RADIOMÉTRIE DES FONDS TERRESTRES DANS LES BANDES [3-5µm] ET [8-13 µm]: MISE EN ŒUVRE, IMPACT DE L'HÉTÉROGÉNÉITÉ , POSSIBILITÉS

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RESUME – Ce travail aborde les problèmes de la radiométrie IR dans la bande [3-5 µm] conjuguée à la bande [8-13µm] et des méthodes permettant de remonter aux propriétés thermo-optiques des fonds terrestres (émissivité, réflectivité bidirectionnelle). En plus de la difficulté théorique due au caractère « mal posé » du problème, la définition, même des grandeurs et la manipulation précise des quantités radiométriques induisent de très sérieuses difficultés , notamment si les instruments sont à bandes larges. Une simple inversion des relations radiométriques a peu de chance de conduire à des résultats précis, mais peut donner un ordre de grandeur. Des méthodes plus élaborées utilisant des contraintes est une voie qu'il apparaît nécessaire d'explorer.

ABSTRACT- *This work aims at addressing problems in IR band [3-5 µm] together with band [8-14 µm]and in methods allowing for retrieval of radiative properties (emissivity, bidirectional reflectivity) of terrestrial surfaces. Beside the theoretical difficulty of this "ill-defined" type of problem, the very definition of variables and accurate usage of radiometric quantities induce severe difficulties, particularly in case of broad band instruments. Simple inversion of radiometric equations is highly unstable and cannot give but at best a rough estimate. More sophisticated methods based in constraints imposed to the system's variables represent a way that is worth exploring.*

1. Introduction

Whereas infrared remote sensing or field radiometry can be performed in any of the [8-13µm] TIR or [3-5µm] MIR windows, the former has been used much more widely for remote access to surface temperature. (NB: in the following, if not otherwise specified, the TIR – resp. MIR bands will be noted band III –resp. band II). One reason for less frequent usage of band II resides in much more difficult interpretation of the signal that, besides the surface emitted and surface reflected down-welling atmospheric radiance, includes an additional reflected direct solar illumination contribution. This additional information has however, been exploited in algorithms for coarse resolution sensors (e.g. AVHRR/2 and TERRA/MODIS) [Wan 97], [Nerr 98]. New space missions such as DLR/ESA BIRD & FOCUS [Jahn 96] with both bands II & III, general trend to higher spatial resolution IR imaging sensors, foster increased efforts toward retrieving and exploiting the spectral and directional information conveyed by band II. The present fieldwork has been initiated in order to experimentally explore various ways through which to retrieve the band

II surface parameters (essentially emissivity / bi-directional reflectivity), evaluate and compare their performance and implementation possibilities.

2. Radiometric equations

The issue addressed here is short range quantitative field radiometry with emphasis on the use of IR cameras.
Let us start with band III. The measured radiance R_{III} from a given homogeneous target writes

$$R_{III} = \int_{III} \varepsilon(\theta_v,\lambda) B^0_\lambda(T_s) f_{III}(\lambda) d\lambda + \int_{2\pi} d\omega' \int_{III} \rho_{b,\lambda}(\theta',\theta_v) R_{atm\downarrow,\lambda}(\theta') \cos\theta' \, f_{III}(\lambda) d\lambda \qquad (1)$$

The first term is the radiance emitted by the target with surface temperature Ts, spectral emissivity ε; the second term is the atmospheric down-welling radiance reflected by the surface with bi-directional spectral reflectivity ρ_b. $f(\lambda)$ is the filter function of the instrument pointing in direction θ_v. (NB: in the following, θ_v will be taken equal to zero – nadir viewing). As it is, eq.(1) is practical neither for calibration nor for interpretation. It can be transformed with the use of averaged or spectrally integrated quantities, e.g. instrument brightness temperature T_{III}, defined through

$$R_{III} = \int_{III} B^0_\lambda(T_{III}) f(\lambda) d\lambda \equiv B^0_{\bar\lambda(T_{III})}(T_{III}) \int_{III} f(\lambda) d\lambda \equiv B^0_{\bar\lambda(T_{III})}(T_{III}) \Delta\lambda \qquad (2)$$

