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MISTIGRI: a new mission in the Thermal Infrared

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Abstract

The land surface temperature LST is a key parameter for monitoring the water and energy budgets of the continental biosphere. Applications in agriculture and hydrology today require new spaceborne LST observational techniques that provide both high revisit capabilities and high spatial resolution to allow one to characterize the rapid changes in surface conditions (irrigation, rainfall) at the field scale. The paper describes a project of microsatellite, MISTIGRI, combining a 50 m resolution with a 1 or 2 day-revisit. The expected applications and the mission requirements are described. The instrumental concept proposed is finally presented.

1. INTRODUCTION

Global change results from the conjunction of climate change and environmental modifications induced by human activities (land use change, urbanization, emissions of pollutants...). Global change induces a lot of potentially severe impacts on the physical environment (such as floods, erosion, deforestation...) and finally on society itself (energy consumption, displacement of populations, health...).

The drifts observed in climate these last years have confirmed the reality of the phenomena (Climate Change 2007: Synthesis report IPCC), and made citizens more and more aware of possible short term environmental consequences (loss of biodiversity, natural hazards...) as economical and geopolitical ones. The contribution of anthropogenic effects and greenhouse gases in the determinism of the drifts is simultaneously more and more recognized (IPCC report). Man interacts very strongly and very rapidly with environment at all spatial and temporal scales (by agricultural practices, landscape organisation, urban planning...), which makes

operational methods for observing and monitoring the various impacts absolutely necessary.

The interactions between the water and carbon cycles and climate processes here play a crucial role. For continental surfaces, the exchanges of water, CO₂ and energy between land surfaces and the atmosphere drive the development and growth of vegetation, and the biogeochemical cycles, which in turn exert strong retroaction effects on climate.

Surface temperature (Ts) is a key signature of the surface energy budgets; it can be directly related to the surface energy fluxes, and particularly to the latent heat flux (i.e. evapo-transpiration) and water stress (Courault et al., 2005; Kalma et al., 2008; Boulet et al., 2007, among others). A lot of methods have been proposed to use thermal infrared (TIR) remote sensing for monitoring the surface conditions and for developing practical applications in different fields: agriculture, hydrology, climatology... But researchers and users still have to face a dilemma between spatial and temporal resolution: systems such as AVHRR, MSG, MODIS provide daily observations at low resolution on the one hand, while systems such as Landsat or ASTER on the other hand provide high resolution images, but with poor revisit capabilities of about 2 weeks. Several attempts have been made to disaggregate low resolution imagery down to a few tens of meters (Agam et al., 2007; Inamdar et al., 2008; Inamdar and French, 2009; Merlin et al., 2010), with the scope of exploiting the daily revisit of AVHRR, MODIS or Meteosat systems, making possible the monitoring of rapid changes in relation with rainfall or irrigation for instance. But despite some progress, the results are not robust enough, partly because it is difficult to account for the variability of the various field within the coarse resolution pixel (in particular fields covered with the same crop may display important differences in water status and evapotranspiration rates, in relation with

irrigation or soil hydrodynamic properties). Significant improvements in the modelling and monitoring of the vegetation/climate system, particularly at local scale, are now expected from the availability of new spaceborne LST observational techniques that provide both (i) high revisit capabilities and (ii) high spatial resolution. This is the goal of the MISTIGRI (**M**icro **S**atellite for **T**hermal **I**nfrared **G**round surface **I**maging) mission designed to associate a resolution of 50m and a revisit of 1 or 2 days.

2. SCIENTIFIC OBJECTIVES

The first priority of the MISTIGRI mission lies in the monitoring of energy and water budgets of the continental biosphere. Nevertheless other fields of applications have also been identified. An important one deals with the urban climatology. A third family finally gathers various applications for which the potential of MISTIGRI is currently being investigated in details, and among which the monitoring of coastal areas and continental waters is of particular interest.

2.1 MONITORING OF ENERGY AND WATER BUDGETS OF THE CONTINENTAL BIOSPHERE

The high revisit capacities of MISTIGRI will allow assessing the land surface water status by providing accurate observations between consecutive irrigations or rainfalls. The estimation of evapotranspiration (ET) will rely on the use of different models in conjunction with MISTIGRI data. Several approaches can be followed:

First simplified algorithms based on the analysis of the relationships between T_s and albedo (or NDVI) and using only little additional input data allow to estimate AET directly from T_s (see reviews by Carlson, 2007 and Kalma et al., 2008). These algorithms are SEBAL (Bastiaanssen et al. 1998, 2005, Jacob et al. 2002), S-SEBI (Roerink et al. 2000, Gómez et al. 2005; Galleguillos et al., 2010), SEBS (Su 2002; Oku et al., 2007; van der Kwast et al. 2009), METRIC (Allen et al. 2007). Temporal interpolation of ET maps between dates when TIR data is available is necessary to ensure a continuous monitoring of water status, whereas assimilating ET into hydrological models can improve their calibration and initialisation (Schuurmans et al., 2003).

The second possibility is to use bio-physical soil-vegetation-atmosphere transfer models (SVAT) associated to inversion (Jacob et al., 2006) and assimilation procedures (Oliosio et al. 1999, 2005; Coudert et Otlé 2007). Assimilation techniques provide well-established mathematical frameworks for introducing information on observation and model errors, and on a priori information. They have been proposed for retrieving model parameters (soil physical properties, stomatal conductance parameters...) or initial values of model variables (e.g. soil water and nitrogen content, sowing date...) using model calibration techniques. Other

methods consist in correcting the time course of model variables (soil moisture, LAI, biomass...) by comparing model simulations to remote sensing measurements each time they are available (Crow et al., 2008; Pellenq and Boulet, 2002). Their application to soil-vegetation-climate interactions models is just starting and almost restricted to the assimilation of reflectance and microwave data at the moment (due to the lack of adequate TIR data). High revisit systems will stimulate the development of TIR data assimilation. This will improve the retrieval of soil moisture and evapotranspiration dynamics for managing water resources in irrigated agriculture area, in particular in situations when a limited amount of water is available (e.g. deficit irrigation systems).

