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Air pollution mapping: relationship between satellite- made observations and air quality parameters

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Résumé
Les villes ne peuvent se permettre d'équiper tous les quartiers, les rues et les places d'un dispositif de surveillance de la qualité de l'air. Dans les articles précédents, nous avons présenté une méthodologie de densification du nombre de points de mesures permettant une nouvelle cartographie des concentrations des polluants. Une des étapes concerne l'établissement d'une loi d'estimation de la concentration des polluants par télédétection. Ce présent article traite des relations existants entre les mesures satellitaires et les mesures par les stations de surveillance. Des corrélations multidates sont calculées entre les réflectances mesurées par le satellite Landsat et les mesures, intégrées dans le temps, de concentrations de polluants. Les résultats montrent la possibilité d'estimer la pollution atmosphérique à l'aide des mesures satellitaires, non seulement dans les bandes spectrales du visible mais aussi celles dans l'infrarouge.
Mots-clefs : *télédétection, pollution de l'air, étalonnage, réflectance, corrélation.*

Abstract
The mapping of air quality over the city of Strasbourg and its vicinity requires an increase of the number of measurements aiming at spatializing information about air pollutants concentrations. A methodology based on a multisource approach for mapping air pollutants concentrations over the city was presented in previous communications. One step of the methodology is the estimation of pollutants concentrations by remote sensing techniques. This paper investigates the strength of linear relationship between satellite-made observations and air quality parameters. Multidate correlations were calculated between reflectances measured by Landsat satellite and measurements of the various pollutants. Those measurements are concentrations of pollutants on a daily average basis, or for the time of image acquisition, or on a basis of average of several hours before the image acquisition. The results add evidence on linear correlation between air quality parameters and satellite measurements not only in thermal infrared range but also in the infrared range.
Keys-words*: remote sensing, air pollution, radiometric calibration, reflectance, correlation.*

Introduction

Nowadays most large cities in Europe have acquired an air quality surveillance. Such a network is composed of a few static measuring stations, which allow a continuous surveillance of air pollution at the station locations. Pollution data are collected in near-real time and used to compute an air quality index (Garcia & Colosio, 2001) : the ATMO index. This index aims to inform local authorities, as well as the population, about air quality in the city. In answer to a high rate of pollution, public authorities are able to take restrictive measures on car traffic and on activities of some polluting companies.

However the real exposure of persons to ambient pollution cannot be estimated with the present network. The costs of a measuring station and its maintenance limit the knowledge to specific points of the town. Given the few measuring stations composing a standard air quality network, an accurate knowledge of the spatial distribution of the atmospheric pollutants over a city is currently impossible. To overcome this problem, a methodology based on a multisource approach for mapping pollutants concentrations over a city has been proposed by Ung *et al.* (2000, 2001). Sources related to air pollution and urban shapes and morphology are exploited to densify the number of potential stations for a mapping by interpolation. One step of the methodology is the estimation of pollutants concentrations at so-called pseudostations. In that case, this paper investigates the possibilities of satellite-made observations for mapping air quality. Some studies have been undertaken using such data. The first section offers a state-of-the-art summarizing the different studies and the results obtained. But such approaches were limited to the black particulates or sulphur dioxide pollutants. And they could not be applied to the studied area presented in the second section, due to the number of measuring stations. The problematic aspect is the establishment of mathematical relations between ground-based measurements of pollutants concentrations and satellite measurements. A multidate approach is presented through an intensive use of Landsat 5 imagery. Multidate satellite measurements are converted into reflectances as shown in the third section. Ground-based measurements of pollutants are concentrations of pollutants on a daily average basis, or for the time of image acquisition, or on a basis of average of several hours before the image acquisition. Multidate correlations were calculated between reflectances measured by Landsat satellite and various measurements of the pollutants.

