RADIOMETRIC NORMALIZATION OF A SPOT 4 AND SPOT 5 TIME SERIES OF IMAGES (ISLE-REUNION) FOR AGRICULTURE APPLICATIONS

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Commission VI, WG I/1, I/2, I/6

KEY WORDS: radiometric calibration, SPOT, time series, atmospheric correction

ABSTRACT:

Series of satellite images acquired with high spatial and temporal resolutions provide a potentially ideal source for agriculture monitoring. For a quantitative use of these data, radiometric normalization is necessary. In this study, results from a normalization method based on invariant targets were compared to results obtained using an atmospheric model. Both methods were tested on a SPOT time series belonging to the ISLE-Reunion database (CNES). The invariant method consists in isolating points of the image with constant reflectance through time and to establish calibration equations between a reference date and the other dates. The atmospheric correction method was performed with SMAC model and AERONET atmospheric data. Other factors of correction were also compared: terrain slope, radiometric calibration coefficients, and environment when atmospheric corrections were applied. Results showed that among these factors the atmospheric effects are from far the most important, resulting to a median increase of NDVI of *ca.* 0.09. Invariant target based method led to an increase of NDVI value of *ca.* 0.03, but this value is linked to the choice of the reference date. Therefore, the comparison has to be performed in evaluating the relative variations of NDVI from one date to another in the satellite time series. Both methods showed differences that could be significant in the calculation of phenological or production indicators, such as the date of maximum NDVI or the NDVI time integral.

RÉSUMÉ:

Les séries d'images acquises à hautes résolutions spatiale et temporelle sont une source de données importante pour les applications agricoles. Pour une utilisation quantitative de ces données, l'étape de normalisation radiométrique est indispensable. Dans ce travail, une méthode de normalisation à partir de points invariants a été comparée à des corrections atmosphériques sur une série d'images SPOT issues de la base de données ISLE-Réunion (CNES). La méthode des invariants consiste à isoler des points de l'image ayant une réflectance constante au cours du temps et à établir grâce à ces points des droites de calibration entre une date de référence et les autres dates. Les corrections atmosphériques ont été effectuées avec le modèle SMAC et des données atmosphériques d'AERONET. D'autres facteurs intervenant dans la correction des images ont également été étudiés : la pente du terrain, les coefficients d'étalonnage radiométrique et l'environnement dans le cas où une correction atmosphérique est effectuée. Les résultats montrent que les effets de l'atmosphère sont les plus importants, conduisant à des augmentations de NDVI d'environ 0.09. La correction basée sur les points invariants se traduit par une augmentation d'environ 0.03 du NDVI, mais cette valeur est liée au choix de la date de référence. Par conséquent, la comparaison doit être effectuée en calculant les variations relatives du NDVI d'une date à l'autre. Les deux méthodes montrent des différences qui pourraient être significatives lors du calcul d'indicateurs phénologiques ou de production tels que la date du maximum de NDVI ou son intégrale dans le temps.

1. INTRODUCTION

Time series of remotely sensed imagery acquired with high spatial resolution provide a potentially ideal source for agriculture monitoring. Among satellites offering this kind of data are SPOT 4 and SPOT 5. Their images have a spatial resolution of 20 m and 10 m respectively in multispectral mode, which is adequate for growth anomalies detection, yield prediction, and trend analysis.

However, before treating a time series of satellite-derived data, the images must first be normalized radiometrically in order to make them comparable. In fact, radiometric values of images are affected by different factors: atmosphere components, variation of sun illumination due to the topography, sensor calibration, and viewing geometry. Normalizing imagery to account for these effects attempts to reduce the non-land cover induced radiometric variation between temporally separate images. Corrections can be made in an absolute or a relative manner. The first necessitates an atmospheric correction model and *in situ* measurements of atmosphere constituents to be done simultaneously with image acquisition, whereas the second does not require data other than the images themselves.

In this paper, we apply different approaches of radiometric correction to a time series of images acquired by SPOT4 and SPOT5 on Reunion Island. First, absolute radiometric corrections are made, and the effect of calibration coefficient, topography, and atmospheric correction are studied. Then relative corrections are done using the invariant targets method. Results of the relative and absolute correction are compared.