The aim of MISTIGRI is (i) to contribute to the improvements and validation of the models and approaches themselves, and (ii) to evaluate their potential for practical applications. For this purpose, a network of experimental sites is associated to MISTIGRI, following the same concept as the VEN μ S mission (<http://www.cesbio.ups-tlse.fr/fr/indexvenus.html>).

The expected main fields of application deal with:

- agriculture: monitoring of the growth, impact of agricultural practices on water use, detection of stress with application to irrigation or forest fire risk...
- hydrology: water budgets of watersheds, monitoring of water tables
- biogeochemical cycles: assessment of carbon fluxes and budgets using vegetation models.
- meteorological forecasting, through the improvement of the parameterization of the surface processes in the meso-scale models.

Methodological progress is expected from MISTIGRI, among which:

- the study of directional anisotropy (Lagouarde et al., 2000; Kurz, 2009)
- the development of TIR data assimilation techniques and the improvement of technique for water stress detection
- the determination of emissivity and temperature-emissivity separation
- the study of aggregation processes and scaling, which should in turn to contribute to an improved use of the low resolution data of the global cover sensors such as AVHRR or MODIS.

2.2 MONITORING OF THE URBAN ENVIRONMENT

The climate over cities is significantly affected by a number of characteristics proper to urban areas. The three-dimensional structure of urban canopies with important heterogeneities both at local scale (heights of buildings, orientation of streets...) and at larger scale (vocation of districts: settlement, industrial, commercial...), alter the roughness of the surface and the

flow within the urban atmospheric boundary layer. The use of a large panel of artificial materials with contrasted surface properties also affects the radiative transfers, while the reduction of vegetated areas and the increase of impervious surface combine to modify water cycles drastically. Human activities also contribute to urban climate by several ways: urbanization, emission of pollutants, increase of energy consumption among others. It finally results in a strong variability of microclimates inside cities and in differences with surrounding rural climate, the well-known urban heat island phenomena.

Since the end of the 90s, important progress has been made on the modeling of surface energy budget at local scale (Voogt and Oke, 2003; Hénou, 2008) and at meso-scale (Martilli et al., 2002; Masson, 2006). In the same time, methods based on the use of 3D descriptions of the urban canopy allowed to describe the TIR directional anisotropy (Soux et al., 2004, Lagouarde et al., 2010). Simultaneously, several models focusing on the radiative transfer have been proposed (Fontanilles et al., 2008; Belot, 2007). The aggregation processes of facets temperatures and emissivities can also be studied using codes such as TITAN (Fontanilles et al., 2008). A large panel of modeling tools adapted to urban canopies is now available. It allows one to relate the measurements from space to the surface characteristics and fluxes, which had remained a difficulty for a long time (Roth et al., 1989). The fields of application of MISTIGRI are

Urban climatology and heat waves. The increase of the frequency and intensity of heat waves expected as a consequence of the climate change makes necessary policies for mitigating their effects (reduction of the number of casualties among the elderly, adaptation to energy consumption increase with the use of air conditioning...). A strong demand exists for building alert systems and improved urban planning (see <http://www.urbanheatisland.info/>, an ESA UHI project). The important literature on UHI confirms the potential of TIR remote sensing (Arnfield, 2003).

Urban hydrology. Accurate estimations and mapping of ET are expected for a better assessment of the water budgets of urban watersheds (Carlson and Arthur, 2000) and for urban planning.

Monitoring of urban vegetation. Vegetation plays a significant role for hydrology (by increasing water storage capacities of ground and limiting runoff) and for the welfare and health of inhabitants (humidification of air, shading effects and reduction of temperatures...).

Diffusion of pollutants and air quality. The surface temperature here brings an indirect but important contribution by the fact it provides means to validate the atmospheric flow and diffusion models.

Anthropogenic fluxes (industrial activity, air conditioning or heating of buildings, transport...). A few recent studies reveal they can be estimated through the closure of the surface energy budgets (Pigeon et al., 2007).

2.3 MONITORING OF COASTAL AND CONTINENTAL WATERS

Many research fields can take benefit of MISTIGRI data (vulcanology, geology, ocean...). Among those we chose to emphasise applications dealing with coastal and continental waters in this paper.

SST, air-sea fluxes and winds: In coastal area, several processes are responsible for intense and narrow SST gradients ~1 km (for instance fresh water coming from rivers or estuaries...) which have an impact on air-sea fluxes as well as winds (Chelton et al., 2007; Donlon et al., 2009). MISTIGRI will allow one to follow such fronts displaying SST signatures (up to 10°C in temperature) not detected with current satellite data.

Submesoscale activity in coastal and open ocean: Submesoscale and mesoscale eddy fields are responsible for most of the kinetic energy of the ocean. At the moment, we can only study mesoscale activity of the ocean with satellite and in situ data. Data are needed to observe submesoscale activity -1 to 100 km scale- (Fu et al., 2009) characterized by fronts, filaments which have a large impact on vertical transport of different properties (nutrients, CO₂...).

