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HYPERRESOLUTION: AN HYPERSPECTRAL AND HIGH RESOLUTION IMAGER FOR EARTH OBSERVATION

R. De Vidi, L. Chiarantini, A. Bini

Galileo Avionica Spa, Via Einstein 35, 50013 Campi B. (FI), ITALY,
Email: romeo.devidi@officine-galileo.finmeccanica.it

ABSTRACT

Hyperspectral space imagery is an emerging technology that supports many scientific, civil, security and defence operational applications. The main advantage of this remote sensing technique is that it allows the so-called Feature Extraction: in fact the spectral signature allows the recognition of the materials composing the scene.
Hyperspectral Products and their applications have been investigated in the past years by Galileo Avionica to direct the instrument characteristics design. Sample products have been identified in the civil / environment monitoring fields (such as coastal monitoring, vegetation, hot spot and urban classification) and in defense / security applications: their performances have been verified by means of airborne flight campaigns.
The Hyperspectral and High Resolution Imager is a space-borne instrument that implement a pushbroom technique to get strip spectral images over the Hyperspectral VNIR and SWIR bands, with a ground sample distance at nadir of 20m in a 20 km wide ground swath, with 200 spectral channels, realizing an average spectral resolution of 10nm. The High Resolution Panchromatic Channel insists in the same swath to allow for multiresolution data fusion of hyperspectral imagery.

1. INTRODUCTION

In the recent past operational satellite systems for imagery, Landsat and SPOT were equipped with high resolution panchromatic cameras and Multispectral scanners with four channels, extended to 8 in ETM+ of Landsat 7. The pertaining image processing has shown that satellite remote sensing is a promising technique in the generation of thematic maps, but since Hyperion it is recognised that the next step forward is done by HyperSpectral Imagery (HSI) which collects hundreds of channels.
Hyperresolution is an hyperspectral and high resolution panchromatic imager for space-borne earth observation mission; the imager has been designed in Galileo Avionica under an ASI contract. In this paper the process to derive the spatial/spectral specifications is described. Then follows a short description of examples of hyperspectral data processing in classification and recognition application. Finally the instrument design and performance prediction are discussed.

2. HSI REQUIREMENTS

The main advantage of this remote sensing technique is that it allows the so-called "Feature Extraction": the material composition in the observed area can be recognised on the basis of its spectral signature and geometrical properties. Examples of feature extraction are the Background Classification (territory mapping based on spectral classification), and Target Recognition (a specific target is identified/localised on the basis of its spectral signature).

2.1 Spectral resolution

Target Detection and Background Classification are the applications that drive the requirement of spectral band, resolution characteristics and continuous high spectral sampling.

In the case of Background Classification, where the task is to identify the number and type of classes on the basis of high dimensional spectral libraries and ground truth data, the analysis aims to minimising the probability of misclassification errors [2]. In the case of Target Recognition typically the task is the characterisation of the target spectral signature as better as possible maximising the probability of detection [1].

Evaluations on the general classification problem [2] have shown that to increase class accuracy it must increase the number of spectral bands, as well as the Signal to Noise Ratio, but to achieve higher accuracy also the number of training samples must increase, and this is not always possible; so for an HyperSpectral Imager the capability of varying spectral sampling allows its use on a wider range of applications.

The requirement of a continuous spectral sampling is issued in the applications where the information comes from the derivative of the spectral signature (e.g. vegetation red-edge slope).

2.2 Spatial resolution

For the spatial dimension and resolution, the capability of geometric feature extraction, or Image Interpretability, is commonly referred to the General Image Quality Equation (GIQE [3]), which is based on the typical figure of merit:

$$Image\ Interpretabilty \propto SNR \times MTF \times GSD^{-1}$$

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which includes the Modulation Transfer Function (MTF), the Ground Sampling Distance (GSD) and the Signal to Noise Ratio (SNR).

When dealing with spectral images, different approach are proposed for the definition of the Hyperspectral Image Quality [4], that deals with the separability of classes: this approach reduces the impact that spatial resolution has with respect to the image quality, because an the hyperspectral image is more used for surface characteristics analysis than geometric analysis.