1 – State-of-the-art

Only a few studies seek for a relationship between satellite data and ground-based measurements. They have been made on the correlation between satellite measurements in thermal infrared and air quality parameters (Finzi and Lechi 1991, Sifakis 1992, Poli *et al.* 1994, Brivio *et al.* 1995, Sifakis *et al.* 1998, Retalis *et al.* 1999, Wald & Baleynaud 1999, Basly 2000). These satellite data are radiances observed by the sensor in thermal infrared band(s). These radiances are a function of the temperature and emissivity of the surface and also of the optical properties of the atmospheric column above the pixel and its surroundings. Most of the bodies of interest have an emissivity larger than 0.8 (e.g. Gaussorgues 1989). In that case, for the spectral band of interest, the emission by the surface is the most important phenomenon. The radiance emitted by the atmosphere towards the sensor after its reflection on the surface accounts for approximately 10% of the total radiance and may be neglected. Accordingly in a first approximation the temperature T_{sat} observed by the space-borne sensor can be written:

$$T_{sat} = \tau \, e \, T_{surf} + T_{atm}$$

where T_{surf} is the surface temperature, e the surface emissivity, τ the transmission factor of the atmosphere, and T_{atm} a weighted-average temperature modelling the emission of the atmosphere itself. This equation should actually be written in radiances. However as long as a limited range of temperature is concerned, the Planck function can be approximated by a linear function and this equation holds. From this equation, it appears that a decrease in the atmospheric transmission factor as caused by the appearance of a pollution layer results in a decrease in T_{sat}. This decrease may be significant enough to be sensed by space-borne sensors such as Landsat TM, the sensitivity of which is 0.5 °C. This was experienced and discussed by Mc Lellan as early as 1973. Actually the change would also have an impact on the radiance emitted by the atmosphere (modelled by T_{atm}) but the impact is negligible in a first approximation because the pollution layer is usually of very limited vertical extension and T_{atm} results from an integration over the entire atmospheric column.

Table 1 (Basly 2000) summarizes all the linear correlation coefficients obtained for several cities between apparent temperatures and concentrations in particulates.

Studied area	Rome •	Naples •• 05/10/97	Naples •• 15/04/98	Naples •• 02/06/98	Nantes •• 20/05/92	Nantes •• 11/04/95	Nantes •• 27/01/00	Nantes •• 27/01/00
Number of values	5	4	6	6	12	10	3	3
Satellite channel	TM6	TM6	TM6	TM6	TM6	TM6	ETM6	ETM9
Pollutant	PTS	PTS	PTS	PTS	FN	FN	PM_{10}	PM_{10}
Concentration average (µg/m^3)	120,0	79,51	63,96	57,82	16,17	15,30	70,00	70,00
Correlation coefficient	-0,97	-0,87	-0,83	0,06	0,57	0,57	-1	-1
Confidence level %	99	87	96	9	95	91	100	100

Table 1: Correlation coefficients between the particulate measurements and the brightness temperatures measured in TM6. • : Poli *et al.* 1994. ••: Basly 2000.

Tableau 1 : Coefficients de corrélation entre les mesures de concentrations en particules et la température de surface TM6. • : Poli et al. *1994. ••: Basly 2000.*

It brings out the high correlation between Landsat satellite measurements in thermal infrared band and air quality parameters for high concentration levels. Wald and Baleynaud (1999) discussed about the relationship between the suspended particulates (PM_{10}) measurements and the apparent temperature. Nevertheless if we assume that the pollution plays a major role in the pattern of temperature, two processes occur simultaneously which explain the relationship between the particulates measurements and the apparent temperature. The appearance of a pollution layer (more absorption and scattering) results in a decrease of the atmospheric transmission factor. On the one hand, this decay leads to a decrease of the solar radiation impinging on ground. The solar heating is thus decreased as well as the resulting temperature of the surface. Hence the emitted radiance is lower, and the signal sensed by the satellite is lower. On the other hand, this pollution layer absorbs as well the emitted radiance, causing a depletion of the upward radiance. This is the second process explaining the relationship. Both processes contribute to the decrease of the apparent temperature as the pollution increases. But the authors are aware of the limitations of the discussion, which is not a demonstration. The authors concluded that the mapping of the black particulates is possible using TM6 image but positive correlations are not explained yet.

On the contrary, the authors are partly conflict regarding sulphur dioxide (SO_2). Finzi and Lechi (1991) analysed two Landsat images of Milan. For the polluted day, the correlation coefficient is -0.84. For the unpolluted day, the correlation coefficient is very low (0.48). Even weaker correlation with SO_2 was observed by Brivio *et al.* (1995) for Milan. Poli *et al.* (1994) found weak and negative correlation for Roma. As for Brivio *et al.* (1995), Basly (2000) found no significant relationship except for one date, and stressed that the results depend on the number of values.