Monitoring of the coastal ocean: A number of applications are expected:

- coastal oceanography (internal waves, etc), sea state (storm surge, etc)
- estuary hydrology
- exchange of properties between the land and the coastal ocean and contribution to carbon, nitrogen and other biogeochemical cycles
- estimations of greenhouse gas fluxes (CO₂, N₂O, CH₄...) at the air-sea interfaces in coastal areas
- pollutant discharge from the rivers, estuaries into the coastal area
- exchanges (ex: heat, pollutant) over the tidally portion of rivers, estuaries and wetland
- coastal zone management, water quality monitoring, shoreline monitoring (i.e. erosion/sediment transport)
- algae blooms
- monitoring of halieutic resources,
- marine services

Continental waters (lakes and rivers): Surface water temperature of lakes has been defined as Essential Climate variable by GCOS. It is planned to introduce this parameter in the future lakes and reservoirs international database (Hydrolare / Hydroweb) hosted by State Institute of Hydrology of St Petersburg and Legos for at least the 150 lakes of the GTN-L list (Global Terrestrial Network for Lakes). The high spatial resolution of the MISTIGRI data will also be used in a variety of other applications (confluence of rivers and lakes, monitoring of floods...)

2.4 STRATEGY OF THE MISSION

As for Venus, the MISTIGRI mission will tightly associate a spatial system with experimental sites monitored by scientific teams at ground. The large number of existing networks (FLUXNET, ICOS, LTER...) ensures that sites representative of different climates and land use will be available in the future.

3. MISSION REQUIREMENTS

3.1 SPATIAL RESOLUTION

The choice of the spatial resolution is guided by two constraints. First, classically as for VNIR channels, it must be compatible with the typical size of the ground units of the studied areas: this imposes an upper limit that should not be overpassed for having the largest number of homogeneous pixels as possible. But in the TIR the resolution must simultaneously cope with the turbulent nature of the surface temperature which displays temporal fluctuations driven by the variations of micrometeorological conditions at the surface: this makes a minimum resolution necessary to provide sufficient reduction of the temporal fluctuations by spatial integration of turbulent structures at pixel scale. The 2 limits are examined in what follows.

3.1.1 Upper limit of the resolution

It is obviously difficult to propose a unique value, as it depends on the type of landscape studied. Nevertheless, we can refer to Kustas et al. (2004) who studied the resolution necessary to separate the contribution to actual evapotranspiration of 2 crops, soybean and corn in the Iowa plain where fields have a typical size of 100x100m.

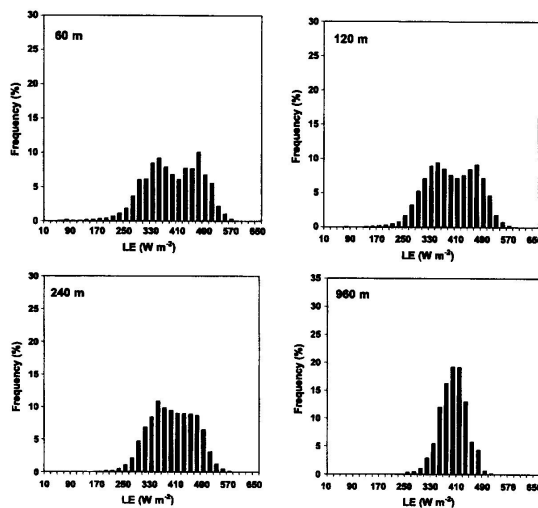


Figure 1: histograms of actual evaporation for a region including 2 crops at resolutions 60, 120, 240 and 960m (after Kustas et al., 2004).

He showed that a resolution larger than about 100m makes difficult to discriminate the contribution of each crop (Fig. 1). In the case of Texas high plains where the typical size of fields is ~800x800m Agam et al. (2007) found that a resolution $\leq 100\text{m}$ is optimal for agricultural applications: such a resolution allows one to resolve differences between fields, and within fields satisfactorily. A similar conclusion was found by Garrigues et al. (2006) who quantified the spatial heterogeneity of the NDVI for 18 landscapes of the VALERI database (<http://w3.avignon.inra.fr/valeri/>) and similarly concluded that 'the sufficient pixel size to capture the major part of the spatial variability of the vegetation cover at the landscape scale is estimated to be less than 100m' (Fig. 2). We can also refer to the recent lobbying of users for requiring a thermal channel on Landsat LDCM at a 60m resolution (<http://www.idwr.idaho.gov/GeographicInfo/Landsat/land-sat-thermal-band.htm>).

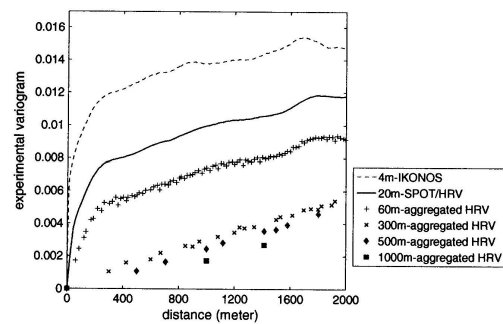


Figure 2: NDVI variograms over a mediterranean shrubland at different resolutions (after Garrigues et al., 2006).

3.1.2 Lower limit of the resolution

The surface temperature displays temporal fluctuations of different frequencies related to turbulence in the surface boundary layer (high frequencies) and in the convective planetary boundary layer (low frequencies). The first ones correspond to turbulent structures of a few meters and can be smoothed by the spatial integration at the pixel scale (the so-called 'ergodicity') while the second ones (a few hundreds meters size) cannot be reduced and contribute to the uncertainty on the T_s measurement. Experiments performed over maritime pine stands using a helicopter-borne TIR camera (Lagouarde et al., 1997) indicate that a resolution finer than ~40m is not useful (Fig. 3). A confirmation of these results is expected in 2010 in the framework of the CNES/MISTIGRI program (i) by repeating the same experiment over a large range of surfaces (from bare soils to cities) in the South of France, and (ii) by performing a numerical study using an improved version of the ARPS LES model developed at the Oklahoma University. To our knowledge no similar results can be found in literature.