In particular for the background classification a GSD of 20m from satellite is considered a good compromise between detectors availability and classification applications. For target recognition, in the hyperspectral images the presence of spectral information allows also the so called "sub-pixel extraction" [1], that is the capability to identify the presence of a particular spectral signature within the pixel, even when the geometrical resolution does not allows its detection. This capability is enhanced by the SNR factor, since the minimum pixel fill factor detectable is evidently limited by the amount of noise.

A good solution to complex recognition applications is to combine the geometric recognition capabilities, typical of high resolution panchromatic imagers, with the surface characterisation capabilities of the hyperspectral imager: this is the scope of Multiresolution Data Fusion techniques that have many application examples in literature [5]. As technology rapidly evolves more and more sensitive detectors have becoming available and the design of state-of-the-art hyperspectral imagers is getting more and more an opportunity for instrument manufacturers;. Galileo Avionica actively involved in this field and in the development of relevant critical technologies, has completed the design of a space-borne Hyperspectral Imager for the HypSEO mission, defined with and financed by the Italian Space Agency (ASI).

3. HSI DATA APPLICATIONS

At the beginning of the HypSEO design, in parallel to the definition of the mission and its subsystem, "level 2" hyperspectral products were examined in order to exploit their potentialities. They have been divided in three areas, Land, Sea and Atmosphere and related parameters have been specified in order to define the subsequent algorithm development. Among the identified products, a subset of them has been selected to perform a sensitivity analysis. The minimum variation for each parameter that HypSEO sensor is able to identify for each VNIR and SWIR channels has been estimated in the assumed range and with the required level of SNR.

The validation of the HypSEO Level 2 Processors was carried out on AVIRIS and MIVIS airborne data over Italian sites focusing on the capability of hyperspectral sensors for unmixing spectral signature. The main investigated topics have been the following:

- Surface reflectance retrieval
- Recognition and classification in urban/industrial area
- Recognition and classification of sea bottom environment in coastal zones
- Mapping and characterization of hot spot in volcanic areas.

Using the same data collected during the airborne campaign they have been evaluated other products addressing security applications. As an example in fig. 1 it is shown an industrial site in which different cover materials are classified, to assess the presence of potentially hazard materials (like asbestos for example).

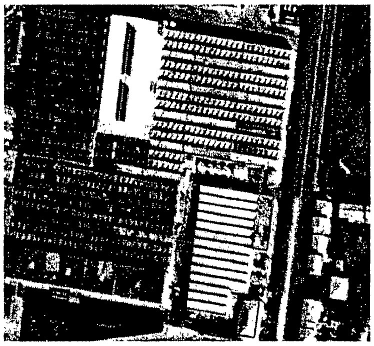

Fig.1a: Panchromatic view of an industrial site

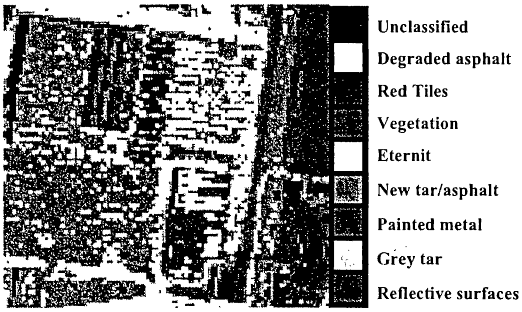

Fig.1b: HSI classification of cover materials

On the target recognition item, as an example, fig.2 shows a camping site where different tents and metallic surfaces (vehicle and roulettes) have been recognized in high dense vegetation area.

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Fig.2a: Airborne HSI true colour view of a camping site

