On the stability of area quantifications and nomenclatures with respect to sensor resolution

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ABSTRACT

The quantification of a covered surface from satellite data is a current area of study in Remote Sensing. The computed area is generally considered as the *in situ* covered area, neglecting the role of the sensor's resolution. We apply some new general results to the particular cases of burnt areas and vegetation covered surfaces, when the latter are defined on the basis of classical indices NDVI, SAVI, TSAVI, for example. We show that the actual *in situ* covered area is within two bounds explicitly computable from satellite data. That allows us to approach the problem of nomenclatures in remote sensing.

1. INTRODUCTION

Quantification of the surface covered by an object is one of the most frequent applications of remote sensing. It is a common output of the automatic algorithms which compose a GIS. It is also necessary for the algorithms attached to the study of the dynamics and physics of our environment by remote sensing.

For example, we commonly want to know the areas covered by snow, water, seaweed, floes, vegetation, burnt areas etc. These areas are computed from satellite mono or multispectral data, at the resolution given by the sensors. The area which is obtained is considered as the actual *in situ* area which is always the effective quantity we need.

For want of something better, we take the "satellite area" as the *in situ* one. Doing so, we consider this value to be scale independent.

This paper concerns itself with the analysis of this behaviour. More precisely, we consider one given pixel Ω having a mono (or multi-) spectral radiometric value and we look at what can be said of the percentage of actual area within Ω covered by a "well-known" object.

We consider this problem in general terms but we apply the results to the two cases of burnt areas and vegetation covered ones. In these two cases, the results obtained take on a typical form.

In fact, the "well-known" objects are not so easy to define, even the very common ones mentioned above. Let's take the case of a NOAA.GAC (global area coverage of AVHRR) pixel classified as burnt. Each of them contains roughly 40,000 SPOT XS pixels. Are they all burnt? Section 2 defines that which can be called a "well-known" object. We state a definition of a "radiometric" or "remotely sensed" object.

In section 3, we illustrate the examples of burnt areas and vegetation in relation to some usual vegetation indices. These two examples respectively illustrate the cases of mono spectral and bi spectral measurements.

The main result is given in section 4. It solves the problem of the possible error which can be made when the so called satellite area is considered to be the actual *in situ* one. In other words it shows that a remotely sensed object cannot have the same definition at any scale. We approach the stability of nomenclatures with respect to change of scales in section 5. The result is based on theoretical results obtained in Raffy (1992, 1993).

2. THE COVERED AREAS

The recognition of anything is linked with measurement. If we are limited to radiometric measurements in given wavebands, the recognition is necessarily linked to the characteristics of the radiometer. Then, necessarily, the definition of anything viewed by a multispectral radiometer is dependant on the spatial (and spectral) resolution of the instrument.

This fundamental point shows that an object which is named "vegetation" or "burnt area" is not a priori scale independant. Indeed, a forest is made of vegetation, but within a 5 km x 5 km area (which corresponds to one Meteosat pixel) we find many clearings amongst the trees. A tree which covers for example one SPOT pixel is also a typical vegetation entity. Nevertheless, we have many spaces between the leaves. On a smaller scale of *in situ* radiometric measurements, a tuft of grass is considered as vegetation but what happens between the blades? The same observation can be made for any natural object which "covers" the Earth. The necessities of our everyday life requires us to standardize on names for the common objects within our environment, such as leaves, trees, houses, ground, puddles. These names are made possible by our common perception, *i.e.* measurements (generally visual) and therefore depend on the usual scale at which they are perceived, which is our "in-situ" human scale. These names which correspond to our common perception cannot, therefore, form part of the nomenclature that we apply automatically to radiometric measurements, and at various scales. For example, this is the reason for the great confusion concerning the forest administrative definitions in the various countries of the European Community (see Kleinn, 1992).

To conclude the previous discussion, we state:

a) An object viewed by a multispectral radiometer is characterized by one point or by one convex region in the radiometric domain.

b) At the scale of the previous measurement, we can associate a name to this point or this region (burnt, vegetation, water,...)

Let us comment on these two points.

The definition concerns only the recognition of a pixel from its measured spectral signature. It does not use complementary information extracted from its behaviour such as structure information.