$\Delta\lambda$ is the effective bandwidth of the instrument. $B^0_{\bar\lambda(T_{III})}(T_{III})$ is the spectral BB radiance at a wavelength $\bar\lambda(T_{III})$. As long as the bandwidth is not small $\bar\lambda(T)$ is not a constant wavelength but depends on temperature and thus also on the equivalent spectral radiance $\int_{III} B^0_\lambda(T) \bar f(\lambda) d\lambda$ where $\bar f(\lambda) = f(\lambda)/\Delta\lambda$. Given the filter function, relationships $\bar\lambda(T)$ and $\bar\lambda(B^0_{\bar\lambda}(T))$ must be carefully worked out. Both are necessary for practical handling of the radiometric quantities and equations. Similar definitions occur for band II.
Consider the first term of the rhs of eq. (1): assuming a measured temperature T_{III}, it can be written

$$\Delta\lambda B^0_{\bar\lambda}(T_{III}) = \int_{III} \varepsilon(\theta_v,\lambda) B^0_\lambda(T_s) f(\lambda) d\lambda \equiv \bar\varepsilon \int_{III} B^0_\lambda(T_s) f(\lambda) d\lambda \qquad (3)$$

that defines the averaged emissivity. Since this quantity depends on temperature through the BB function, it is not intrinsic target quantity and not best appropriate if determination of the target's characteristics is the searched objective. The effective band emissivity is thus defined as $\varepsilon_{III} = \int_{III} \varepsilon(\lambda) \bar f(\lambda) d\lambda$ that anyhow is instrument dependent. Eq. (3), the measured radiance, is now

$$\Delta\lambda B^0_{\bar\lambda}(T_{III}) \equiv \varepsilon_{III} \int_{III} B^0_\lambda(T'_s) f(\lambda) d\lambda \equiv \varepsilon_{III} B^0_{\bar\lambda(T'_s)} \Delta\lambda \qquad (4)$$

This means that with a wide band instrument, the spectral behavior of the target combined with the instrument transfer function has an impact on the retrieved value of either the surface temperature or the integrated emissivity [Beck 95].
Regarding the second term of the rhs of eq. (1), a similar procedure is applied. The further simplification was made that for this term Lambertian behavior of the target is here assumed an acceptable approximation. Eq. (1) now writes:

$$B^0_{\bar\lambda}(T_{III}) \cong \varepsilon_{III} B^0_{\bar\lambda(T'_s)}(T_{s'}) + (1-\varepsilon_{III}) R_{atm\downarrow,III} \qquad (5)$$

$$\text{with } R_{atm\downarrow,III} = (1/\pi) \int_{III} \bar f(\lambda) d\lambda \int_{2\pi} R_{atm\downarrow,\lambda}(\theta') \cos\theta' d\omega'$$

Note that in eq. (5) and (6) all quantities have dimension of spectral radiance [Wm-2 sr-1µm-1].

The radiometric equation for band II is similar to that of band III, but for band index interchanged and, at daytime, the additional solar reflected contribution:

$$B^0_{\bar{\lambda}}(T_{II}) \cong \varepsilon_{II} B^0_{\bar{\lambda}(T_s')}(T_s) + (1-\varepsilon_{II})R_{atm\downarrow,II} + \rho_{b,II}(\theta_s,0)E_{sun}(\theta_s) \qquad (6)$$

The atmospheric transmission from Sun to Earth has been included in the definition of solar irradiance; the solar sky radiation is included in the down-welling atmospheric contribution. These equations do not incorporate any contribution from nearby objects, nor radiation effects of the thin air layer between target and sensor. A further complication arises if the sensor bandwidth includes the CO2 absorption band around 4.3 µm. This is not the case with, for instance, AVHRR band 3 but is encountered with most band II cameras including the one used in this work. Hence, the camera transfer function must include the notch filter produced by CO2 absorption.