2. DATABASE

The data set used in this study consisted of twenty three SPOT4 and SPOT5 images acquired on Reunion Island between June 2002 and June 2005 (cf. table.1). These images come from the “ISLE REUNION” database which is part of the CNES Kalideos Program aiming to provide to research temporal series of optical and radar satellite images, with the highest possible quality level and with exogenous and ground truth data (de Boissezon and Sand, 2006).

Reunion Island (north-east of Madagascar) is a small territory (*ca.* 60 × 70 km^2), with a very varied landscape, strong agricultural activities on hilly land. The ISLE REUNION database is currently in process of development, so data are not processed, as they should be in the future. All the treatments presented here are then applied to SPOT4 and SPOT5 images acquired in level 1a.

Concerning atmospheric data, 7 dates of measurements, from December 2003 to October 2004 were available from the AErosol RObotic NETwork (AERONET), see Table 1. The data provided are atmospheric optical thickness at 550 nm (τ_{550}) and water vapor content measured at S^t Denis (North Reunion).

For all images, view angle is comprised between -26° and +26°, which does not induce high directional effects (no hot-spot configuration, see Table1); the targets are then assumed to be lambertian.

A digital elevation model (10 m resolution) was available (slopes between 0° and 15° on the area of interest).

					Atmospheric data	
Date	Satellite	Incidence angle °	Solar elevation °	Phase angle °	τ_{550}	H_2O_{atm} (g cm^{-2})
06/12/02	SPOT4	3.20	39,20	52,00	–	–
08/08/02	SPOT4	10.70	44,30	51,30	–	–
08/14/02	SPOT4	-19.20	43.60	39.10	–	–
09/09/02	SPOT4	-19.20	51.60	29.80	–	–
10/09/02	SPOT4	24.80	65.70	45.40	–	–
01/10/03	SPOT5	-4.65	64.10	21.30	–	–
02/26/03	SPOT5	-11.90	58.50	22.10	–	–
03/25/03	SPOT4	3.60	55.10	37.50	–	–
04/26/03	SPOT4	-26.30	45.40	36.70	–	–
05/04/03	SPOT5	10.90	46.70	48.10	–	–
06/17/03	SPOT4	-26.20	37.00	46.90	–	–
08/21/03	SPOT5	18.20	48.80	51.20	–	–
12/19/03	SPOT5	-2.90	67.25	19.80	0.05	3.31
03/17/04	SPOT5	-19.10	54.39	25.00	0.059	2.77
05/13/04	SPOT5	-11.83	42.79	43.90	0.056	1.85
06/18/04	SPOT5	3.25	38.97	52.10	0.023	2.43
08/19/04	SPOT5	17.96	48.44	51.30	0.042	1.76
09/11/04	SPOT4	-12.00	53.70	34.50	0.079	2.93
10/26/04	SPOT5	3.30	68.00	24.90	0.087	3.53
12/07/04	SPOT5	-12.30	66.65	11.20	–	–
01/12/05	SPOT5	3.40	64.54	28.80	–	–
03/10/05	SPOT5	10.67	58.84	39.80	–	–
06/06/05	SPOT5	25.00	41.30	59.30	–	–

Table1. Characteristics of the image data base (Source BD ISLE REUNION/CNES) and available atmospheric data (Source AERONET; http://aeronet.gsfc.nasa.gov/).

3. NORMALIZATION OF A TIME SERIES OF SPOT IMAGES

In this section, the effects of various factors on reflectance and on vegetation index values (NDVI) are illustrated:

- effect of calibration coefficients;
- effect of surface slope and aspect;
- effect of atmospheric correction (with or without influence of the environment).

To study these effects, we worked on a cropped area, close to the AERONET measurements site (North Reunion). We extracted the digital counts of the pixels of 108 fields, computed the different corrections and calculated the mean value for each field.

The effects are evaluated on reflectances in SPOT bands (green G, red R, near infrared NIR and shortwave infrared SWIR) and on NDVI values:

$$NDVI = \frac{\rho(NIR) - \rho(R)}{\rho(NIR) + \rho(R)} \quad (1)$$

3.1 Method

3.1.1 Calibration coefficients. The following equation is used to convert digital counts into reflectances:

$$\rho = \frac{D_c \cdot \pi}{G \cdot \cos(\theta_S) \cdot E_S} \quad (2)$$

where ρ is the TOA (Top Of Atmosphere) reflectance, D_c is the digital count, G is the sensor absolute calibration gain, θ_S is the solar zenith angle and E_S is the solar radiation in the appropriate wavelength. The values of G are calculated thanks to calibration coefficients. Two sets of coefficients were available: the first one was provided by Spot Image before November 2004 and the other one consisted in updated values taking into account sensor drift (provided by CNES). It was interesting to measure the impact of this update on radiance values.