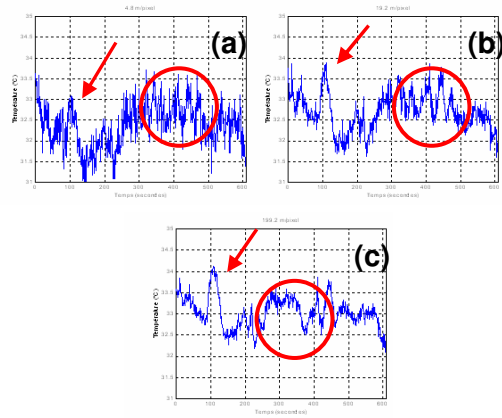


Figure 3 : temporal evolution of the surface temperature over a 600s period (1Hz acquisition frequency) above a maritime pine stand in the South-West of France (Le Bray Carbo-Europe INRA site, August 16, 1995, helicopter-borne measurements) for ~5 m (a), ~19 m (b) et ~200 m (c) aggregated pixel sizes. The low frequency fluctuations related to convection in the PBL (arrow) remain present regardless of considered spatial resolution, whereas high frequency fluctuations are smoothed by spatial integration at pixel scale. The Y axis ranges between 31 and 35°C.

In conclusion, taking into account the elements of justification above mentioned the proposed resolution around 50m seems to be a good compromise. It is consistent with the 60 and 90m of Landsat ETM+ and ASTER. Moreover it is practically compatible with a reasonable swath (~25 km) at nadir.

3.2 REVISIT

For agriculture and water monitoring applications which are the first priorities of the mission, users generally consider it is necessary to fulfil the condition of 1 TIR cloudfree image available every five days. Two complementary studies were recently performed to analyse the revisit capacities (1 or 2 days?) adapted to this goal:

The first one is based on the analysis of a hourly solar irradiance database from the INRA AGROCLIM network. It was performed on 18 years datasets (1992-2009) over 5 French stations corresponding to different locations and climates. Hourly values of solar irradiance under cloudfree conditions for each time of the day and date of the year was first extracted from the database and confirmed using an empirical model. Statistics were then made on the number or satellite acquisition possibilities using a simple ratio criteria applied on the measured solar irradiance. The impact of the revisit was evaluated by sampling the data base previously to reanalysis. This approach also allows to make a comparison between potential acquisition times (and to evaluate the possible impact of phenomenas such as morning haze or afternoon development of convective summer clouds... on data availability)

The second study is based on the analysis of MODIS products of cloud masks (2000-2008), and similar statistics are proposed.

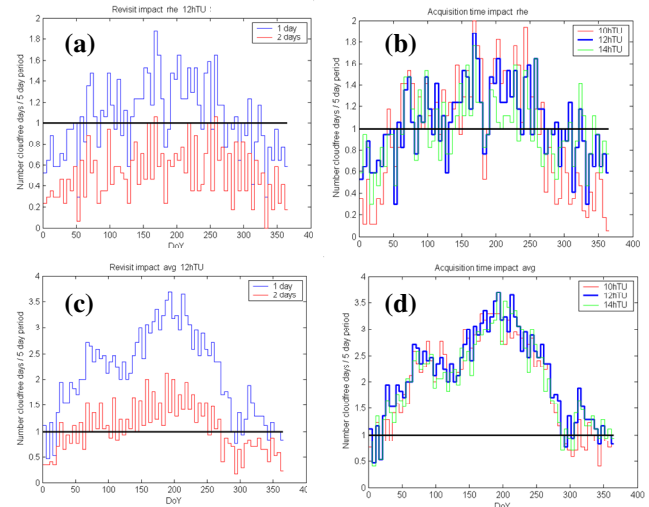


Figure 4: Impact along the year of the revisit (1 or 2 days) on the availability of data by 5 days periods (a: Rennes, c: Avignon). Impact on the acquisition time (b: Rennes, d: Avignon). [Yaxis: 0-2°C (a, b), 0-4°C (c, d). Xaxis DoY].

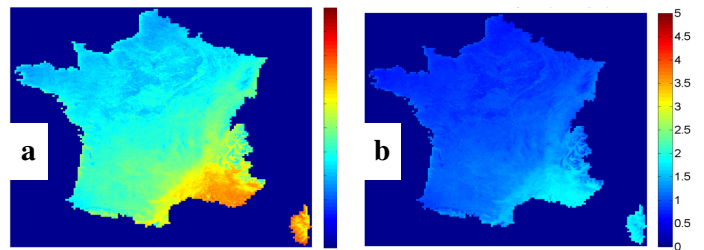


Figure 5: frequency of cloudfree days by 5 days periods during summer over France derived from MODIS at 1 (a) and 2 (b) days revisit. [Colorbar scale: 0 - 5 days].

The results obtained by the two methods are quite comparable. Fig. 4 illustrate that the 1 data per 5 day-period condition can be approached with a 2 day revisit only for a Mediterranean location, Avignon, and only during spring and summer. More detailed analysis (i) considering interval between clear days and possible redundancies when consecutive, or (ii) crossing criteria of vegetation water stress with cloudiness are currently being done for MISTIGRI specifications, but preliminary results are even more critical, and seem to confirm that the 2 day-revisit is not suited to fit requirements on data collection. For instance, for datasets in SW France and Morocco, a 2-day revisit would not warranty that at least one image is acquired per water stress period. The results obtained with MODIS at France scale confirm quite well -at France scale- those derived from the meteorological network data (Fig. 5). The other important conclusion of this study is that acquisition times between 10 and 15 UT have no significant impact on the expected satellite data availability.

