FROM IMAGE PROCESSING CONCEPTS TO INSTRUMENT DESIGN IN REMOTE SENSING SATELLITES

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ABSTRACT

Through two examples drawn from the French National Earth Observation programme : Spot-5 and Pleiades-HR, the paper illustrates the dramatic impact of image processing techniques on the performances and sizing of remote sensing missions.
In the Spot-5 case, improved performances have been achieved with minimal modifications on an already designed instrument. Pleiades-HR is a new development for which a global optimization can be carried out from the start.

1. INTRODUCTION

Sophisticated Signal processing is one of the key factors to achieve high performance remote sensing missions from space at an affordable price.
This is illustrated in this paper through the two main earth imagery programmes conducted by the French National Space Agency, CNES: Spot-5 and Pléiades.
In both cases, image processing is not a mere add-on but has been taken into consideration as part of an end-to-end design from the space sensor to the ground processing.

2. SPOT-5

2.1. The Spot programme

Operational since 1986, the Spot programme is the main on going civilian optical Earth observation programme in Europe. Led by France, it involves a participation of Sweden and Belgium, each contributing to 4% of the programme cost.

Spot-5, launched May 4, 2002, is the latest satellite in the Spot series. It delivers panchromatic images with a ground resolution of 5 meters and in a special mode dubbed supermode, of 2.5 meters.

Spot-5 also provides multispectral images with a 10 meters resolution in three spectral bands (Red, Green, Near Infra Red) and a 20 meters resolution in Short Wave Infra Red.

All standard Spot images cover a size of 60x60 km. The combination of high resolution, precise localization and swath width make the Spot products very well suited for a wide range of applications in the field of cartography, land use, etc.

To increase the image capacity acquisition, Spot-5 like its predecessors, is fitted with two similar instruments, named HRG. Each of them encompass a rotatable mirror which allows more frequent revisit of a given site using off nadir viewing.

An on-board memory allows to store images from all over the globe. They are dumped on the two main system receiving stations located in Kiruna (Sweden) and Toulouse (France). It is also possible for foreign customers to receive directly the data from the satellites on their own Earth station.

A private company, Spot-Image, is in charge of the interface with the users.

On Spot-5, the two main telescopes are complemented by an instrument dedicated to along track simultaneous stereoscopic viewing. Its data are used to produce Digital Elevation Models.

Spot-5 like its predecessor Spot-4 (launched in 1998 and still fully operational) embarks a payload from the Vegetation programme. This programme is devoted to the operational monitoring of the vegetation and the study of the biosphere. It is a cooperative venture gathering the European Commission, Belgium, Sweden and France.

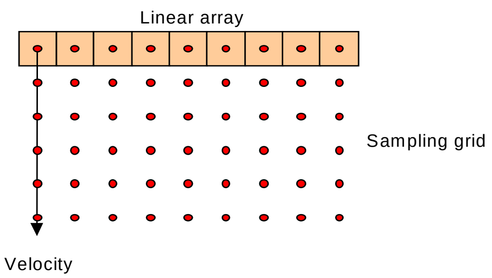
The Vegetation system acquires daily a complete picture of the emerged land in four spectral bands (blue, red, NIR and SWIR) with a ground resolution of 1 km at nadir, a radiometric resolution of 0.003 and an absolute calibration accuracy better than 5%.

2.2. Classical instrument design

The Spot satellites, like several other earth sensing satellites, use the so-call “push-broom” acquisition scheme. On Spot-5, 12 000 elementary detectors, each of a size p x p = 6.5 x 6.5 µm are fitted in line on a single CCD device.

An image line is generated by integration of the incident light. Successive lines are generated by the satellite motion perpendicular to the CCD line.

In a standard way, the sampling period Te, corresponding to the integration time, is such that the velocity of the sub-satellite point multiplied by Te is equal to the projected size of an elementary detector. This yields an orthogonal sampling grid, the sampling interval in line and column of which are equal.



Standard sampling
inherited from classical photography

Signal to noise ratio considerations generally lead to instruments the cut-off frequency of which is defined not by the optics but by the detector size and is equal to 1/p. The above acquisition techniques then leads to an improper sampling scheme where the sampling frequency 1/p is exactly the system cut-off frequency.

With such a design, commonly used in earth observation instruments, the higher frequencies transmitted by the optics are not taken advantage of. Moreover, the improper sampling creates, through aliasing, visible artifacts and generates an inadequate basis for further processing such as resampling or deconvolution.