3.1.2 Surface slope and aspect. In equation (2), the calculation of reflectance does not take into account the effect of the surface slope and aspect. In regions such as Reunion Island where slopes can be very steep, this effect has to be considered. Then it is interesting to quantify the error made when this parameter is neglected (or when no digital elevation model is available). When taking into account effects of surface slope, cos(θ_S) in equation (2) is replaced by:

$$\beta_S = \cos(\theta_S) \cdot \cos(\theta_n) + \sin(\theta_S) \cdot \sin(\theta_n) \cdot \cos(\varphi_S - \varphi_n) \quad (3)$$

where θ_n is the surface zenith angle (slope), φ_S is the solar azimuth angle and φ_n the surface azimuth angle (aspect).

Surface slope has also to be introduced in atmospheric correction.

3.1.3 Atmospheric correction. It is an old and currently addressed issue and many codes for atmospheric correction exist: we can quote Lowtran 6 (Kneizys *et al.*, 1988), Turner and Spencer's model (Turner and Spencer, 1972), 5S (Tanré *et al.*, 1990) and 6S (Vermote *et al.*, 1997). The SMAC code (Rahman and Dedieu, 1994) is a simplified and operational version of 5S code. It does not pretend to reach the high precision of more complex codes but it is faster. The major issue of these codes is to retrieve the TOC (Top Of Canopy) reflectance from the TOA reflectance derived from radiance measured by sensors. The main factors inducing a modification of reflectance by the atmosphere are: the view and solar angles (influencing the thickness of atmosphere), the atmosphere composition (optical thickness assessed by τ_{550}, air water content, atmospheric pressure, ozone content…), the target slope and its environment. The SMAC model was implemented for the 7 dates for which data on atmospheric optical depth and water content were available from AERONET (level 1.5).
The effect of environment was also quantified: first, the TOC reflectance was estimated independently of the environment. Then, for each pixel, we calculated the reflectance of its environment according to the first run. In a second step, we used as input of SMAC the environment reflectance to estimate its effect on the reflectance of pixels. This is not mathematically correct, but it is more straightforward.
The effect of slope was also introduced in SMAC by using a correction coefficient proposed by Richter (1997) to calculate the diffuse lightning of the target:

$$C = e^{-\tau/\mu_s} \cdot \beta_s + \cos^2\left(\frac{\theta_n}{2}\right) - e^{-\tau/\mu_s} \cdot \mu_s \cdot \cos^2\left(\frac{\theta_n}{2}\right) \qquad (3)$$

where $\mu_s = \cos(\theta_s)$ and τ is the atmosphere optical thickness at 550 nm.

3.2 Effects of several correcting factors

In next sections, results will be shown thanks to boxplots. In these figures, box has lines at the lower quartile, median, and upper quartile values. Other values are figured by dots.

3.2.1 Effects of coefficients and of surface slope. Figures 2 and 3 show the effect of coefficients set and surface slope on near infra-red reflectance values and NDVI values respectively calculated for pixels of 108 fields at the 23 dates of acquisitions. The coefficients values have a little impact on near-infra red reflectance values, with a difference of 0.01 at the median: this effect is significant at 0.05 confidence level. Coefficients values have also an effect on the first band (not shown). Slope, nonetheless, have no significant effect on reflectance. By construction, the NDVI is not influenced by slope. It is indeed one of the advantages of this index: indeed, since β_s (see eq. 1, 2 and 3) is not a function of wavelength, β_s disappears when NDVI is calculated. Furthermore, NDVI is not affected by coefficient values.