Those studies add evidence on the correlation between satellite measurements in thermal infrared and air quality parameters. It has been shown that particulates concentrations are correlated to apparent temperature. But the number of values is too small to be conclusive (Basly 2000). Though of limited extension the present study investigates multidate data allowing to increase the number of values and to measure changes in aerosols between several images of Landsat. Since this depletion of visibility is caused by scattering and not by gaseous absorption (Wald and Baleynaud 1999, Sifakis *et al.* 1992, Carnahan *et al.* 1984, Richards 1986) a major consequence is that the pollutants should affect visible and infrared bands and not only the thermal infrared band. Hence our study investigates whether pollutants can also be observed in these channels.

2 – Description of the area of interest

The city of Strasbourg is located in Eastern France at the border of Germany. A set of eight Landsat 5 Thematic Mapper (TM) quarter scene images was acquired on March 31, 1998, August 15, 1998, September 10, 1999, June 8, 2000, April 1, 2001, May 10, 2001, July 22, 2001 and August 14, 2001. Landsat TM images are acquired at 1030 mean solar time, in clear sky conditions. The Landsat TM sensor provides images with a 30 m pixel and seven spectral bands from the blue band TM1 to the thermal infrared spectral band TM6 (table 2). The thermal infrared band presents a spatial resolution of 120 m but interpolated to a pixel size of 30 m.

Channel	TM1	TM2	TM3	TM4	TM5	TM6	TM7
Wavelength (µm)	0,45 - 0,52	0,52 - 0,60	0,60 - 0,69	0,76 - 0,90	1,55 - 1,75	10,40 - 12,50	2,08 - 2,35
Spectral bands	Blue	Green	Red	Near IR	Midle IR	Thermal IR	Midle IR
spatial resolution	30	30	30	30	30	120	30

(from Landsat 4 Data Users Handbook, 1984, USGS)

Table 2: Landsat TM bands.
Tableau 2 : Les bandes spectrales du satellite Landsat TM.

A sample of an image of the city of Strasbourg, acquired on 31 mars 1998, is presented in figure 1. The size is 15.36 km, with a pixel size of 30 m. The channel TM4 reveals the patterns of the streets and roads in the city (in dark tones). The airport is clearly seen in the South-West. Also appearing dark are the Rhin river and lakes. Light tones are mostly related to vegetation as several large parks are found in Strasbourg. The pollution data corresponding to the overpass of the satellite were acquired by the measuring network and archived by the ASPA team, the local organization in charge of the air quality measuring network in the city of Strasbourg and its vicinity. This network is composed of fourteen measuring stations in the city. The number of measuring stations per pollutant is about 6, which is too few to establish an accurate relationship. The measurements are concentrations of a pollutant every 15 minutes in near real-time. Table 3 shows that the pollution levels for the studied days were below critical levels.

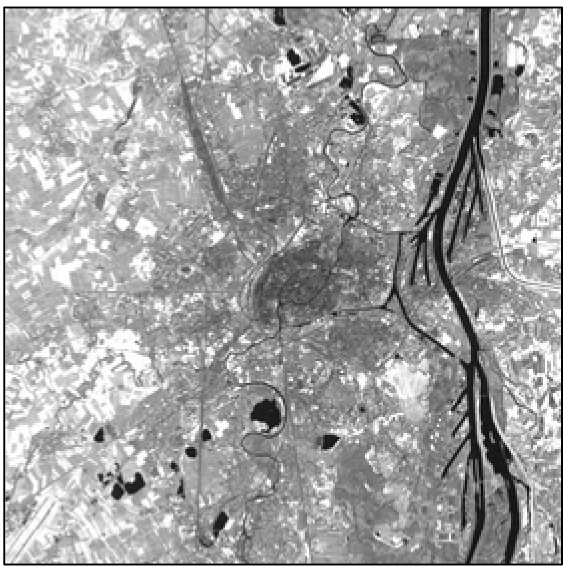

Figure 1: Image of the city of Strasbourg (Landsat TM4), on 31 Mars 1998. © Eurimage.
Figure 1 : Image de la ville de Strasbourg (Landsat TM4) du 31 mars 1998. © Eurimage.