The priority objectives of the campaigns were the exploitation of band II measurements, alone or in association with band III. Focus was on emissivity and bi-directional reflectivity, not on surface temperature retrieval.

3. Field campaigns

Two campaigns have been organized in France: one at the Colmar/INRA site in the framework of the ESA funded DAISEX'99 experiment, one in year 2000 at the ONERA/Fauga-Mauzac PIRENNE* facilities.

The measurements reported below pertain to the latter that took place during the period 15 to 29 June 2000. Main instruments deployed include a band III matrix camera [Inframetrics 760] and a band II matrix camera [Inframetrics SC1000]. Both cameras were installed on a platform 6m high and pointed to a compound scene on ground approximately 2m x 1.6m. The artificial scene included various targets: Fontainebleau , beach and river sands, agricultural soil, brick and concrete materials, SiC (120µm) powder, water body with temperature probes, diffuse reflector (flame-sprayed aluminum, equipped with surface temperature probe) and two black bodies for reference temperatures. Data discussed are for June 26-27 [very fine weather, no clouds, maximum global incident radiation 1050±50 W.m-2; atmospheric profiles from radio-soundings, total PW 2.45 ± 0.35 g.cm-2].

Prior to campaigns all IR instruments were calibrated against a reference black body; calibration was checked again after the campaigns.

4. Exploitation of the campaigns

A lesson learned from the preliminary 1999'campaign is that unless accurate co-registration of band II & III measurements is achieved, highly inconsistent results may occur. This is due to the radiometric heterogeneity of the surface that is always present, often quite high (> 10°)

For the 2000' campaign, measurements now come from IR cameras and co-registered band II & band III images. Both cameras are wide band instruments, which filter functions are given in fig. 1

a) experimental determination of E_{sun}: the scene includes a reference diffuse reflector (aluminum) that was independently characterized (reflectivity spectral signature, BRDF): fig. 2 shows its BRDF $\rho_b(\theta_s,0)$ in band II. Sun / shadow measurements provide a direct determination of $E_{sun}(\theta_s)$ that is compared to the MODTRAN [Knei 96] calculated quantity (fig. 3). Field determination of sun irradiance thus appears feasible.