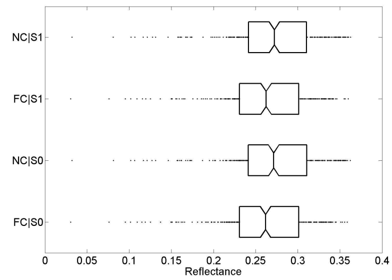

Figure 2. Effect of coefficient set (NC: new coefficients; FC: former coefficients) and of slope (S1: slope effect considered; S0: slope effect neglected) on near infra-red reflectance values.

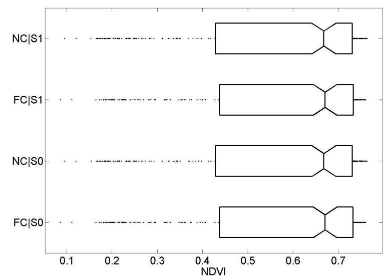

Figure 3. Effect of coefficient set (NC: new coefficients; FC: former coefficients) and of slope (S1: slope effect considered; S0: slope effect neglected) on NDVI values.

3.2.2 Effect of atmospheric correction. Figures 4 and 5 illustrate the effect of atmospheric corrections versus effect of slope and calibration coefficients. The data concern the 108 fields but this time only for the 7 dates for which input data necessary for SMAC were available. Atmospheric corrections made by SMAC have a noticeable effect on reflectances and on NDVI values (the differences between the medians of corrected and non corrected values are about *ca.* –0.017; –0.004; 0.09; 0.030 and 0.088 for Green, Red, NIR, SWIR spectral bands and NDVI respectively). In red band, atmospheric correction has no significant effect (0.05 confidence level). Differences are more important in Green and NIR bands than in SWIR. Comparatively, the influence of other parameters (slope and coefficients) is largely smaller, even if the effect of radiometric coefficients is still visible (significantly different in Green band).

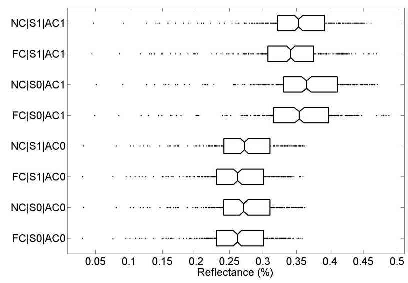

Figure 4. Effect of atmospheric correction (AC1: correction by SMAC; AC0: no correction), coefficient set (NC: new coefficients; FC: former coefficients) and of slope (S1: slope effect considered; S0: slope effect neglected) on near infra-red reflectance values.

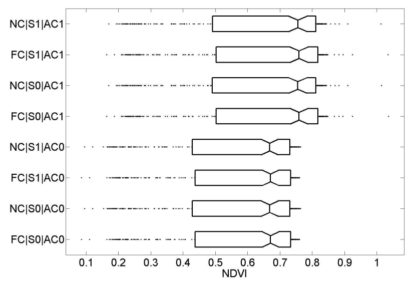

Figure 5. Effect of atmospheric correction (AC1: correction by SMAC; AC0: no correction), coefficient set (NC: new coefficients; FC: former coefficients) and of slope (S1: slope effect considered; S0: slope effect neglected) on NDVI values.

For NDVI, the most influent factor is from far the atmospheric correction. Slope and coefficients values still do not have effect on NDVI values.

Figure 6 shows the influence of environment when an atmospheric correction is applied. Coefficients values and environment are significantly influent only in Green and NIR. NDVI is not affected by any of these factors.

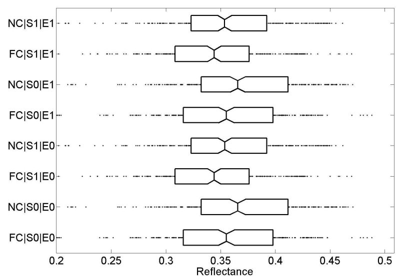

Figure 6. Effect of coefficient set (NC: new coefficients; FC: former coefficients), slope (S1: slope effect considered; S0: slope effect neglected) and of environment (E1: environment considered; E0: no environment considered) when atmospheric correction is applied on near infra-red reflectance values.

To summarize this part, atmosphere effect is the most important factor. Effect of calibration coefficients (former and update set) is the second influent parameter, and then come the environment and, lastly, the slope. We can assume that stronger values of slope would lead to a greater influence of this factor.