	SO2	NO2	NO	PM10	O3
31/03/1998	21	62	27	40	50
15/08/1998	17	39	4	27	88
10/09/1999	25	58	22	37	65
14/08/2001	14	56	25	36	80
22/07/2001	41	31	6	21	73
01/04/2001	12	48	24	28	57
08/06/2000	17	50	18	26	66
20/05/2001	12	44	23	33	71

Table 3: Daily averages of pollutants concentrations for the studied days (in µg/m^3).
Tableau 3 : Concentrations journalières de polluants pour les dates étudiées (en µg/m^3).

3 – The processing of the Landsat data

The Landsat TM images are geometrically corrected and remapped to a same regular grid in a same standard map projection. This is accomplished by constructing a mapping between pixel coordinates in the images and geographic coordinates on the BD TOPO® geographical database available over the area (Michel 2000, Veillet et Leconte 1995). Looking into the physics of the problem, a nearest-neighbour interpolation method is applied. This method does not modify the digital accounts of the images, so the representation of reality for measured radiances is conserved. This processing allows superimposition of Landsat images.

To allow comparisons of measurements of radiances, a radiometric calibration is then processed of concerting raw digital numbers observed by the TM sensors into physical units, except for the thermal band TM6. The radiometric calibration of the thermal band, is fundamentally different than the reflective bands as the instrument itself contributes a large part of the signal. The Landsat 5 TM was radiometrically calibrated prior to launch, and processing algorithms were developed that estimated detector gain based on the internal calibration lamp response. Even if the instrument were designed to maintain a constant bias level, the users may observe radiometric differences. Teillet *et al.* (2001) propose a lifetime radiometric calibration. According to the U.S. Geological Survey (USGS, 2003), the percentage difference observed in the gain between 1998 and 2002 didn't exceed 4%. We apply the resulting updated gains.

The radiance measured by the Landsat instrument at the top of the atmosphere is dependant of the solar irradiance at that level. To avoid variations of the radiance due to yearly variation of the solar irradiance one has to normalise the radiance measured by the satellite to reflectance. The values will then be comparable from one date to the other. This allows inter-date comparison of images. The obtained accuracy is just dependant on the calibration accuracy. The equation to be applied to each single pixel is the following :

$$r = \pi L / (I_0 \varepsilon \cos \theta_z)$$

$$r = \alpha L$$

with: r : reflectance at the top of the atmosphere

L : spectral calibrated radiance at the top of the atmosphere in $W/m^2/Sr/\mu m$

θ_z : solar zenith angle

I_0 : mean spectral solar irradiance at the top of the atmosphere in $W/m^2/ \mu m$

ε : radius vector (ration of mean to actual sun-earth distance)

α : $\pi / (I_0 \varepsilon \cos \theta_z)$ conversion coefficients from radiance to reflectance in $Wm^2 Sr\mu m W^{-1}$

Spectral solar irradiances are unique for each spectral band (Markham and Barker, 1985). The radius vector and solar zenith angle are given by the project SoDa Service (Integration and exploitation of networked Solar radiation Databases for environment monitoring, supported by the EC, DG-XIII "INFSO", IST-1999-12245, web site: http://www.soda-is.com/).

Table 4 shows the calculated conversion coefficients α from radiance to reflectance for each date.

canal	*31/03/1998*	*15/08/1998*	*10/09/1999*	*14/08/2001*	*22/07/2001*	*01/04/2001*	*08/06/2000*	*10/05/2001*
TM1	2,330	2,081	2,285	2,051	1,963	2,315	1,894	1,954
TM2	2,495	2,229	2,448	2,197	2,103	2,479	2,028	2,093
TM3	2,926	2,614	2,870	2,576	2,466	2,907	2,378	2,454
TM4	4,365	3,900	4,281	3,843	3,678	4,337	3,548	3,661
TM5	20,819	18,600	20,421	18,328	17,544	20,684	16,923	17,461
TM7	61,171	54,649	59,999	53,851	51,547	60,775	49,724	51,303

Table 4: Radiance - reflectance conversion coefficients for Landsat 5 images (10^{-3} $Wm^2Sr\mu mW^{-1}$).
Tableau 4 : Coefficients de conversion luminance - réflectance pour Landsat5 (10^{-3} $Wm^2Sr\mu mW^{-1}$).