Points a) and b) are indeed the usual basis of *in situ* construction of spectral signatures catalogues.

An object so defined is not necessarily homogeneous at the scale of the observation, since it can be characterized not only by one single point in the radiometric domain but by a convex (generally small) region.

Although points a) and b) are physically justified at a given scale, we will show that they cannot systematically hold at any scale. In other words, what is usually done is to define an object at the human *in situ* scale of say, one metre resolution, which corresponds to *in situ* experiments. This cannot be automatically applied to spatial recognition of the same object without inducing large errors.

More precisely, we show that if an object is radiometrically defined at a local scale, the area covered by this object at this scale may be very different from the area computed from space after recognition of the object with the same nomenclature. The results are illustrated on burnt and vegetation covered areas.

3. DEFINITIONS OF BURNT AREAS AND VEGETATION

The two cases of burnt surfaces and vegetation will illustrate respectively mono spectral and bi spectral measurements.

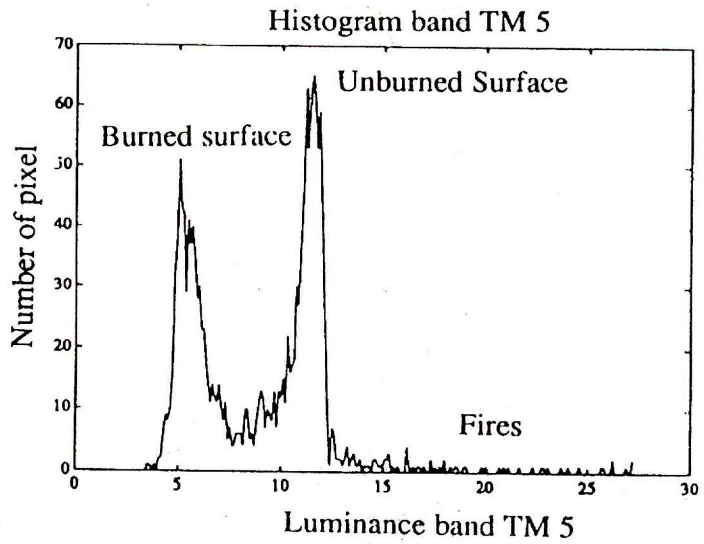
Burnt surfaces:

Following the definition stated previously, we use the experimental measurements of **Figure 1 (a)** to define a burnt area. These measurements have been made in the [1550, 1750] nm waveband. Although they are extracted from (Brustet *et al.*, 1991) with TM measurements in this waveband (Channel 5 of TM), we will consider them to be *in situ* measurements. This assumption will not affect the purpose, as will be clearly shown in the following. So, the domain of all possible radiances is $D = [a, b] = [4, 13]$ in and the characteristic radiometric region of burnt surface is obviously

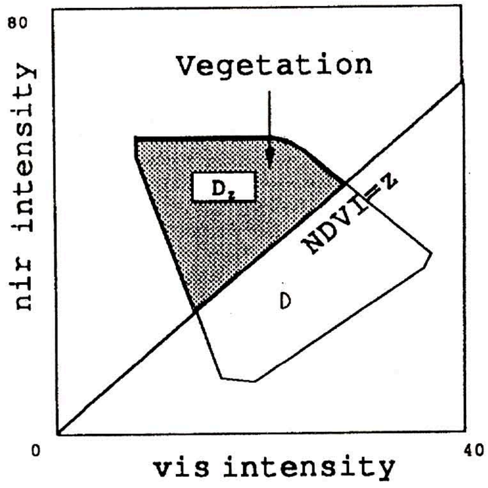
$$Dz = [a, z] = [4; 7.5] \quad (1)$$

It means that for any (microscopic) point ω of radiance $\ell(\omega)$, the recognition procedure for ω is:

$$\begin{array}{l} \text{If } \ell(\omega) \in Dz, \text{ then } \omega \text{ is burnt,} \\ \text{If } \ell(\omega) \in Dz, \text{ then } \omega \text{ is not burnt.} \end{array} \quad (2)$$



1 (a)



1 (b)

Figure 1 - a) The characterization (in the [1550, 1750] nm. waveband) of the radiometric domain of burnt regions, at the in situ resolution. The x-axis represents radiances, the y-axis, the number of pixel
b) The characterization of the radiometric domain of the vegetation is the domain D_z such that the NDVI satisfies NDVI(ℓ red (ω), ℓ nir (ω)) $\geq$ z for a well chosen threshold z at the in situ resolution

Remark: In the previous characterization we can replace the radiances by the corresponding reflectances without changing the sense of the discussion.