3.3 SPECTRAL BANDS

The choice of an optimal spectral configuration is motivated by an accurate obtaining of surface emissivity and radiometric temperature. (Dash et al., 2002 ; Jacob et al., 2008). For MISTIGRI mission, the possibilities are (i) the use of multispectral information only collected over 3 to 4 channels between 8 and 12 μm , (ii) the combining of temporal and spectral information and (iii), the use of reflectance information over the solar spectrum through vegetation indexes or vegetation cover. On the one hand, the combining of temporal and spectral information relies on assuming temporal stability, and is therefore incompatible with the objective of capturing temporal dynamics of hydric status. On the other hand, the use of reflectance information over the solar spectrum depends on ancillary information about soil and vegetation emissivities (Sobrino et al., 2004a ; 2004b). Therefore, the selected option is to use multispectral information only with the Temperature Emissivity Separation (TES) algorithm. The design of the spectral configuration requires developing a simulator based on various spectral libraries (ASTER spectral library V21, MODIS spectral library V2, MEMOIRE database of ONERA...), simple radiative transfer equations for bare soils, a thermal infrared version of the SAIL model for vegetation canopies, the ONERA MATISSE atmospheric radiative transfer code, and the spectral filter functions of the MISTIGRI instrument.

4. PROPOSED MISSION ARCHITECTURE

The mission architecture presented hereafter is the result of technical studies and trade-off led by CNES with the support of TAS as far as the Payload concept is concerned. A MISTIGRI phase 0 was performed over 2008 and early 2009 and a phase A activity is currently on going up to mid 2011.

The MISTIGRI phase 0 led to select a technical base line based on a TIR camera using an “on the shelf” ULIS microbolometer mounted on a bus satellite based on the maximal re-use of the MYRIADE product line. This microbolometer solution is able to fulfill the primary radiometric requirements although requiring any cooling system.

On the other hand, one of the most stringent mission requirement applies to the revisit delay. The one day revisit delay is linked to an orbit altitude of 561 km, while the two days revisit delay is linked to an altitude of 720 km. One day revisit delay is fulfilled at the expense of the earth coverage. The choice among these two altitudes is still open.

Most of the MISTIGRI system elements involved in this base line have strong heritage. ESA and Spain studied the Fuego mission, based on a Thermal Infrared Camera. Infra-red cameras based on microbolometers were developed at CNES for CALIPSO and IASI projects. Finally, the concept of multi-temporal observations is

deeply investigated at CNES for the Venus mission, and at ESA for the Sentinel-2 mission. This will ease the design of the ground segment and of the processing chains.

This heritage will significantly reduce program costs, and technical and schedule risks.

4.1 PAYLOAD AND INSTRUMENTAL CONCEPTS

This section is based on the paper presented at the 2009 SPIE symposium “MISTIGRI Instrumental concept for high resolution thermal infrared imaging” (Tinto et al., 2009).

4.1.1 KEY PARAMETERS

The selected instrumental concept is aimed to be compatible with the MYRIADE microsatellite platform, in its standard configuration. The key parameters defining this scenario are listed in the table 1 below:

Parameter	Value		Comment
Orbit altitude	720 km		2-day revisit phased orbit
Line of sight steering (roll)	Satellite		No folding mirror
Spectral bands	10.3, 11.5, 8.6, 9.1 μm 450, 670, 865, 910 nm		4 TIR bands + 4 VNIR bands
Swath width	25 km		
	VNIR	TIR	
Resolution	20 m	50 m	
Entrance pupil diameter	80 mm	270 mm	
Focal length	468 mm	255 mm	
Aperture	F/7.8	F/0.94	
Detector type	CCD 1D array	Micro- bolometer	Uncooled
Imaging mode	Pushbroom	Supermode TDI-like binning	
TDI-like images / lines	-	8	On-ground binning
Smearing compensation	1.5		By satellite slow down
MTF @ Nyquist	≥ 0.12	≥ 0.12	
NedT @ 290K	-	0.2 to 0.6 K	
SNR @ min radiance	70 to 180	-	
Mass	68 Kg		Including 20% margin
Power consumption	Imaging mode: 54 W Standby: 46 W		Nominal, without margin

Table 1: Key parameters defining the base line scenario

4.1.2 INSTRUMENT MAIN FEATURES

TIR focal plane

A French company called ULIS develops a 640 x 480 micro-bolometer array with a pixel pitch of 25 μm . A trade off was made leading to the selection of this detector for the TIR instrument. Although the sensitivity of micro-bolometers is less than that of cryogenic detectors, such detectors have the main advantage of not needing a cooling system.

In addition, the ULIS detector has several features that are well adapted to the application such as windowing capability or programmable gain. Its main technical characteristics are summarised in Table 2.

Parameter	Value
Technology	Amorphous silicon
Array format	640 x 480 pixels
Pixel pitch	25 μm
Thermal resistance	40 MK/W
Temperature Coefficient of Resistance (TCR)	2 to 3 %K
Thermal time constant	9.2 ms

Table 2: ULIS micro-bolometer main characteristics

It is important to notice that the micro-bolometer thermal time constant introduces a constraint to the satellite operation. Indeed, the sampling time shall be longer than the time constant in order to achieve good MTF and linearity performances. According to the latest measurements on such detectors, the sampling time must be set between 1.5 to 2 times longer than the time constant, i.e. a minimum of 13.8 ms for the present case. Given the orbit at 720 Km altitude, the satellite slow down is by a factor of about 1.9.