4 – Air quality parameters

Most studies, presented in the state-of-the art, deal with the daily averages of pollutants concentrations. But Landsat TM images are acquired at 1030 mean solar time (around 10h UTC) and can hardly contain information about the daily pollution.

For the 8 studied dates and for each pollutant, we calculate the average concentration between the time of satellite image acquisition (10h UTC) and several time before. This parameter represents an integrated concentration of a pollutant on a basis of average of several time before the image acquisition. Figure 2 illustrates the resulting parameters for suspended particulates pollutants (PM_{10}). The surveillance network for suspended particulates pollutant was composed of five measuring stations (Illkirch, Centre, Nord, Clemenceau, Est) on August 14, 2001. The first parameter at coordinates (x = 10 h, y = 35 µg/m^3) in figure 2 represents the concentration measurement by the station "Centre" at 10h UTC. And the parameter at coordinates (x = 8h, y = 47.4 µg/m^3) represents the average concentration between 10h UTC and 8h UTC.

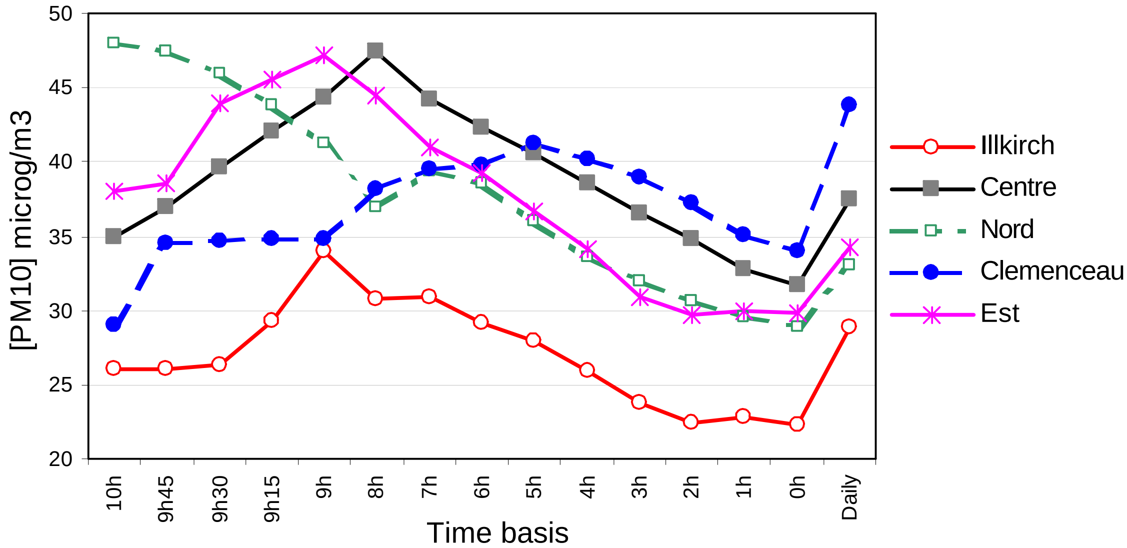

Figure 2: Average concentrations on a time basis for August 14, 2001. - the x-axis and y-axis refer to the time basis and the concentrations in particulates.
Figure 2 : Concentration moyennées sur une base de temps pour le 14 août 2001 – les axes x et y des ordonnées représentent la base de temps et les concentrations en particule.

5 – Comparison between air quality measurements and satellite observations

Locations of the fourteen measuring stations are reported onto a digital map of Strasbourg. This map is superimposed onto the Landsat images. The multidate radiances corresponding to the stations are extracted from the images for the 8 studied dates.

For each time basis and each pollutant, a linear correlation is calculated between integrated concentrations of the pollutant and reflectances of the measuring station places. Data from every dates are processed together. It results in an increase of the number of values for the correlation : 70 for SO_2, 56 for NO_2, 51 for NO, 33 for PM_{10} and 36 for O_3.