Vegetation covered surfaces:

Vegetation is characterized by radiometric measurements in the red and near infrared (nir) bands. The characteristic domain D_z (**Figure 1 (b)**) is defined by the domain of the two dimensional radiometric region D of all the possible values (ℓ red, ℓ nir) where the NDVI satisfies

$$\text{NDVI}(\ell\ \text{red}, \ell\ \text{nir}) \geq z \quad (3)$$

for a well chosen value z. Then, the same algorithm as in (2) applies to characterize vegetation. For a (microscopic) point ω where the measured radiances are $\ell_{red}(\omega)$, $\ell_{nir}(\omega)$

$$\begin{aligned} &\text{If } \ell(w) = \ell_{red}(\omega), \ell_{nir}(\omega)) \in D_z, \\ &\text{then } \omega \text{ is vegetation covered} \\ &\text{If } \ell(w) = \ell_{red}(\omega), \ell_{nir}(\omega)) \in D_z, \\ &\text{then } \omega \text{ is not vegetation covered} \end{aligned} \quad (4)$$

Again, the property of belonging to D_z is taken as a radiometric characterization of vegetation at a given resolution. **Figure 1 (b)** describes D and D_z, where the wavebands correspond to the SPOT XS channels.

Let us remark that since D_z is defined from the NDVI, then it is dependent upon this vegetation index. Other indices may lead to other domains (*i.e.* to other radiometric definitions of vegetation). For example, the RVI = $\frac{L_{nir}}{L_{red}}$ (Ratio V.I.), Pearson and Miller (1972), gives the same D_z as (2) when RVI $\geq (1 + z) / (1 - z)$, while it is easy to show that the other classical vegetation indices such as the SAVI (Soil Adjusted V.I.), Huete (1988), the TSAVI (Transformed SAVI), Baret and Guyot (1991), the DVI (Difference V.I.), Clevers (1986) and the PVI (Perpendicular V.I.), Richardson and Wiegand (1977), cannot give the same definition of vegetation as (3) by thresholding.

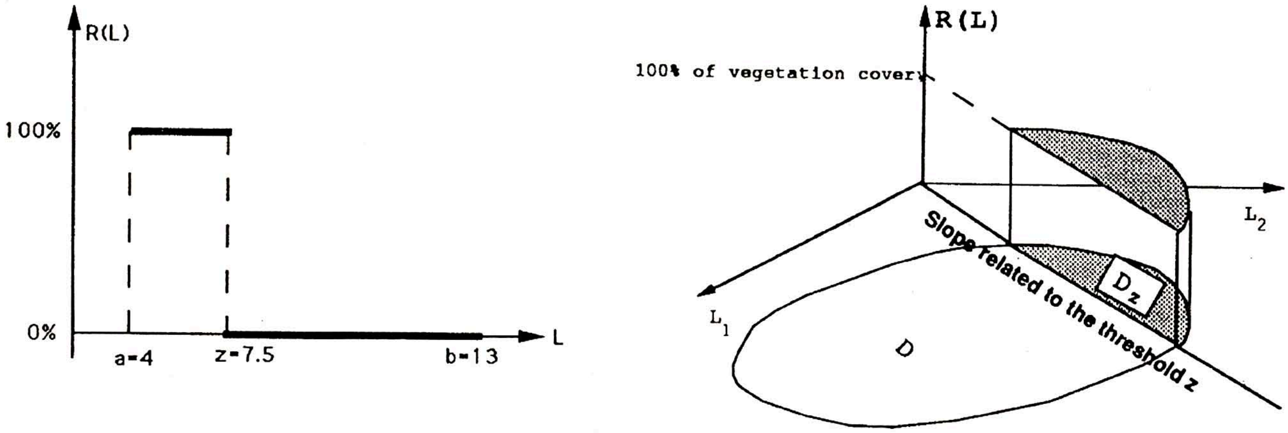
Following the general frame of section 2, we have defined burnt surfaces and vegetation covered ones. These definitions are somehow classical. We will see in section 4, that if we consider that they hold true at any resolution, the covered areas at the *in situ* resolution can be very different from the "satellite" ones.

