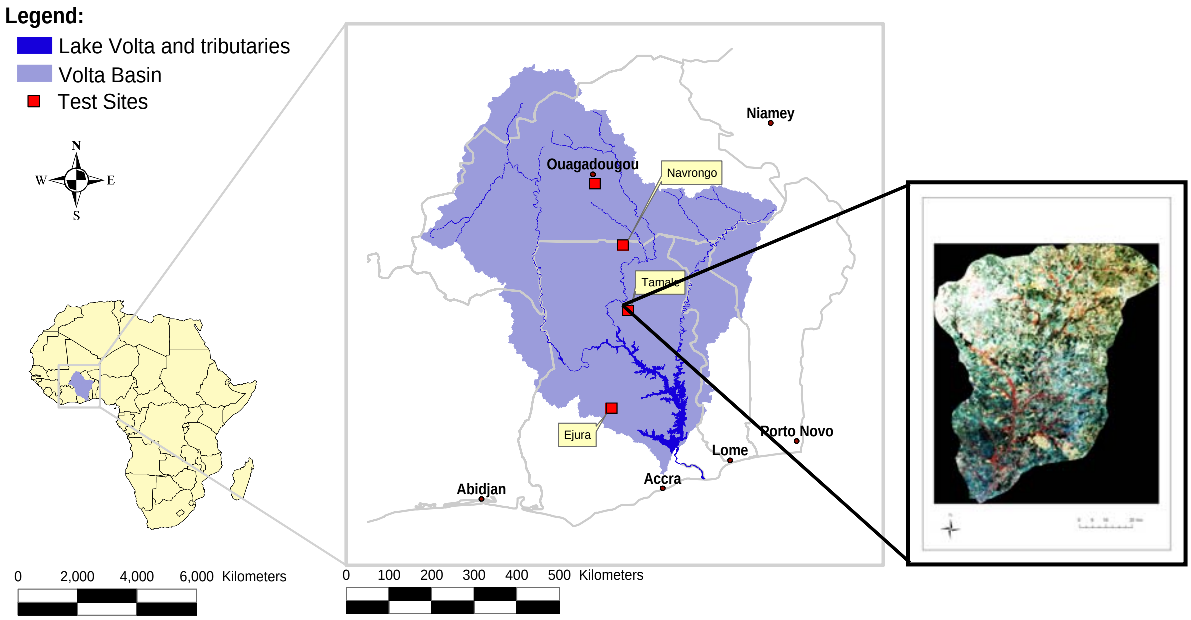


Fig 1 Location of the Volta river basin in West Africa Source: Modified after GLOWA-Volta Project [9]. The Tamale study areas is shown as the right-hand-side Landsat ETM+ image acquired on 5th January 2004; RGB=Band 4, 3, 2. The surface area of the Volta basin, the Volta Lake and the study area are 400,000, 8,500 and 5,300 km^2, respectively.

MATERIALS AND METHODS

The Study Area

The study area covers the Tamale Volta catchment (see inset of Fig 1), whose landscape characteristics are quite representative of the Guinea savannah region in West Africa. The Volta basin encompasses six West African countries (Benin, Burkina Faso, La Côte d'Ivoire, Ghana and Mali) covering an area of about 400,000 km^2. Over 70 million of West Africans depend on the Volta for food and water resources, housing, energy in terms of hydropower supply, and lake transport. The need to understand fluctuations in the key energy processes that control water availability in the region is therefore of utmost importance.

The climate of tropical West Africa is largely influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), which is an area of low pressure cells, where the Northeast Trade Winds meet the Southeast Trade Winds near the Earth's equator [10]. As these winds converge, moist air is forced upward causing water vapour to condense, and as the air cools and rises a band of heavy precipitation results. West Africa is also characterised by high daily/annual temperatures (~29^0 C), which are closely related to the region's position in terms of the Equator, Gulf of Guinea and Sahara desert. West Africa is largely drained by three transboundary river systems - the Niger, Senegal and Volta. The Volta Lake (~8,500 km^2) developed from the Volta River (see Fig 1), forms a massive inland drainage and flow regulating system, whose hydrological conditions is central to the region's economy. The geology of the area is often valued in terms of rich mineral resources, but shallow aquifers also significantly contribute to the rural economy in terms of surface flow discharge and borehole water supply, particularly during the dry season [11].