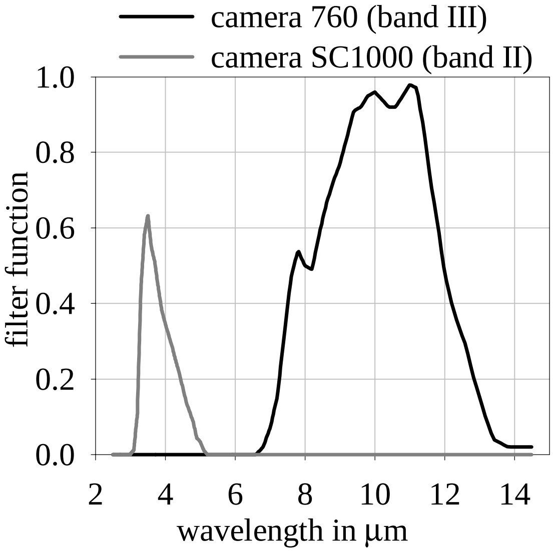

Figure 1: Spectral responses of Cameras

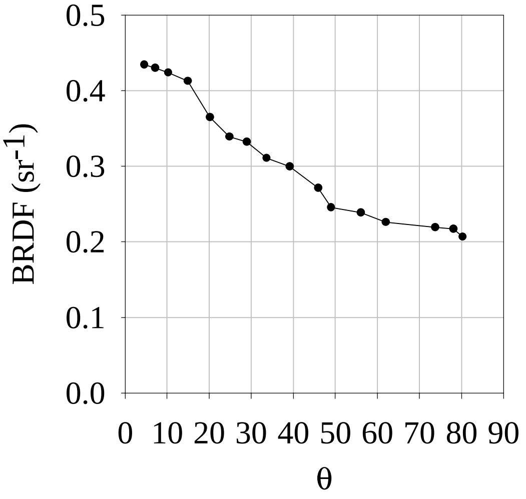

Figure 2: BRDF of reference diffuse reflector

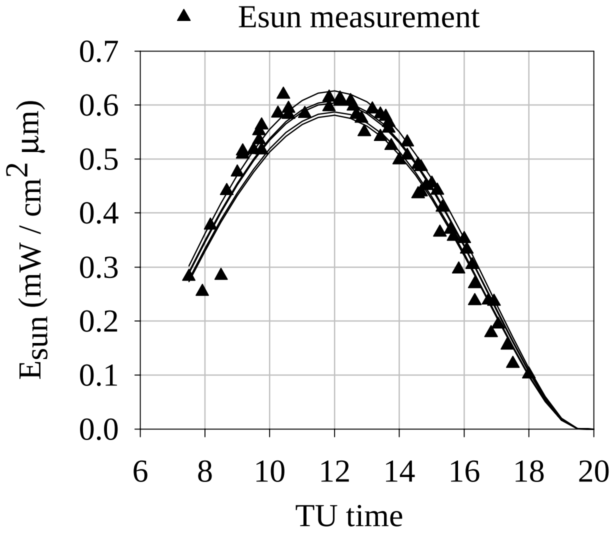

Figure 3: Sun irradiance in band II Measured and modeled

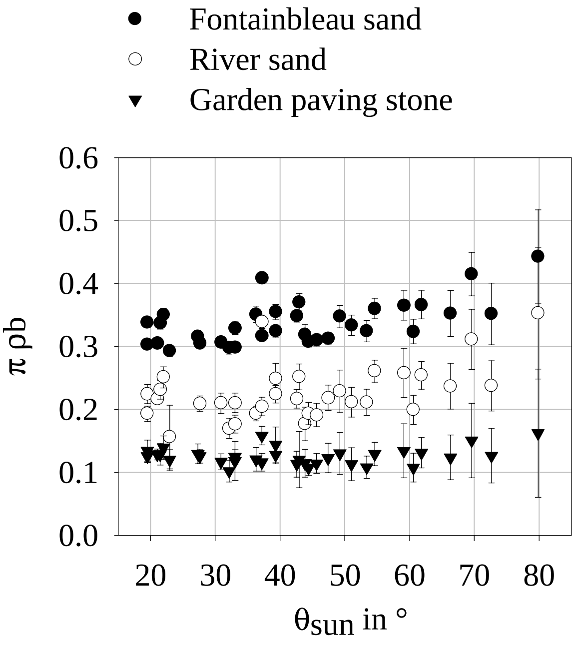

Figure 4: Examples of bi-directional reflectivities

b) bi-directional reflectivity of targets: with $E_{sun}(\theta_s)$ determined as in 4a), $\rho_{b,II}(\theta_s,0)$ is measured for all targets composing the scene (fig 4). Note that simultaneous imaging in band III allows checking for no change in surface temperature (or correcting for small change if necessary).

c) simultaneous band II & III measurements: this is not, strictly speaking, a way to solve for the underdetermined radiometry problem. It is however found informative for practical implementation of band II field radiometry. Simplest elementary approach is direct inversion of eq. (6) (assuming Lambertian behavior). $E_{sun}(\theta_s)$ and $R_{atm\downarrow}$ are measured and calculated as above, and the surface temperature is assumed given from inverting band III measurement corrected for emissivity and atmosphere. Tentative implementation was found exceedingly unstable and thus inapplicable. This is entirely due to the numerical values taken by the radiance terms of eq. (6) that resulted from the actual conditions of measurements ($E_{sun}(\theta_s)$, $R_{atm\downarrow}$, surface temperature).