4. DIFFERENCE BETWEEN MICROSCOPIC AND SATELLITE QUANTIFICATION

Let us consider one pixel Ω. We denote by $|\Omega_b|$ the burnt area within Ω and in the same way we denote the area of vegetation by $|\Omega_v|$. In addition, let us define the functions pertaining to burnt and vegetation areas:

For each microscopic point $\omega \in \Omega$ (**Figure 2**),

$$R(\ell(\omega)) = \begin{cases} 1 \text{ if } \ell(\omega) \in D_z \\ 0 \text{ if } \ell(\omega) \notin D_z \end{cases} \quad (5)$$



2 (a) 2 (b)

Figure 2 - The graphs of the function R defined by (5).
a) For burnt surfaces. The domain [a, b] is the domain of the possible radiances.
b) For the vegetation covered surfaces. The domain D is the domain of the possible radiances in the two channels nir and red

In (5), ℓ (ω) is, according to the case, a mono spectral radiometric measurement corresponding to the channel [1550, 1750] nm., in which case D_z must be defined by (1) **(Figure 1 (a))** or a multispectral measurement l (w) = $(\ell_{red}(\omega), \ell_{nir}(\omega))$ and therefore D_z is defined by (3), **(Figure 1 (b))**. The corresponding membership functions are represented in figure 2. In both cases, we have:

$$\text{covered area } (|\Omega_b| \text{ or } |\Omega_v|) = \int_\Omega R(\ell(\omega))\, d\omega$$

Then, the percentage of cover within Ω at the microscopic resolution is given by

$$\frac{1}{|\Omega|}\int_\Omega R(\ell(\omega))\, d\omega \tag{7}$$

while, with respect to (2) or (4), the value R (L) is used for the pixel Ω when using the satellite data L:

$$R(L) = \begin{matrix} 1 \text{ if } L \in D_z \\ 0 \text{ if } L \notin D_z \end{matrix} \tag{8}$$

These considerations show that if we take the same definition of an object (burnt area or vegetation for example) at the satellite resolution and at the microscopic scale of *in situ* experiments, the quantifications of covered surfaces (7) and (8) are not necessarily equal.

Now, the problem is: what is the greatest difference between these values

$$\Delta_\ell = \left| R(L) - \frac{1}{|\Omega|}\int_\Omega R(\ell(\omega))\, d\omega \right| \tag{9}$$

when the microscopic multispectral radiance ℓ (ω), ω ∈ Ω takes all the possible distributions which give the same satellite value L?

If we suppose that all the atmospheric corrections have been carried out, then the distributions ℓ (ω), ω ∈ Ω, constitute the set

$$\mathcal{L}_L = \left\{ \text{distributions } \ell(\omega), \omega \in \Omega \,/\, \frac{1}{|\Omega|}\int_\Omega \ell(\omega)\, d\omega = L \right\} \tag{10}$$

This set is the set of all the radiance distributions at the microscopic scale which are indistinguishable from the satellite.

The answer to the previous question is given in the mono spectral measurement in (Raffy, 1992) and in the general multispectral case in (Raffy, 1994).

The main results of these papers for our present objective can be summarized as:

1. *The set of all the values of (7) when ℓ takes all the possible distributions in $\mathcal{L}_L$ constitutes a bounded interval.*

2. *The bounds of this interval can be easily computed from the knowledge of* D, D_z *and* L. *Let us denote by* [R_v (L), R^ (L)] *this interval. The method used to obtain the bounds* R_v (L) *and* R^ (L) *for* L ∈ D *is the following. We remark that they correspond to two functions* R_v *and* R^ *defined on D. We then consider the boundary of the convex hull of the graph of* R. *[The graph is classically*

defined as the set of points $\{L, R(L), L \in D\}$*]. The lower (resp. upper) part of this boundary is the graph of the function* R_v *(resp.* $R^\wedge$*).*

3. The extreme value of $\Delta\ell$ *expressed by (9) is given, for each ,* $L \in \mathcal{L}_L$*, by*

$$\sup_{\ell \in \mathcal{L}_L} \Delta\ell = R^\wedge(L) - R_{v\,(L)} \qquad (11)$$

Let us illustrate (11) for the two cases studied. **Figure 3 (a)** is the graph of (11) when R is defined by (5), D_z by (1) and represented by **Figure 2 (a)**. **Figure 3 (b)** is the same graph when D_z is defined by (3) and the graph of R represented by **Figure 2 (b)**.