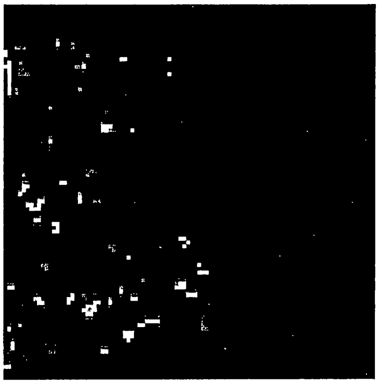

Fig.2b: Target recognition map based on MTMF classification

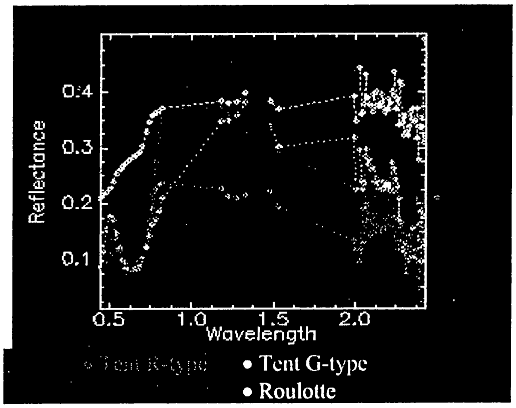

Fig.2c: Target spectral signatures used for the MTMF classification procedure

HypSEO-like images were obtained from the MIVIS airborne campaign data through a simulation software tool [6] implemented in ENVI-IDL environment. The tool basically consists in degrading high quality spectro-radiometric images having good spatial and spectral resolution and low noise levels in order to convert them into images with the desired characteristics through procedures of convolution, re-sampling, noise addition and simulation of atmospheric effects. This simulation tool has been extensively used to evaluate the overall performances of the new space-borne imager; to simulate final and intermediate products over areas where high resolution airborne and ground truth data were available; in the definitions of hyperspectral imager requirements, allowing trade-offs between different design solutions, and selecting the optimal imager characteristics.

An example of possible simulation results are shown in Fig.3a,b where a space-borne HypSEO hyperspectral camera radiance image at 20m of spatial resolution was simulated on the basis of an airborne MIVIS reflectance image (S.Rossore Park, Tuscany, Italy).

In Fig. 3c,d a comparison between simulations of the HypSEO-like panchromatic image obtained from an IKONOS image at different pupil diameter is shown for low radiance conditions.

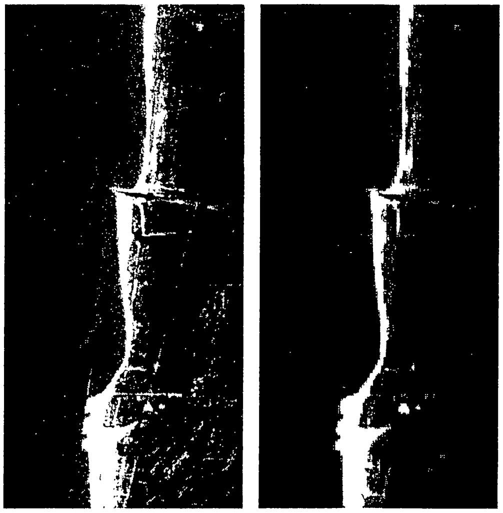

Fig.3: a) RGB of the input MIVIS airborne reflectance image (2.5m); b) RGB of the output simulated Radiance (20 m)

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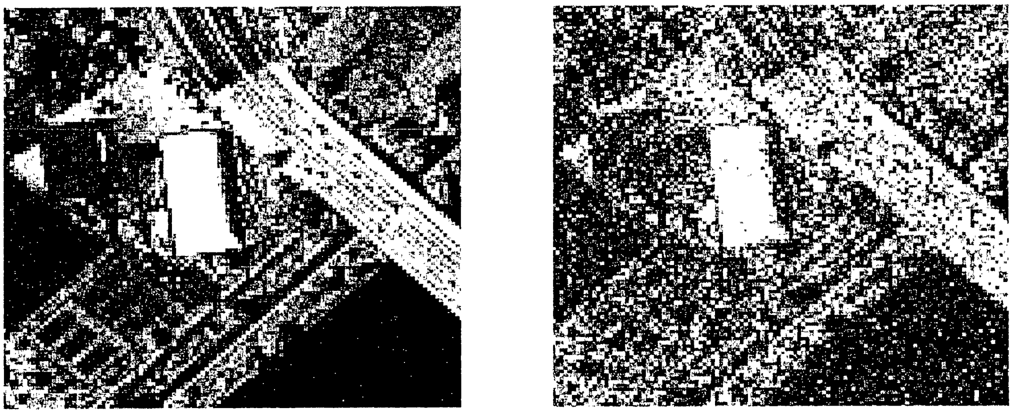
a) b)

Fig 3: Compared simulations of a panchromatic image at equal spatial sampling interval (2.5 m) with different pupil diameter: c)300 mm; d) 150 mm. (SNR corresponds to a low radiance of 18 W*m^{-2}*sr^{-1}*µm^{-1}):