Data Sources

NASA's Landsat ETM+ and ESA's AATSR Level 1B imagery (Table 1) were used as the main sources of remotely sensed data [12]. It must be noted that Level 1B products do not directly contain images however; they contain calibrated data which are often used by other software applications to construct the images. A 40-year (1961-2000) record of daily air temperatures as a well as historical (1970-1980) daily wind speed and sunshine data monitored from five widely spaced (>100 km apart) ground stations upstream the Volta Lake served as the main source of reference data [13]. It was difficult to obtain spatially observed surface temperature (T_s) data for this research. However, the above data sets were complemented by energy flux (eddy correlation) data (Fig 2) measured for the Tamale district, courtesy of the GLOWA-Volta Project [9]. The brightly-coloured north-western section of the Landsat ETM+ image in Fig 1 largely covers the Tamale district. For purposes of validation, field surface temperatures were observed from thermal data loggers at the time of satellite overpass (Table 2). The thermal loggers named A-E were sited in the study area as follows: north-western (urban), north-eastern (grassland bush), central (agriculture), eastern (open woodland) and southern (closed woodland) locations of the study area (see inset of Fig 2).

Table 1 Characteristics of AATSR and MODIS data used for the study

Image Date	Satellite overpass (UTC)	Orbit	Track	Frame	Central coordinates	
					Lat	Lon
			AATSR Sensor			
040103	10:13:07 - 10:14:43	4441	380	3500	9^0 51'N	1^0 58'W
131104	10:04:47 - 10:06:23	14146	65	3500	9^0 18'N	0^0 04E
021204	10:07:35 - 10:09:11	14418	337	3500	9^0 36'N	0^0 35'W
181204	10:04:44 - 10:06:20	14647	65	3500	9^0 19'N	0^0 04'E
250105	10:10:25 - 10:12:01	15191	108	3500	9^0 37'N	1^0 18'W
			Landsat ETM+			
050104	10:40:00 - 10:41:00	-	194	53	10^0 06'N	00^0 36'W

Note: The Landsat ETM+ scene acquired on 5^{th} January 2004 was used mainly because of the absence of cloud-free data coincidental with the MODIS and AATSR overpass.

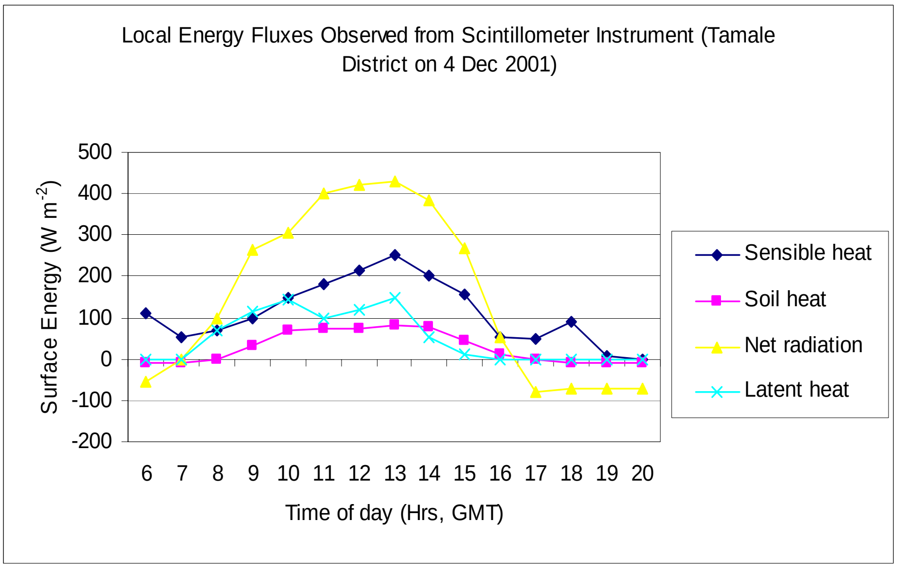


Figure 2 Local energy flux observations from the Dutch-type scintillometer instrument, which measures turbulent intensity fluctuations of the refractive index of air. Source: Reproduced from field data retrieved from the GLOWA-Volta database [9].

Table 2a Soil temperatures (K) observed from thermal data logger at the time of MODIS & AATSR overpass.