The analysis of the previous results leads to various observations.

From **Figure 3 (a)**, we deduce that for a given radiance L, the possible difference between the satellite computed burnt area and the actual *in situ* one can vary from 0 to 100 %. The increase in this error is linear and the maximum error occurs for radiances near to the threshold, while the minimum is at the bounds of the domain D = [a,b].

The conclusions arrived at for the quantification of vegetation are approximately the same as for burnt areas. For a given radiance $L = (L_{red}, L_{nir})$ the possible difference between *in situ* and satellite computed areas may reach 100 % around the threshold of the NDVI and be very low around the boundary of D.

In both mono and multispectral cases, the range of this difference, which is also the range of the possible errors is easily computable.

5. CLASSIFICATION OF NOMENCLATURES

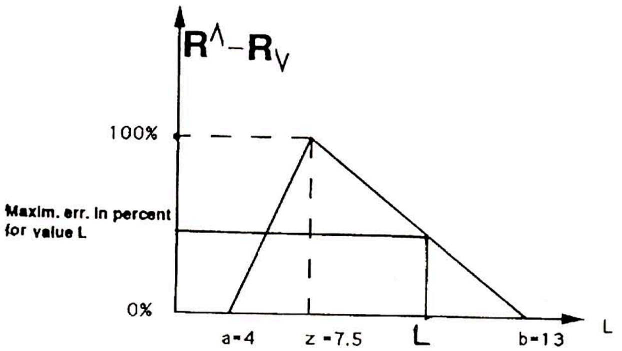
From the previous section, we deduce interesting results on the nomenclatures of objects as defined in section 2.

Indeed, the contour lines of the graphs of (11), represented in **Figure 3**, lead to a partition of the spectral domain D into sub-domains. **Figure 4** shows such a partition in the case of vegetation. These sub-domains have the following property: they classify the nomenclatures of vegetation with respect to their capacity to represent objects which are easy to quantify from remote sensing measurements. More precisely let's denote by the convex subset of D which defines an object, as defined by a) in section 2. We are then allowed to associate a name with D_0 **(Figure 4)**. Depending upon the position of D_0 within D, the possible errors $R^\wedge - R_v$ can take on greater or lesser values. The areas within D determined by the contour plot of $R^\wedge - R_v$ give the exact radiometric regions where the object has an area easily (or not so easily) observable from space. In the latter case, we can say that the nomenclature corresponding to D_0 is not appropriate for space observation.

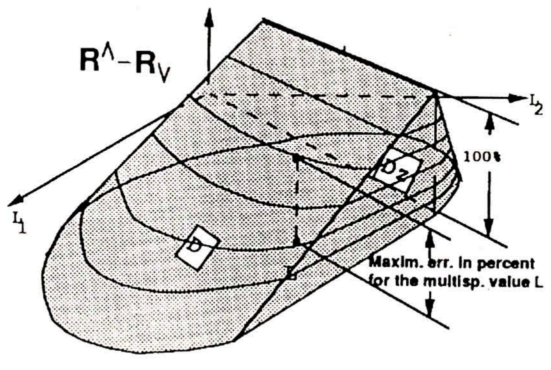
Let's classify the nomenclatures such that NDVI $\geq$ z with respect to their increasing stability when the resolution changes from the one which corresponds to the spectral domain D to the finer ones. Then, we can suppose that the radiance $L = (L_{red}, L_{nir})$ of the pixel Ω satisfies NDVI (L) $\geq$ z.

The coarser nomenclature is: " Ω = vegetation pixel". This corresponds to giving the name vegetation to the (convex) part D_0 of D where NDVI $\geq$ z. The use of smaller sub-domains of D leads to finer results.