4. HYPERSPECTRAL IMAGER DESIGN

The instrument specifications addressed two bands, where most of the interesting products material spectra lay: the VNIR and SWIR bands, ranging from 400 to 2500 nm, with spectral sampling chosen around 10 nm, programmable by pixel grouping. Spatial resolution was specified at 20m, so to have good SNR and a reasonable swath of 20Km; to enhance the geometric capability of recognition, it was added a panchromatic channel with GSD of 5m, and to extend the coverage an across track pointing mirror has been specified. The reference SNR was specified at fixed sun illumination characteristics typical for the northern emisphere latitudes, i.e. at Sun Zenith Angle of 60°, and with surface reflectance albedo of 0,3: the specifications for it ranged from >100 for SWIR band to >200 in the VNIR band. To allows higher SNR at greater GSD, it has been requested also a programmable binning of pixels.

The driving factors for the HYC design [7] were then its SNR, the GSD, the spectral bands and resolution and finally the overall dimensions and mass. The SNR imposed an high throughput of the overall optics, large aperture and a prism spectrometer design, which offers better performance than grating based design. The GSD imposed the focal length to the optics, and the choice of fast-readout detectors (with several output channels) in order to respect the pushbroom continuity of the image. The prism spectrometer design presents a non linear dispersion of the spectrum, which can be easily calibrated. The Instrument block diagram is shown in Fig 4.

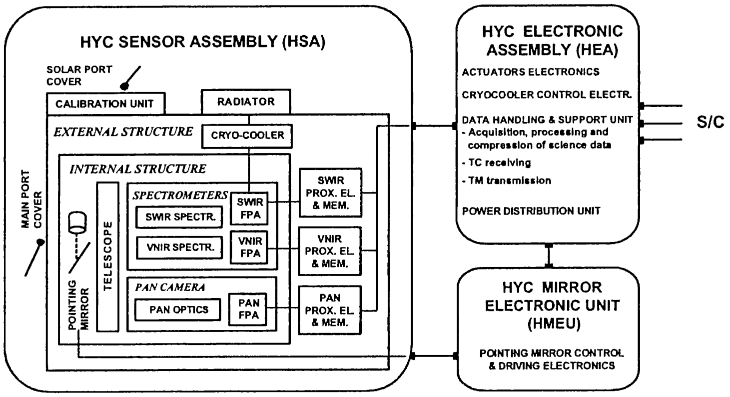

Fig 4: HYC Block Diagram

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The sensor optical head has been separated by the electronics unit to allow a better thermo-structural location within the spacecraft. In the optical head, the telescope is common for the spectrometer channels and the panchromatic camera; also the first dispersion section of spectrometer is common to both channels, leaving to the final section the separation VNIR/SWIR. The FPAs are based on state-of-the-art detectors, custom designed, with main characteristics given in the following Table 2.

Channel	Technology	Size	Outputs	Max readout rate	Remarks
VNIR	Si	1024×256	16	> 5 MHz	Custom design
SWIR	HgCdTe	1024×256	16	> 5 Mhz	Custom design
PAN	CCD	4096×1	4	> 7.5 MHz	COTS

Table 2: HYC Detectors

Fig 5: Pointing mirror, telescope and spectrometer assembly

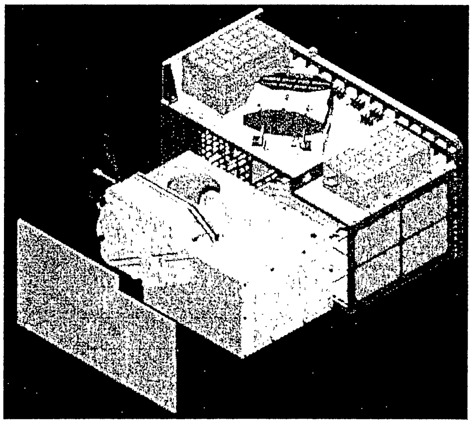

Fig 6: HYC Sensor Optical Head configuration

The structural configuration takes into account different requirements coming from thermal and structural considerations, allocation of coolers for SWIR detector and positioning of the proximity electronics boxes close to the detectors. The large pointing mirror and the telescope optics are the core of an internal structure (see Fig. 5) which is also the support for the spectrometer; the proximity electronics and FPAs coolers are located in an external structure, which is also the support for the calibration unit (upper entrance in Fig 6).The active cooling system of the SWIR FPA and the passive radiators to thermally balance the whole sensor head are attached to the external structure.