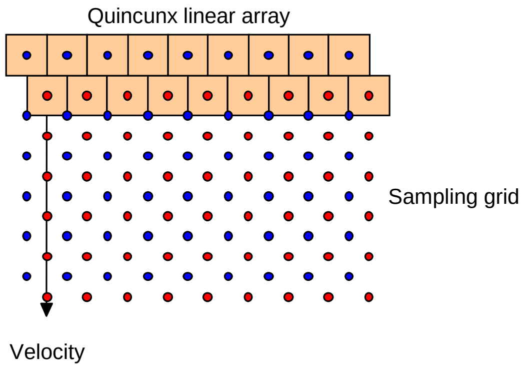
2.3. The Supermode techniques

In the course of the Spot-5 development it has been decided to increase the resolution of the HRG instruments which was initially set to 5 meters.

To do so, without redesigning completely the instruments, the so-called “supermode” techniques (CNES patent [1]) has been applied.

The basis of this techniques is to increase the sampling frequency. To that effects, the HRG instruments have been fitted with 2 linear arrays positioned in quincunx. Those two CCD lines generate two 5 meters sampling grids separated by 0.5 pixels in the raw and column directions (the actual shift in the column direction is 3.5 pixels, corrected by processing).

In order to improve the detector MTF in the column direction, its size has been reduced from 6.5 to 4.5µm.

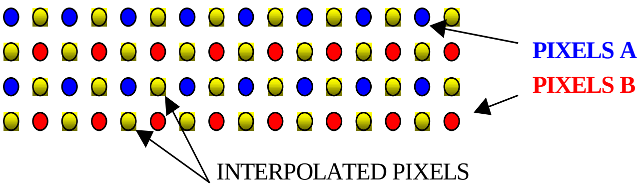


Quincunx sampling
Supermode Spot-5

The ground processing for supermode is composed of three main steps [2].

a) Resampling

A new image with a 2.5 sampling grid is created by interleaving the two 5 meters images generated by each of the CCD line and by interpolating the missing information.



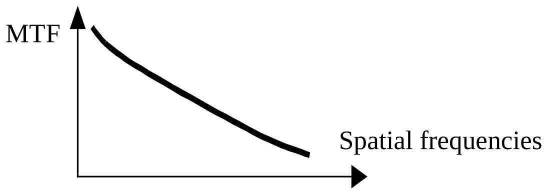
The resulting image meets the Shannon condition for proper sampling. It can be modelized as :

$$\text{Image}(x,y) = H \otimes \text{Landscape}(x,y) + \text{Noise}(x,y)$$

where : Landscape (x,y) is the observed scene,
H is the instrument impulse response,
Noise (x,y) is the noise introduced by the acquisition chain.

b) Deconvolution

With the new sampling scheme higher frequencies are now available. However the transfer function of the instrument for these frequencies is low. Indeed the general shape of the instrument modulation Transfer Function, the Fourier transform of the impulse response, is as follows :



A deconvolution process is applied which in effect sharpens the image. It tends to recover the observed scene as :

Landscape restituted (x,y) = $H^{-1} \otimes$ image (x,y)

c) Denoising

Applying the deconvolution filter also affects the noise. The initially white noise on the raw images is transformed into a colored noise, the frequency variation of which match those of the deconvolution filter. The increase of high frequency noise is particularly visible on uniform areas.

The noise model for a CCD type of instrument depends on the incoming signal strength :

Var[noise] = A + B signal strength

The denoising process must then take into consideration both the spatial location on the image (mean signal strength on an image region) and the spatial frequencies to account for the deconvolution filter. This leads to use a wavelet packet decomposition of the image and to apply attenuation factors on the wavelet coefficients [4], [5].

Those attenuation factors are established by using simulated uniform images with noise and by defining a fixed noise only output target image [3], [4], [5].

3. PLEIADES

3.1. The Pleiades High Resolution programme

It has been recognized that the fulfillment of the various needs from potential users of space systems would require the establishment, in a coherent manner, of a multi-sensors system. In France, such thinking are undertaken in the frame of the so-called Pleiades programme.

As a first concrete step, France and Italy have engaged a cooperation to develop a joint system providing both optic and radar images with a metric resolution. France assumes the leadership of the optical component named Pleiades-HR while Italy, with its COSMO programme, assumes the leadership of the radar component.

Pleiades-HR will have a ground resolution of 0.7 meter (at nadir), in panchromatic with a 21 km swath.

Multi-spectral images (RGB-NIR) at lower resolution will be simultaneously acquired.

3.2. Pleiades-HR system sizing

The Pleiades-HR satellites will benefit from technology improvements in various fields which will allow to achieve, at an affordable price, performances once reserved to ambitious military spacecraft. The Pleiades-HR satellites will be compact (about 1 ton weight) and agile, meaning that the whole spacecraft body is tilted to achieve off-nadir viewing.

A side from technology breakthrough a key factor in achieving this goal is a proper dimensioning of the instrument. Considering from the start image processing techniques has allowed to define an instrument much smaller than would have been required if it had have to support by itself the system performances.

This approach has greatly benefited from the work carried out on the Spot-5 acquisition and processing chain.