Figure (5) illustrates another way to look at the problem: now are represented the surface temperature extracted from band III measurements (corrected for emissivity and atmosphere) against the surface temperature deduced from eq. (6) where the quantities are measured or known and band II emissivity given its value (from spectral signature). One can see that statistically the scatter is well along the first diagonal; maximum deviation is up to ± 5 K (rms = 2.3 K), a figure that is not unrealistic in view of all the sources or errors that may add up. Closer look to the data reveals a systematic deviation as a function of sun zenith angle. This deviation is being evaluated, yet unexplained since it may have different origins (target, atmosphere, measurement technique,..).

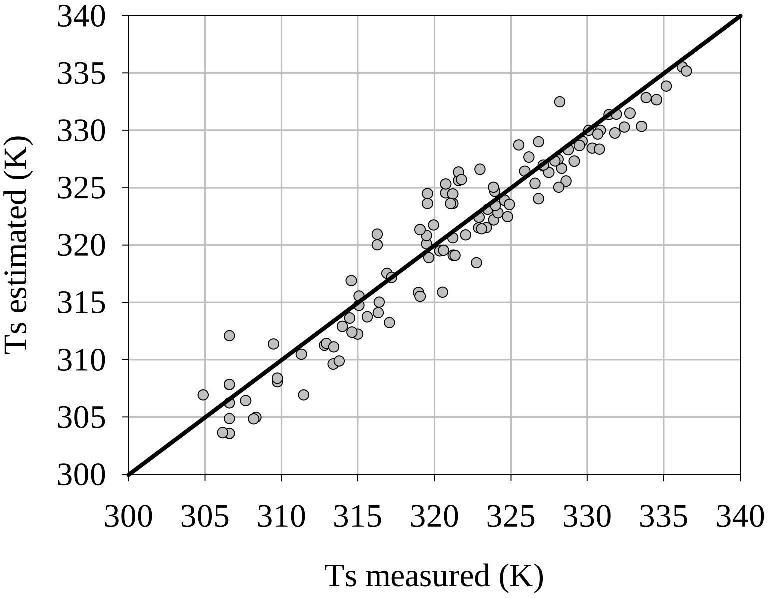

Figure 5: Ts estimated from band II in function of Ts retrieved from band III

5. Discussion and attempts to using more subtle methods

In spite of its theoretical limitations (ill-defined problem) and practical limitations in term of accuracy attainable when applied to objects in natural scene context, simultaneous usage of band II& III images provides additional information on the characteristics of the target. With simple method, as above, much better result is unlikely since it would require too high an accuracy of the estimate of surface temperature, as well as on E_{sun} and to a lesser extent atmospheric quantities. Other ways to explore should make use of constraints imposed on the retrieval procedure.

One such way is the TISI [Beck 90] method, built-up so as to get rid of the surface temperature, where the constraint is on band emissivity ratio assumed a constant. The drawback is the necessity to combine day / night data. It still remains verifying that TISI method can safely been applied with broad band instruments such as those used here.

Another approach would rely on retrieving the correct time variation of the measured at-sensor band II and band III radiance over day-time, with constraint imposed on surface temperature estimate provided by band III data, and possibly some constraint on the target emissivity. Test of such an approach is planned.

6. Conclusion

IR radiometry is known to be intrinsically very difficult if accurate quantitative results are to be expected. Day-time band II radiometry is even more complex due to intervening effect of Sun irradiation and further complicated if atmospheric CO2 absorption band comes into play. Combination of band II & III should nevertheless have increased potential provided it is very carefully implemented with appropriate sensors: i) spatial co-registration is critical, best achieved with imaging sensors; ii) sensors should use as much as possible sufficiently narrow bands, in order to avoid extremely cumbersome and tricky handling of the measured radiance in case of non BB targets; iii) band II sensor should not include the CO2 absorption band; iv) complex retrieval methods that make use of time dependence and constraints imposed appear necessary to get correct result; v) best approach is still not clear and anyhow would certainly be sensor / case dependent. Progress in this domain aims at improved interpretation of IR band II imagery and improved evaluation of the “at sensor” signal.

7. References

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*PIRRENE: Programme Interdisciplinaire de Recherches en Radiométrie en Environnement Extérieur.