	Logger A	Logger B	Logger C	Logger D	Logger E
Date: 131104					
Time 10:12	309.19	310.21	309.19	308.72	307.58
10.32	309.27	310.32	309.97	308.86	307.97
11:12	309.27	310.29	309.92	308.45	308.49
Av. Temp (K)	309.24	310.29	309.69	308.68	307.95
Date: 021204					
Time 10:12	312.67	312.08	312.39	308.11	307.88
10.32	312.98	312.21	312.33	308.07	307.70
11:12	312.98	312.29	312.38	308.64	308.66
Av. Temp (K)	312.88	312.19	312.37	308.27	308.08

The locations of the thermal loggers named as A-E are given in Table 3b

Table 2b Geographical locations of the thermal loggers

	Geographical description (see Fig 2)	Latitude (^{0}N)	Longitude (^{0}W)	Land cover class
Logger A	North-west	09^0 26'	00^0 51'	Urban
Logger B	North-east	09^0 28'	00^0 26'	Grassland-bush
Logger C	Central	09^0 14'	00^0 37'	Agriculture
Logger D	East	09^0 04'	00^0 28'	Open Woodland
Logger E	South	08^0 56'	00^0 50'	Closed Woodland

For regional-scale studies, the AATSR has very useful capabilities. For example, it provides data from both the reflectance and thermal infrared bands, which supplies useful land-based parameters such as land-cover and surface temperature, which are often needed as key inputs to energy and water balance models. In terms of temperature mapping, the AATSR scenes are supplied to users as a ready source of brightness temperatures [3]. This is extremely valuable because users can circumvent problems which are often associated with the calibration of (raw) radiance values such as the AVHRR and MODIS Level 1B data. It is also worth noting that the digital data structure of AATSR provides capabilities which easily lend it for integration with new-generation GIS-based data assimilation schemes [4]. Table 3 displays the general characteristics of the applied satellite data sets.

Table 3 Technical characteristics of key sensor data sets applied in this study

Data source	Spatial resolution (m)	Spectral range (µm)			
		*VIS	NIR band	MIR band	TIR band
Landsat ETM+	30 (15m for panchromatic and 60m for thermal band)	Band1 (0.45-0.52) Band2 (0.52-0.60) Band3 (0.63-0.69) Pan (0.5-0.90)	Band4 (0.76-0.90)	Band5 (1.55-1.75) Band7 (2.08-2.35)	Band6 (10.4-12.50)
ENVISAT AATSR L1B	1 km	Band1 (0.545-0.565) Band2 (0.649-0.669)	Band3 (0.855-0.875)	Band4 (1.580-1.640)	Band5 (3.50-3.89) Band6 (10.40-11.30) Band7 (11.50-12.50)

Sources: Various NASA and ESA websites e.g. http://daac.gsfc.nasa.gov; http://www.msct.ssai.biz; http://envisat.esa.int/instruments/. *VIS=Visible, NIR=Near Infrared, MIR=Middle Infrared & TIR=Thermal Infrared band

Study Methods

The main image processing, modelling and data up-scaling methods are described below.

- The raw Level 1B AATSR images (Table 1) were first read using the Windows version of the European Space Agency (ESA) Basic ERS & ENVISAT AATSR and MERIS software (BEAM) (**http://www.brockmann-consult.de/beam/**). Brightness temperatures at the top of atmosphere (T_B) were directly retrieved after running the BEAM software; the software automatically implements an inverted version of the Planck's equation where image radiances are converted to T_B [see (1)]. The T_B files were then exported and stored as GeoTIFF for further use.
- Examination of the Landsat ETM+ header files enabled the retrieval of calibration constants from the reflectance (Bands 1-5, 7, 8) and radiance (Band 6) files of the composite product. The reflectance and radiance values were then used to calculate calibrated versions of time series data following NASA's re-calibration procedures described in an online manual. The inverted Planck's equation was then applied to convert the image radiances (L) of each of the thermal infrared bands (TIR) to T_B following the approach of [14] as:

$$T_B = \frac{c_2}{\lambda \ln\left[c_1 / \lambda^5 L + 1\right]} \tag{1}$$

where c_1 = 3.74*10^8 and c_2 = 1.439*10^4 and λ = wavelengths of the TIR band. T_B was subsequently used to calculate T_s using the split-window algorithm and empirical coefficients derived by [7] as:

$$T_s = 0.39T_1^2 + 2.34T_1 - 0.78T_1 * T_2 - 1.34T_2 + 0.39T_2^2 + 0.56 \tag{2}$$