For the Instrument calibration design a special effort has been dedicated by an interdisciplinary team composed of scientists, products developers and instrument manufacturer: first the instrument calibration needs of the users have been identified, then a plan for the on-ground calibration before launch and in flight calibration updates has been defined, generating requirements both for the instrument (the embedded in-flight calibration unit), the instrument AIV activities on-ground, and the calibration products development specification.

The instrument electronics is divided in an hardware block that controls detectors, their sampling and memorisation; a solid state memory of 42 Gbits has been designed in the Imager to allows storage of up to 10 images at full resolution for delayed transmission to Earth. Sampling rate and pixel grouping and binning are selectable, in order to have both spectral grouping and spatial binning linearly programmable.

An important feature of the HYC is the availability of the PAN channel at higher spatial resolution; the utilisation of multi-resolution data-fusion techniques enhance the feature extraction capabilities, especially in the "sub-pixel extraction" mode.

The resulting instrument draws, in daily average, 60 Watt; the sensor head has dimensions of 900x600x1100 mm and the overall mass (sensor head and electronics box) is 110 Kg.

The Instrument characteristics and performances as result from the phase B design are reported in the following Tables 3 and 4:

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Table 3: HypSEO Imager characteristics (a)

Optics	
Pointing Capability	Imaging modes: ± 22° (±250 km across track at 620Km altitude) Calibration mode: 180°
Spatial Sampling	VNIR: programmable GSD from 20 to 80 m SWIR: programmable GSD from 20 to 80 m PAN: GSD 5 m SWATH: 20 Km
Telescope	Effective pupil = 150 mm Focal Length = 557 mm IFOV = 6.67" (20 m) FOV = ±0.926° (20 Km) F# = 3.7
Spectral Band	VNIR 0.4 ÷ 1.1 μm (≅ 66 bands) SWIR 1 ÷ 2.5 μm (≅ 134 bands) with overlap for water content calibration
Channels separation	VNIR / SWIR: dichroic separation PAN / VNIR & SWIR: in field separation
Average Spectral Sampling	VNIR 10.6nm (prism dispersion) SWIR 11.2 nm (prism dispersion) VNIR & SWIR programmable from 11nm to 44nm
Focal Planes	
VNIR FPA	Si matrix array hybrid CMOS technology 1000X100 pixel
SWIR FPA	HgCdTe matrix array hybrid CMOS technology 1000X150 pixel
Thermal Design	
VNIR FPA Cooling	Passive
SWIR FPA Cooling	Actively cooled to ~ 160° K by means of a cryocooler
Instrument Cooling	Main radiators on cold face
Calibration	
Radiometric Calibration	Single diffuser for sun irradiance measurement Dark signal by shutters in front of spectrometers slit
Spectral Calibration	2 lamps (one for each channel) + redundancy

Table 4: HypSEO Imager characteristics (b)

Performances	
SNR (@ ρ=0,3 and SZA=60°)	VNIR: 200 @ 0.7 μm SWIR: 130 @ 1.25 μm 110 @ 1.6 μm 60 @ 2.1 μm) PAN: 160
Polarisation Sensitivity	< 1%
MTF at Nyquist frequency	≥ 0.2
Electronics	
Proximity Electronics	Dedicated for each channel
Analog chains & ADC	12 bits ADC
Data Rate	
VNIR FPA to PE	16 links at 1.5 MSPS
SWIR FPA to PE	16 links at 3.04 MSPS
PAN FPA to PE	4 links at 1.41 MSPS
Total data rate	≅ 1 Gbps
HEA to S/C	2 Mbps average (peak 25 Mbps)
Power Consumption	
Imaging & Calibration	180 W
Stand By	22 W
Average (24 h)	59 W
Mass Memory	
	42 Gbit
Mass	
HSA	95 Kg
HEA	10.5 Kg
HMEU	0.9 Kg
Cabling	3 Kg
Overall HYC	110 Kg
Dimensions	
HSA static	900 x 600 x 1100 mm
(HSA cover open)	(1100 x 650 x 1100 mm)
HEA	291 x 380 x 283 mm
HMEU	190 x 160 x 40 mm