4. CORRECTION BASED ON INVARIANT TARGETS

An alternative to absolute radiometric correction is relative “correction”. Several methods have been proposed (Schott et al. 1988, Hall et al. 1991, Moran et al. 1992, Furbyand Campbell 2001, Du et al. 2002). They proceed under the assumption that the relationship between the TOA radiances recorded at two different times from regions of constant reflectance is spatially homogeneous and can be approximated by linear functions. The normalization of our time series of images was carried out by a method of correction based on invariant targets. This technique attempts to uniformly minimize effects of changing atmospheric and solar conditions relative to a reference image selected by the user.

4.1 Method

4.1.1 Selection of reference image. The reference image is the scene to which the other scenes are related. It is important that it be cloud and haze free, and captured with a small incidence angle. The reference image chosen for our normalization procedure is the one acquired in 12 June 2002; it is almost released from clouds and it is captured with an incidence angle of 3.2°.

4.1.2 Selection of Invariant Targets. Invariant targets are features which have constant reflectance over time. These reflectance values are used to define linear functions that will be applied to transform each overpass image to a normalized image. An invariant target should be homogenous and its size must be sufficient to compensate for errors of registration. Moreover, reflectance values of selected invariant targets must cover a large band. Examples of invariant targets are: large buildings, dense forest, volcanic lava, etc…

In our series of images, 46 invariant targets distributed on the whole island surface were selected. Among them, for each band and each overpass image, we kept the invariants which have almost stable values.

4.1.3 Calculation of regressions. After selecting invariant targets, linear regressions were established between overpass images and reference image for all reflectance bands and for NDVI. The slopes, intercepts and coefficients of determination of regressions calculated for Near-infrared and for NDVI are represented in Table 7. We notice that slope and intercept values in the Near-infrared vary in an erratic way; this is due to difference in the geometrical conditions of acquisitions and atmospheric conditions. Similar results were found for the other bands. A further important remark is that all NDVIs regressions are close to the first bisector (intercept values are almost zero, and slopes are near to one) which shows that this index requires few correction. Numbers of invariant targets used to establish regressions in Near-infrared band and NDVI are also mentionned.

	NIR regressions				NDVI regressions			
Date	a	b	r^2	# Invariants	a	b	r^2	# Invariants
06/12/02	1,00	0,00	1,00	26	1,00	0,00	1,00	26
08/08/02	1,01	-0,33	0,99	27	1,00	0,02	0,99	20
08/14/02	0,95	-0,89	0,97	31	1,01	0,02	0,99	25
09/09/02	0,98	-2,05	0,97	31	1,02	0,02	0,97	23
10/09/02	0,95	-0,50	0,99	19	0,98	0,03	0,99	10
01/10/03	1,08	-2,14	0,99	16	1,09	0,00	0,99	11
02/26/03	1,20	-2,94	0,99	18	1,14	0,00	0,98	14
03/25/03	0,94	-0,33	0,95	20	1,11	-0,05	0,99	15
04/26/03	1,00	-1,27	0,97	21	1,12	-0,03	0,99	14
05/04/03	1,22	-1,82	0,94	20	1,15	-0,06	0,94	13
06/17/03	1,04	-1,96	0,96	29	1,05	-0,01	0,99	25
08/21/03	1,23	-1,96	0,97	9	1,14	0,00	0,99	8
12/19/03	1,18	-3,28	0,99	16	1,09	0,02	0,99	14
03/17/04	1,14	-3,43	0,99	14	1,08	-0,04	0,96	10
05/13/04	1,18	-0,79	0,96	27	1,01	0,00	0,99	21
06/18/04	1,23	-0,27	0,95	22	1,02	0,00	0,98	18
08/19/04	1,19	-1,04	0,97	14	1,08	0,01	0,99	9
09/11/04	1,00	-1,87	0,97	27	1,02	0,01	0,99	21
10/26/04	1,12	-1,36	0,95	22	1,04	0,02	0,99	17
12/07/04	0,98	-2,25	0,75	10	1,18	-0,01	0,99	8
01/12/05	1,08	-2,28	0,95	19	1,13	-0,01	0,97	14
03/10/05	1,08	0,30	0,93	17	1,04	-0,04	0,97	9
06/06/05	1,22	-0,46	0,97	22	1,07	-0,05	0,98	17

Table 7. Linear regressions coefficients calculated in the Near-infrared band and NDVI (06/12/02 is the reference image).