It has also fully taken advantage of improved means which render the making of simulated images more readily available. Realistic images generated from aerial pictures which are passed thought a complete simulation of the acquisition and processing chain can be presented to users panels. The simulation allows to play with the various sizing parameters of the instrument and with the ground processing features in order to optimize the overall system design.

The Pleiades-HR system design is chiefly determined by the specifications for radiometric image quality in the panchromatic band which supplies the images with the sharpest resolution.

In the Spot-5 case, the instrument was already designed when the decision to embark the “supermode” scheme was taken. Pleiades-HR is a new development allowing to optimize globally the radiometric image quality defined by the 3 following components :

- the sampling interval: this is set at 70 cm for nadir viewing
- the MTF: this must be quite high over the interval [-fe/2, fe/2] and low as from fe/2
- the SNR: this must be sufficient to maintain the high frequencies transmitted by the MTF and the sampling.

For a sampling frequency fe, a sampled image will be of good quality if its MTF is near zero at fe/2, which comes down to saying that the finest details visible on the sampled image (spatial frequencies close to fe/2) are blurred. This conclusion may be confusing for users unfamiliar with sampling notions, who may rightfully wish the image to be as sharp as possible. Still, the information supplied to the user in a correctly sampled image (MTF ~0 at fe/2) is guaranteed, and allows him to perform interpolation processing with no risk of undesirable artifacts.

Like in the Spot-5 case, to make the raw image sharper, we seek to raise its high frequencies. As for SPOT5 “supermode” deconvolution, we therefore define a higher MTF_{target} than the real instrumental MTF, whose variations are realistic, i.e. decreasing according to spatial frequencies. The filter $D=MTF_{target}/MTF$ is called a deconvolution filter and restores the image contrasts.

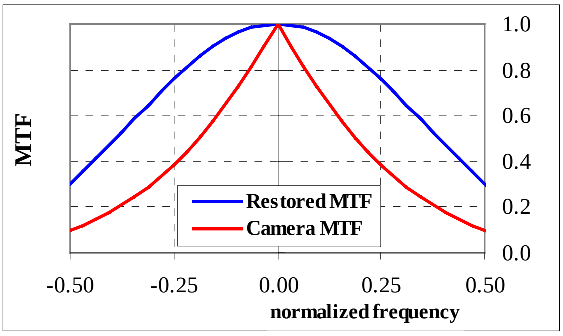
The operation is linear filtering, which is legitimate since the image is correctly sampled. A denoising process, as seen in paragraph 2.3., is then further applied.

3.3. Radiometry requirements definition

As shown in the previous paragraph, the MTF considered here is that of the restored product. We cannot, however, reduce the quality of the image to a restored ideal MTF curve without considering the instrumental MTF, since it is precisely this which determines the band of spatial frequencies that are effectively useful in the image. The main design parameter is the SNR.MTF product which determines the useful support of the MTF and hence image resolution. It is nevertheless understood that for the same value of this product, all the pairs (MTF, SNR) do not correspond to images of the same quality. This is because the information attenuated by a near zero MTF cannot be used, even if the SNR is very high. On the other hand, a detail submerged by excessive noise cannot be restored, even if it was transmitted in the sharpest manner by a very high MTF. We therefore consider the full specification of the instrumental MTF and the SNR to be written as follows, at the given frequency fo:

$\forall$ $\|f\| \leq$ fo,	MTF(f)	$\geq$ 0.07
	SNR	$\geq$ 90
	MTF(f).SNR	$\geq$ 7

These thresholds were determined by consulting a group of users (cartographers, military leaders, urban planners, forest managers, geologists, environmental agencies) to whom we submitted several simulated images that are representative of the onboard acquisition system + ground processing, with the pair (MTF, SNR) varying in the [0.06, 0.15] x [70, 130] field. The conclusions to this experiment identified the rejection of low SNR (approximately 70) and a good tolerance to "low" MTF around 0.07 to 0.08 when the SNR is adequate (over 90). As a result, the specification in the panchromatic band was established at the following values:



Raw MTF versus restored MTF

The Pleiades PA image has an information content of greater quality than a non-restored image that would have been acquired by a much larger and therefore far more costly instrument : to obtain a comparable level on a raw image, we would have needed a camera diameter D~1.30m , which is twice larger than Pleiades-HR diameter . Moreover, this “sharp” raw image would be polluted in fact by the substantial aliasing inherent to image acquisition by CCD, where the MTF_{optics} is very high.

4. CONCLUSION AND FUTURE DEVELOPMENTS

End to end design including ground processing techniques has already proven its benefice.

Future developments include even more integrated approaches for the restoration problem : deconvolution and denoising and encompassing even compression – decompression.

3D modeling is another field where image processing techniques are likely to open innovative routes in system design.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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