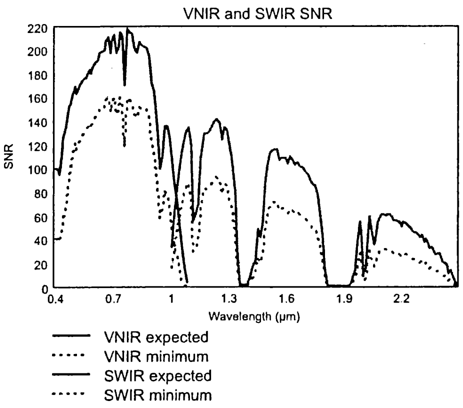

Fig 7 – SNR at reference nominal conditions

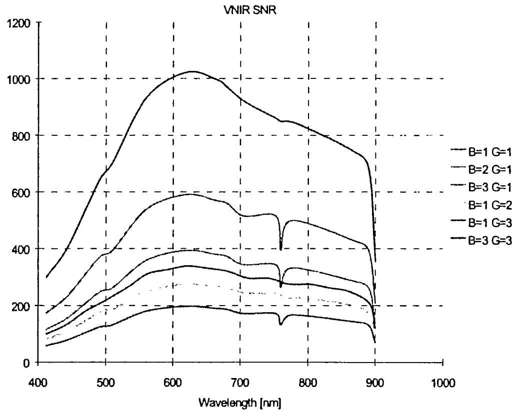

Fig. 8: VNIR SNR with grouping and binning

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5. INSTRUMENT PERFORMANCES

Instrument SNR performances at nominal conditions, predicted by a mathematical model whose parameters are based on the design results, are reported in the following Fig 7. Comparing also to other hyperspectral imagers for space application, the HYC SNR is a state-of-the-art figure given its aperture and GSD characteristics.

Other SNR performances, still at $\rho=0.3$ and SZA = 60°, but at different spectral grouping and spatial binning are reported in Fig 8 and Fig 9.
As can be seen the SNR range can be modulated choosing different GSD or spectral sampling interval (SSI). In fig. 8 and 9 SNRs up to GSD=60m and SSI = 33nm are shown.

The grouping and binning factors linearly modify GSD and SSI as below:

$$GSD = B \times 20[m]$$

$$SSI = G \times 11[nm]average$$

And in the plots from the graphs one can appreciate that the linear increase of SNR with spatial binning, and the increase by square-root with spectral grouping; this is particularly true when adjacent pixels have similar reflectance

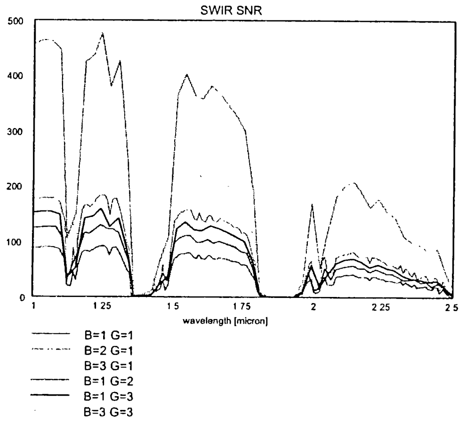

Fig 9: SWIR SNR with grouping and binning

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. Manolakis D., *Overview of Algorithms for Hyperspectral Target Detection: Theory and Practice*, Proc. of SPIE 2002, vol. 4725, 202-215.
2. Landgrebe D., *Information Extraction Principles and Methods for Multispectral and Hyperspectral Image Data*, Information Processing for Remote Sensing, ed. C.H.Chen, NY,1999,.
3. Leachtenauer J.C. et al., *General Image Quality Equation: GIQE*, Applied Optics – IP, vol. 36 is 32, Nov 1997.
4. J. Sweet, J. Granahan, M. Sharp, *An objective standard for hyperspectral image quality,* BAE SYSTEMS Comercial Remote Sensing Group
5. Pohl C., *Tools and Methods for fusion of images of different spatial resolution*, International Archive of Photogrammetry and Remote Sensing, vol. 32, Valladolid June 1999, Spain.
6. Coppo P., R.Bonsignori, L.Chiarantini, A.Capanni, Performance simulation of space-borne optical sensors using airborne hyper-spectral imagery, Workshop on "Airborne Remote Sensing for Geophysical and Environment", Rome 14-16 April 2003 (to be published on Geophysical Annals)
7. Bini A., L. Tommasi et al., *Hyperspectral Camera for HypSEO Mission*, IAF – 2001, Tolouse October 2001, France.

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