The spectral selection is done by a thin-layer interference filter in front of the detector. The filters must be wide enough to acquire the same line of the scene 8 times, thus allowing TDI-like image binning.

TIR optical design

The optical layout is shown in Figure 6. it consists of 4 lenses, one of them being aspheric. In order to limit the number of lenses and keep the objective as compact as possible the entrance pupil is located in front of the back lenses (not at the front lens). The materials selected for the lenses are Germanium and ZnSe. They are chosen to ensure good transmission and the aberration correction in the entire spectral domain.

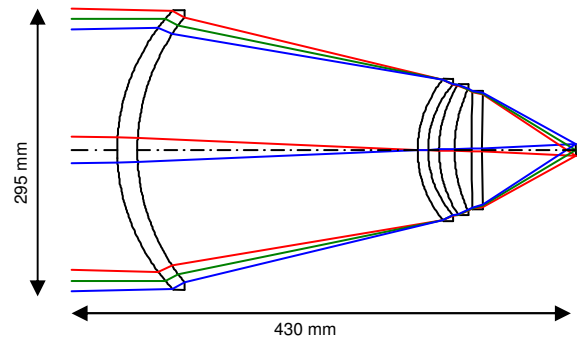


Figure 6: Optical layout

Mechanical & thermal design

The mechanical design of the instrument has been done taking into account the constraints imposed by MYRIADE bus in its standard configuration.

The payload is composed of the following main subassemblies: VNIR telescope and focal plane, TIR telescope and focal plane, three electrical units for payload control and video electronics of each camera, the TIR calibration subsystem and two radiators, one for the focal plane and another for the electronics.

A CAD view of the preliminary mechanical design is shown in Figure 7.

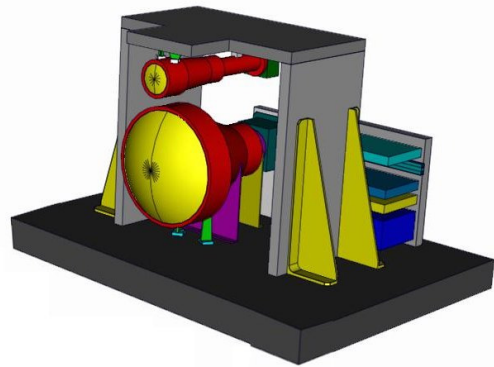


Figure 7: CAD view of the instrument

Calibration

Calibration systems for infrared instruments generally include blackbodies at their entrance so that the entire optical chain is calibrated. Given the size of MISTIGRI's TIR instrument, this solution would need a voluminous blackbody which would be incompatible with the Myriade platform. Instead, it is proposed to implement two blackbodies in front of an intermediate pupil placed next to the back lenses assembly. A diagram of the calibration system is shown in Figure 8; with this solution the size of the blackbodies is reduced.

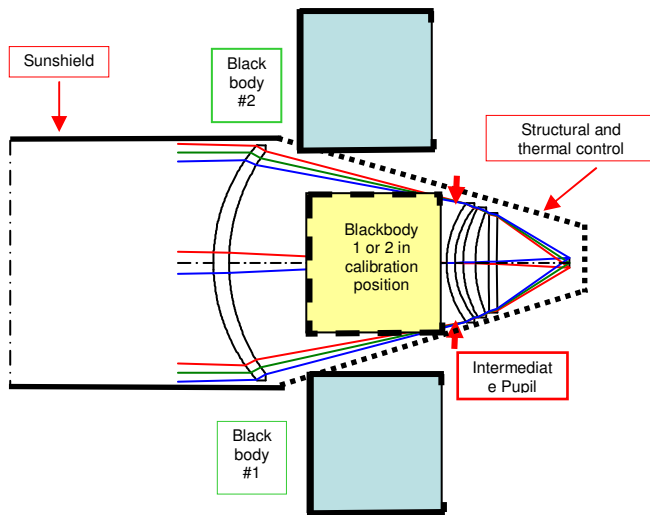


Figure 8: Calibration system diagram

Two blackbodies at different temperatures, 283 K and 313 K, are needed to calibrate the instrument and retrieve the gain and offset values to be applied during image processing. The calibration process should not disturb the thermal equilibrium of the instrument, especially the temperature of back lenses assembly. Therefore a mechanism is needed to slide the blackbodies in front of the optics and then remove them..

Besides, deep space calibration is also needed in order to assess optics' transmission and emissivity drift in-flight. Since there is no folding mirror in the design, deep space steering is achieved by satellite manoeuvring. This operation will certainly disturb the thermal equilibrium of the instrument and therefore should not be performed frequently.

4.2 ORBIT CHOICE

One of the most stringent mission requirement applies to the revisit delay.

In case of only one satellite, one day revisit delay is linked to an orbit altitude of 561km, whereas two days revisit delay is linked to an altitude of 720km. So a preliminary analysis of this altitude alternative has been carried out from the technical point of view.

The choice of one altitude among the two refers to various topics, including instrument and satellite design, launch opportunity and desorbitation, earth coverage, agility ...

- **Instrument TIR & VNIR design**

The design and the performance budget was so far established in case of the 720km altitude. This design is of course easier in case of a lower altitude, allowing to loosen constraint on pupil size or on the number of TDI lines to be acquired.