Analysis of the correlation coefficients reveals that the correlations between SO_2 and satellite data in all spectral bands are weak according to previous studies. It is likely that the concentration level of

SO_2 is too low. For [NO_2], [NO], [PM_{10}] (primary pollutants), the sign of the correlation coefficients is negative according to previous studies. Figure 3 shows the correlation coefficients between suspended particulates concentrations PM_{10} and reflectances of the measuring stations places. An increase of those primary pollutants concentrations causes a depletion of the upward radiance measured in the visible and infrared spectral bands. Confidence levels are up to 95 %. Better correlation coefficients are observed for the three infrared spectral bands (TM4, TM5 and TM6). In the case of O_3 (secondary pollutant), the sign of the correlation coefficients is positive.

The results clearly indicate that the correlation coefficient depends on the time basis used for the average. Better levels of correlation are observed when using large time basis. When the time basis increases, the integrated concentration parameters better reflect the background pollution situations. It results that mapping background pollution by remote sensing is more accurate than a real-time mapping by remote sensing. But the variation of correlation coefficients are not fully understand yet and might be related to the pollutants properties or emissions. For example, the abrupt decrease of correlation for PM_{10} occurs at 7 o'clock, when traffic pollution is high.

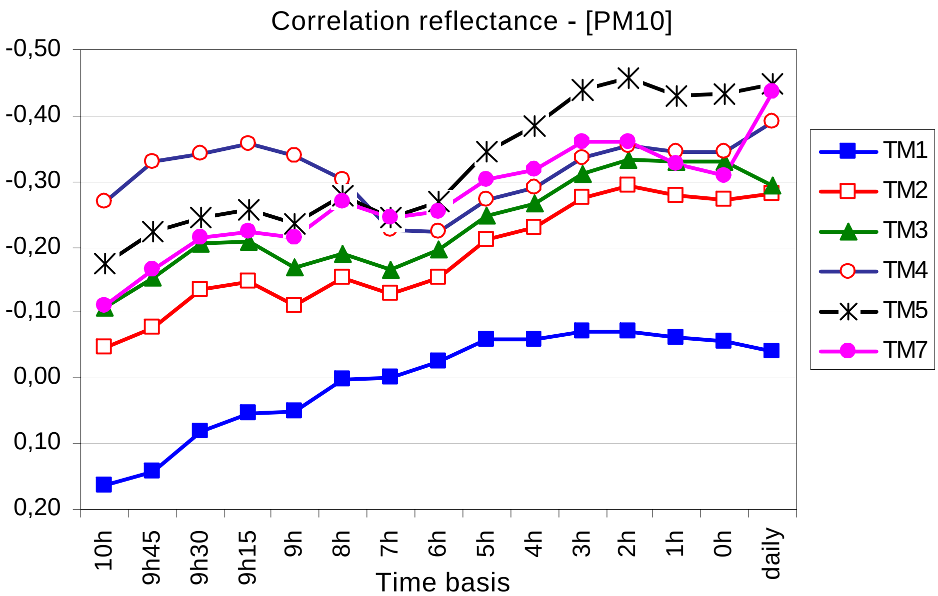

Figure 3: Linear correlation between integrated concentration of suspended particulates PM_{10} and reflectance derived from Landsat satellite- the x-axis and y-axis refer to the time basis and the correlation coefficients.

Figure 3 : Corrélation linéaire entre les mesures intégrées dans le temps de concentrations de particules PM_{10} et les réflectances dérivées des mesures satellitaires – les axes x et y des ordonnées représentent respectivement la base de temps et les coefficients de corrélation.

Conclusion

This study adds evidence on the correlation between air quality parameters and satellite measurements in infrared range. The results demonstrate that satellite observations of upward radiance can be used to estimate the pollutant concentration levels, not only at the time of image acquisition but for an integrated time basis. The use of remotely sensed data for mapping of pollutant concentration in towns brings a better spatialization of the phenomena under study. Mapping background pollution by remote sensing is more accurate than a real-time mapping by remote sensing. Such results will be exploited for a better definition of virtual station presented in Ung *et al.* (2000, 2001). Further analysis related to the variation of correlations are needed to definitely assess its causes. And a relationship could be derived through a multi-regression analysis for example.

Acknowledgements

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