1) $D_0 \subset C$ **(Figure 4)**. The percentage of vegetation within Ω may be very different from the actual *in situ* one in a range defined by the contour level of the graph of (11)



3 (a)



3 (b)

Figure 3 - The representation of the range of the differences between microscopic and satellite surface quantification, as expressed by (11)
(a) The case of burnt surfaces when they are defined by (2). (b) The case of vegetation covered surfaces when they are defined by (4)

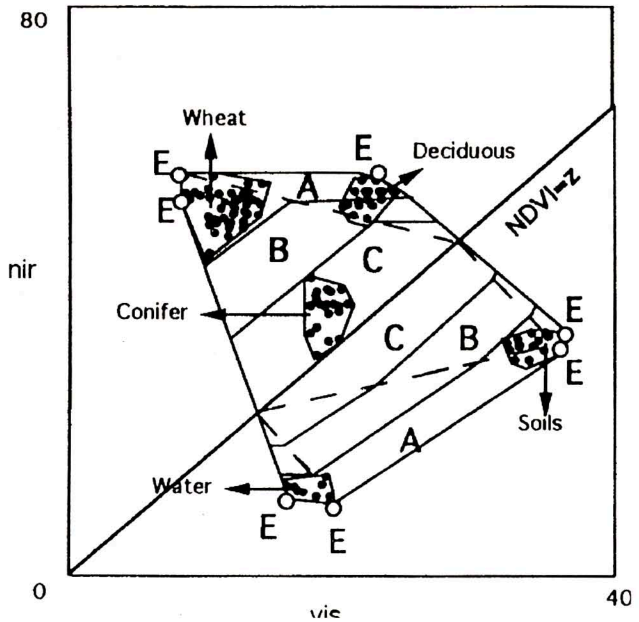


Figure 4 - Classification of the vegetation nomenclatures with respect to their stability to the upscaling process. The zones A, B, C, are defined by the contour plot of the graph of $R^{\wedge} - R_v$ represented byFfigure 3b. The points E are the vertices of the polygonal boundary of the radiometric domain D (i.e. the extremal points of the convex set D)

(Figure 3(b)). The nomenclatures within C such as "conifers" **(figure 4)**, are very sensitive to the change of resolution.

2) If $D_0 \subset B$, this sensitivity is lower in proportions easily computable.

3) If $D_0 \subset A$, the assertion " Ω = vegetation pixel" is closer to the actual one.

4) In the particular case where $D_0 \subset C$ boundary of D, the previous assertion is exact (contour level equal to zero).

5) Finally, the nomenclatures D_0 defined by one of the points E **(Figure 4)** are stable at any resolution. In other words, if $L \in E$, the assertion "Ω is covered by the Species named E" is exact. These points which can be called extremal spectral signatures correspond to the only nomenclatures insensitive to the change of resolution.

Remark: Similar conclusions hold for the simpler case of burnt areas.

6. CONCLUSION

One of the most important geometrical properties of an object distributed over a surface is its area. This justifies the interest in area estimation of parameters such as vegetation or burnt surfaces from space.

The quantification of the covered area depends on the resolution of the sensors. More precisely, we have shown that this dependency cannot be studied without a clear definition of the distributed object in relation to the sensor. We give such a definition appropriate to remote sensing studies. This leads us to state clearly the problem of estimating the maximum difference between the actual *in situ* area covered by the object and the area computed from satellite data. We give the optimal bounds of this difference (in the sense that the bounds can be reached). Since these bounds can be easily calculated from satellite data, we suggest that this computation be systematized for any area estimation.

The results take on particularly interesting forms for the cases of burnt and vegetation covered areas.

Finally, we approach the problem of the stability of the nomenclatures with respect to their ability to lead to accurate area estimation. The radiometric object, as it is defined, allows us to associate a nomenclature to convex separate subsets of the radiometric space. We show that, depending upon the position of this object within the radiometric space, the precision of its area estimation from the satellite data can vary within a very large range. One consequence is the ability to evaluate the appropriateness of a particular object to be taken into consideration for space studies, for a given multispectral radiometer.

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