4.2 Results

4.2.1 Normalization. Linear regressions calculated in all bands and in NDVI are used to normalize the time series of 23 images. Figure 8 presents the effect of correction thanks to Invariant targets versus no correction for near infra-red band. An ANOVA proves that there is an effect of this correction on the median value. But, of course, the level of this difference between means is linked to the choice of the reference image. Figure 9 presents the same comparison for NDVI, and an ANOVA also indicates that the means are significantly different. We can furthermore notice that the level of modification is lower than that of SMAC.

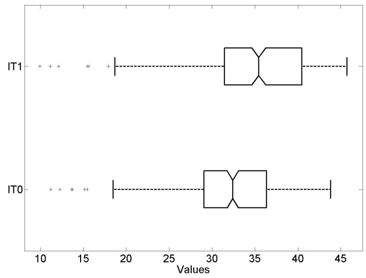

Figure 8. Effect of correction based on Invariant Targets (IT0: no correction; IT1: correction) on near infra-red reflectance values.

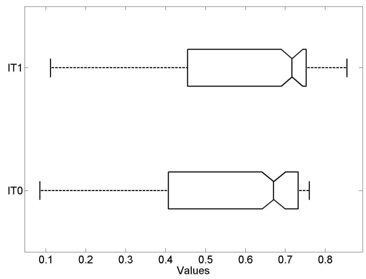

Figure 9. Effect of correction based on Invariant Targets (IT0: no correction; IT1: correction) on NDVI values.

4.2.2 Effects of sensor and view angle. In order to study the impact of satellite difference on invariant targets, we divided the series of images into two groups: images acquired by SPOT4, and the ones acquired by SPOT5. For each invariant, we calculated the average of the reflectances by satellite in each band and in the NDVI. Afterwards, we established regressions between SPOT4 and SPOT5. In Figure 10.a, we observed that the difference in the Near-infrared between SPOT4 and SPOT5 reflectance values of invariant targets was significant as far as these values are high. It was also the case in the other bands. For the NDVI, the satellite difference was not noticeable (c.f. Figure 10.b).

Furthermore, the effect of the difference in viewing angle was studied. We gathered the images according to two categories: those which have a viewing angle ranging between -5° and +5°, and those acquired with a view angle smaller than –10° or greater than +10°. Thanks to average values by invariants, regressions in all bands and in the NDVI were calculated; Figure 11 represents the result obtained in the red band (a) and in the NDVI (b). We noticed once again that the NDVI was not sensitive to the different acquisition conditions while the spectral reflectances were influenced.

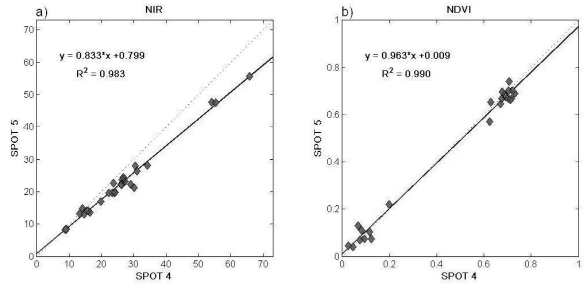

Figure 10. a) Mean reflectance values in NIR of invariant targets for SPOT 4 images versus SPOT5; b) Mean NDVI values of invariant targets for SPOT4 images versus SPOT5.

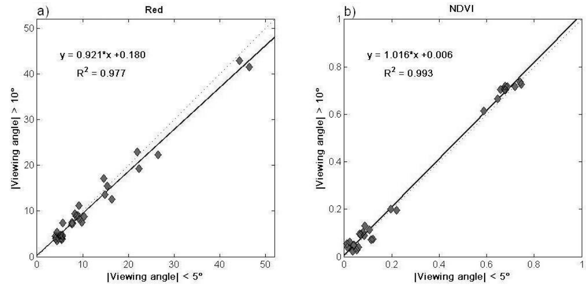

Figure 11. a) Mean reflectance values in red band of invariant targets for images with incidence angle comprised between –5°and +5° versus images with incidence angle greater than +10° and smaller than –10°; b) Same for NDVI.