- **Satellite design**

The standard reaction wheel must be replaced by more powerful wheels for agility purpose. As a result, the Myriade bus is compatible with an 561km altitude. This

561km is moreover easier for desorbitation requirement and thus easier for the hydrazine budget.

At a first sight, the altitude criteria is not decisive for the satellite design

- **Launch opportunity**

It appears to be difficult to find a co-passenger flying at 561 km. So the launch opportunity can be regarded as more difficult at 561 km than at 720 km. However a multiple launch can be considered counting on a launch re-boost enabling to change orbit. This re-boost capability is for instance provided by the SOYUZ launcher.

- **Global access capability : Earth coverage**

The figure 9 below shows the potential earth coverage for the two altitudes assuming a maximum roll angle (across the track) of 30 degrees. These pictures clearly show the gap between the two considered altitudes:

- In case of a 720km altitude, the coverage is pretty satisfactory: it reaches 85 % at the 45° latitude
- In case of a 560 km altitude, the coverage drops down to only 34 % at 45° latitude

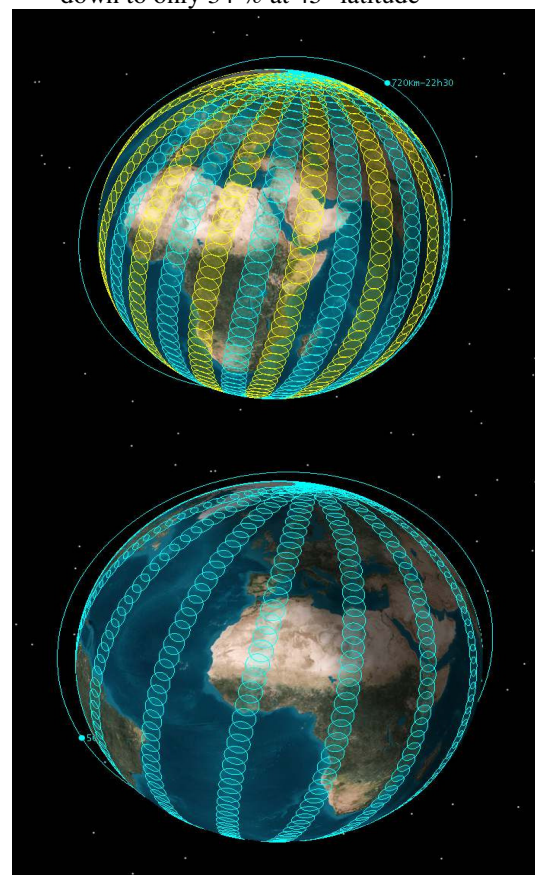


Figure 9: Earth coverage depending on altitude. Top: 760 km, blue and yellow tracks correspond to day 1 and 2 (2 day-revisit). Down: 560 km (1 day-revisit). The circles correspond to a 30° depointing across track.

It is worth to notice that this coverage is only dependent on the roll angle of 30° which is a scientific requirement on geometrical observation conditions of ground sites. This coverage is not limited by satellite capabilities.

- **Acquisition capacity**

In our microsatellite base line, the accessibility of the sites is obtained by rotating the platform, across (roll rotation) or along track (pitch rotation). The objective is to enable an acquisition capacity, i.e. a number of sites to be visited as large as possible.

In the whole, the acquisition capacity is limited by the time duration needed to achieve the manoeuvre including tranquilisation delay, and by the picture duration taking into account the slow down ratio.

Manoeuvre delay is driven by the satellite agility, which depends on the satellite inertia and on the reaction wheels torque and kinetic moment capability. For agility purpose, the standard wheels will be replaced by more powerful wheels.

Part of the wheels whole capacity must be dedicated to the orbit control at the expense of the manoeuvre capacity. This part is higher in the case of 561 km than in the case of 720 km because drag perturbations. Given a satellite agility and a sequence of sites to be visited, roll and pitch rotation will be larger in the case of 561km for geometrical reasons. As a result, acquisition capacity is much lower in case of 561 km.

- **Conclusion :**

Finally, the mission faces an alternative to be chosen between revisit delay and global accessibility. This choice is so far still open.

4.3 SATELLITE

The base line of the spacecraft design, described hereafter, is the use of the micro-satellite platform MYRIADE. The accommodation study performed by CNES, has shown that the MISTIGRI payload described above is compliant with this baseline.

4.3.1 MYRIADE FAMILY

MYRIADE is a multi-purpose flight proven platform developed by CNES in partnership with industry. In June 2010, 8 satellites are already orbiting leading to 35 years of in orbit cumulated life time, including 6 years for the first launched (Demeter). In addition, 10 satellites are currently being developed with 2 of them to be launched in 2nd semester of 2010.

4.3.2 MISTIGRI SATELLITE MAIN FEATURES

The MISTIGRI spacecraft general architecture is based on the last version of the standard MYRIADE bus. This bus features a new mechanical structure, enabling a total satellite mass of at least 200kg. This structure is currently being developed while the TARANIS mission is intended to be the first user. According to the MYRIADE policy, this new structure will be multi-purpose qualified, taking

into account a wide area of mechanical configurations (including the MISTIGRI one) and launchers (Soyuz, Vega, Dnepr, Rockot, PSLV, Falcon 1E).

The only noticeable MISTIGRI change related to this standard version relies on the reaction wheels. The standard MYRIADE reaction wheels are to be replaced by more powerful ones (torque multiplied by about 5) for agility purposes. The current choice is based on 4 MSCI reaction wheels, featuring 2 wheels on the roll axis. MSCI wheels class is regarded as a limit for the MYRIADE bus, mainly for consumption & lay-out reasons.