- Further, ERDAS spatial modelling tools were used to calculate NDVI (normalized difference vegetation index) for time series imagery using the equation below [15]:

$$NDVI = (NIR - R)/(NIR + R) \tag{3}$$

where *NIR* and *R* are light reflectance in the near infrared band and the red bands of the electromagnetic spectrum, respectively. The data generated from (1-3) were applied as key inputs to the Surface Energy Balance Algorithm for Land (SEBAL) code [16, 17] which was run through MATLAB software interface. The theoretical basis of the SEBAL is that it solves the energy and radiation balance equations (4) & (5) on per pixel basis, from which ET may be derived as the residual term of the regional energy balance model at the time of satellite overpass.

$$ET = R_n - H - G_0 \tag{4}$$

where ET = latent heat flux (evaporation), R_n = net radiation, H = sensible heat flux, and G_0 = soil heat flux. The units for all the above parameters are Wm^{-2}. Following (4), the net radiation (R_n), which is the amount of radiation left after all outgoing radiation ($L^{\uparrow}$) is subtracted from all incoming radiation ($L_{\downarrow}$), was calculated as follows:

$$R_n = K_{\downarrow}(1-\alpha) + (L_{\downarrow} - L^{\uparrow}) \tag{5}$$

where $K_{\downarrow}$ = incoming shortwave radiation, α = albedo (dimensionless) and $L_{\downarrow}$ and $L^{\uparrow}$ are incoming and outgoing long wave radiation, respectively and the shortwave radiation (Wm^{-2}) reaching the Earth's surface under cloud-free conditions. The procedure for calculating R_n intermediate parameters, model assumptions and physical constants applied in this study are already detailed in [7]. Also, empirical models used for calculating soil heat (G_0), sensible heat (H) and daily evapotranspiration (ET_{day}) and their assumptions are fully described by [16, 17].

RESULTS AND DISCUSSION

Results

The scarcity of spatially observed ground data is a major concern for hydrological modelling in the Volta basin. Table 1 presents energy flux results derived from AATSR, which may be used as intermediate data inputs for hydrological models. The results are compared with other data sets.

Table 4 Energy fluxes derived from ENVISAT-AATSR data

Energy fluxes	AATSR	Landsat ETM+	*Observed (Tamale)*	Deviation *(AATSR)*	Deviation *(Landsat)*
Net Radiation (R_n)	378	352	*304*	-74	-48
Sensible heat (H)	300	208	*150*	-150	-58
Latent heat (λET)	68	134	*142*	+74	+8
Soil heat (G_0)	24	51	*71*	+47	+21

NDVI (surrogate for land cover), surface temperature (T_s) and evapotranspiration (ET) are the most influential parameters which drive the energy/water balance model [7]. Figs 3 & 4 show T_s and ET models derived from the AATSR sensor and how they compare with other satellite sensors and ground data.