5. COMPARISON OF BOTH METHODS

The objective was to determine whether the invariant targets based correction method was equivalent to a more reliable but more demanding method of correction. The problem is that no reference measure can be used in this study to formerly conclude. All that can be done is a sort of sensitivity analysis to see if both methods have a similar effect.

Figure 12 compares the evolution of NDVI for two fields, considering TOA values, values corrected by invariant target method or by SMAC. Obviously, SMAC introduces a bias and a small smoothing of the temporal profile in these examples. Invariant targets based correction maintains values at the same order of magnitude but smoothes the temporal profile in a greater extent.

The main purpose of the invariant based method is to cope with the atmospheric correction without the data necessary to implement codes as SMAC. It does not intend to correct images but only to normalize them. Thus, it is more relevant to compare the relative increase from a date to another one when comparing the results of both methods. Figure 13 figures out this comparison of NDVI slopes for all fields: SMAC vs. invariant targets correction and SMAC correction vs. no correction. Except a few points, both correction methods lead to a very comparable temporal evolution of NDVI. We can thus assume that IT based correction is a valuable alternative to more robust atmospheric corrections when the necessary data are not available, as long as the relative evolution of reflectance or indices have to be retrieved, and not the absolute values. Nonetheless, figure 13-b shows that the situation without correction is also close to SMAC output. Atmospheric correction may have a great impact in the case of specific time series, but not in all cases considered as a whole. The equivalent figures for the different bands (not shown) show that SMAC correction does not greatly modify the values of temporal slopes compared to TOA values, while IT correction does.

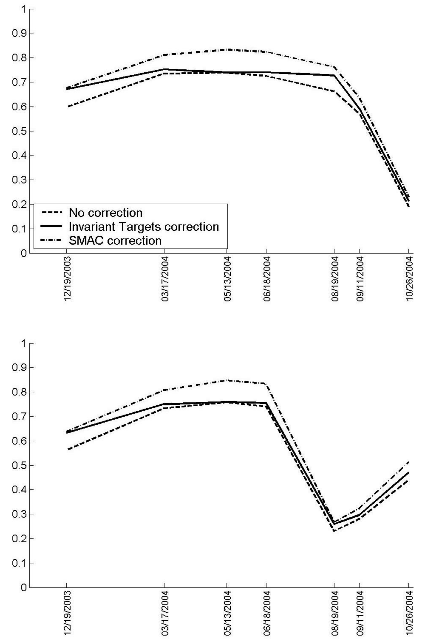

Figure 12. Examples of NDVI time series for two fields, without or with correction (Invariant targets or SMAC).

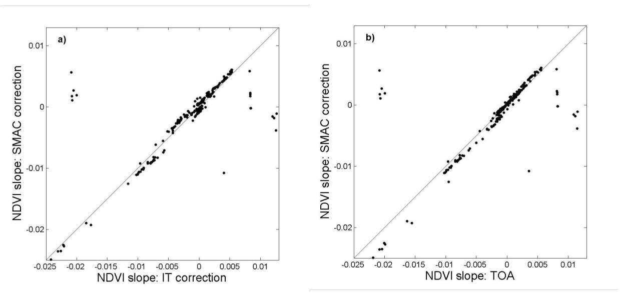

Figure 13. a) Comparison between NDVI slope values corrected by SMAC and those corrected by invariants targets method (7 dates, all fields). b) Comparison between NDVI slope values corrected by SMAC and those non-corrected values (7 dates, all fields).

6. CONCLUSIONS

In this paper, effects of atmospheric, terrain slope, radiometric coefficients, and environment corrections were studied. Radiometric corrections were realized in two different manners: absolute corrections thanks to the SMAC code, and relative corrections according to the invariant targets method.

The two methods were compared by evaluating the relative variations of NDVI from one date to another one in the satellite time series. Both correction methods showed differences that could be significant in the computation of phenological or production indicators, such as the date of the maximum NDVI or the NDVI time integral.

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ACKNOWLEDGEMENTS

Vianney Houlès and Mahmoud El Hajj are supported respectively by a CNES postdoctoral and a Cemagref-Région

Languedoc Roussillon Ph.D. fellowships. Special thanks to Hélène de Boissezon (CNES) for her work with the ISLE-Reunion database. We also thank Brent Holben, AERONET/PI for his effort in establishing the REUNION S^{t} Denis site.