As an example, the figure 10 below shows the agility performance brought by the MSCI reaction wheels. Figure shows the duration required to perform an angular rotation, either on the roll axis or on the pitch axis.

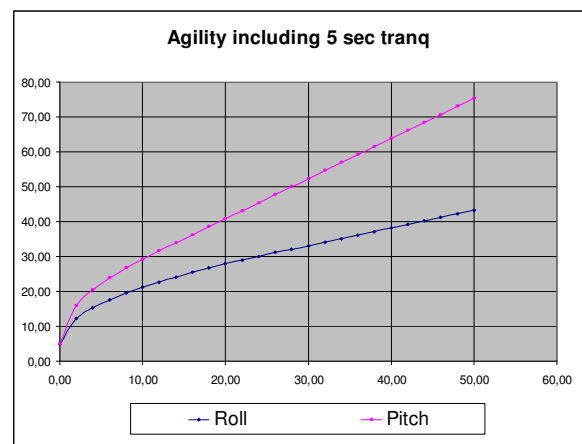


Figure 10: agility performance with the MSCI reaction wheels.

The scientific data produced by the TIR and VNIR instruments are stored in the 16 Gbits Myriade Mass Memory. Downloading of these data is realized through an X band link based on the Myriade High Rate Telemetry (16,8 Mbits/sec).

These Myriade equipments allow to fulfill the MISTIGRI mission needs with a large margin. With the assumption of 80 pictures (VNIR + TIR) per day (which is the current Venus hypothesis), the data volume is about 8 Gbits to be downloaded every day.

Figure 11 below shows a Satellite in orbit general view.

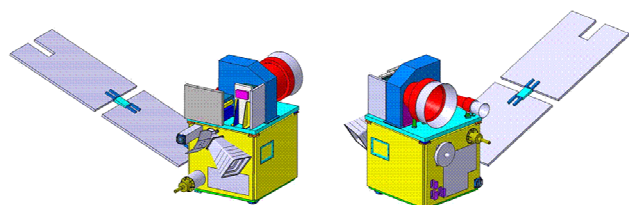


Figure 11: In-orbit Satellite view

4.4 LAUNCH

The following launcher options are kept for starting phase A :

- European launchers : Soyuz, Vega
- Others launchers or dedicated launch on Dniepr as back-up

Two scenario can be considered for the launch :

- Microsatellite as an auxiliary payload flying with a main passenger. This scenario is for instance an ASAP flight on Soyuz launcher. The maximum mass for the future Soyuz / Vega ASAP is about 200 kg. This 200 kg value will be considered as a maximum for MISTIGRI satellite. This ASAP configuration is as well the more demanding regarding the allowable volume under fairing.
- Microsatellite on a dedicated launch, flying with a co-passenger or not.

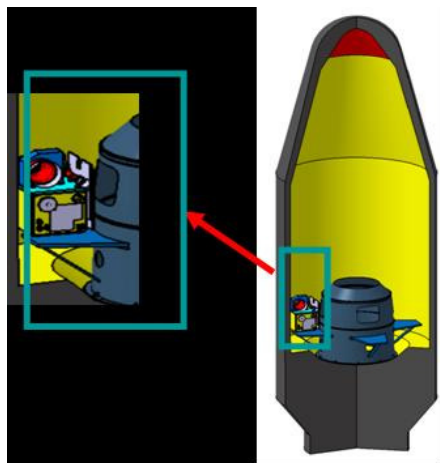


Figure 12: MISTIGRI Satellite in SOYUZ ASAP launch configuration.

It is worth to notice that a desorbiting requirement is taken into account. The MISTIGRI duration in orbit will be less than 25 years, after the end of the operational mission

4.5 GROUND SEGMENT

The following diagram provides with an overview of the five components of the system and the data exchanges between them:

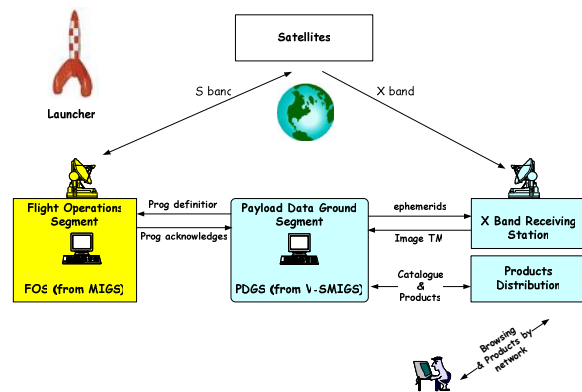


Figure 13: System overview

The MISTIGRI system encompasses 4 main components:

1. a satellite,
2. a Flight Operations Segment. Based on the generic CNES micro satellite ground segment (MIGS), already used for several years. This MIGS features a control centre with the regular functions (telemetry processing and archiving, telecommand generation and sending, ...), as well as a link to the CNES 2 GHz earth terminal network, interfacing with the satellite when in visibility of an S band Earth Terminal,
3. a Payload Data Ground Segment. Based (PDGS) on the Venus Scientific Mission Ground Segment (Venus SMIGS). At date, SMIGS development is completed, and the SMIGS integration in the rest of the Venus system has started. PDGS encompasses three main functions : the image data processing, the image quality monitoring, and the products distribution,
4. a connection to an existing X band earth terminal. Maybe, at this point, depending on the X band ET to be used, a MISTIGRI receiving kit will have to be developed, in order to achieve the interface PDGS-X band ET. Such a kit was developed for Venus (Venus receiving kit VRK). At date, a X band ET is in use at CNES Toulouse; in the forthcoming years, another X band ET might be manufactured and located in Northern Europe.

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