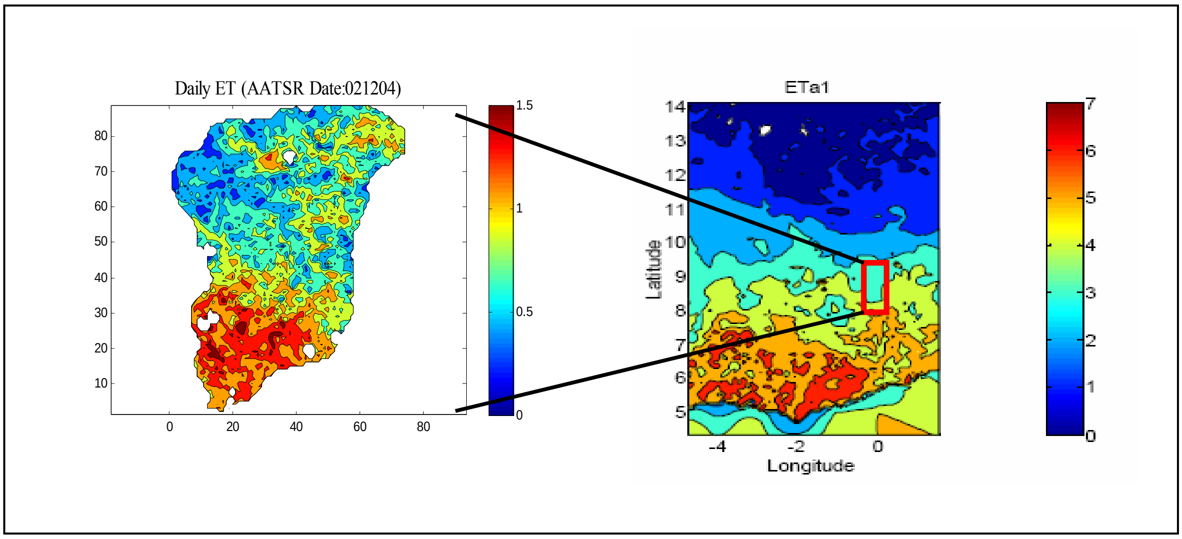
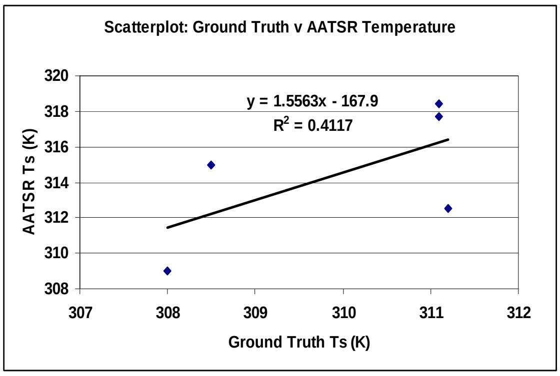
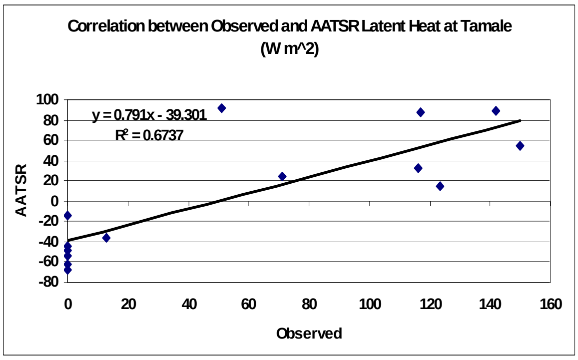
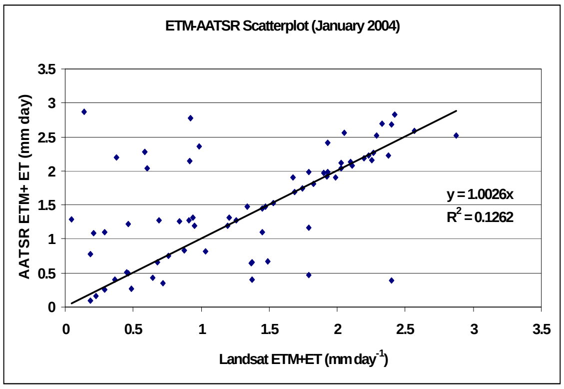


Fig 3 Spatial ET derived from AATSR data







Method (ET mm day^{-1})	Scale	Range	Mean	Standard deviation
Penman-Monteith	Local (Tamale)	1.53 – 4.87	3.90	0.66
Scintillometer	Local (Tamale)	-	1.79	-
Landsat ETM+	Regional	0.15 – 2.93	2.10	0.42
MODIS	Regional	0.05 – 2.83	2.07	0.37
AATSR	Regional	0.01 – 2.09	1.21	0.86

Fig 4 Comparison of T_s and ET estimates derived from AATSR

Discussion

The results shown in Table 4 and Figs 3 & 4 tend to show that T_s estimates by the AATSR sensor are higher than ground temperatures (HOBO thermal probes) (R^2 = 0.44). Aside T_s, ET models are driven by related parameters such as NDVI, R_n, r_{ah} [5, 7]. In this case, the interactive effect of NDVI, T_s and R_n seems to be most important (R^2 = 0.61; p<0.001) [7]. In terms of ET, there was poor spatial correlation (R^2 = 0.13) between the 1-km pixel AATSR and the 30-m Landsat ETM+ data. When the AATSR was compared with ground ET observations, there was also an error margin of ~2.0 mm day^{-1}, which was somewhat similar to previous findings by [5, 7]. The observed differences may be explained in two ways: (1) differences in sensor calibration; and (2) spatial mismatch between satellite and ground observations. Indeed, there are no easy and accurate methods for comparing satellite measurements with ground information. Also, ground-based temperatures and satellite radiometric temperatures are not the same and may only be compared for the sake of practicality [18].

CONCLUSION

Although the AATSR was originally designed to measure sea surface temperature, hence, not well calibrated over land targets, its initial estimates of ET and other energy balance parameters over the Volta basin in Ghana are quite promising. In this context, the spatial correlation between AATSR L1B and Landsat ETM+ was found to be poor (R^2 = 0.13), however, this may be explained by differences in sensor calibration. Further work needs to done using the improved AATSR L2 product to see whether the current results could be improved.

Acknowledgements

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