Combining High Spatial Resolution and Revisit Capabilities in the Thermal Infrared: the MISTIGRI Mission Project

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Abstract. This paper describes the MISTIGRI project of a satellite designed to observe the Earth in the thermal infrared (TIR), that could be developed by the French space organisation CNES in cooperation with Spain. MISTIGRI is a precursor mission which has the originality of combining a high spatial resolution (~50m) with a daily revisit. The scientific goals and expected applications of the mission are first described: they deal with (i) agriculture and hydrology, (ii) urban and (iii) coastal areas. Emphasis is set on the justification of the spatial resolution and revisit specifications. The other mission specifications are briefly examined and rapid overviews of the instrumental concept and of the proposed mission architecture given.

Keywords. thermal infrared, surface temperature, micro satellite, MISTIGRI

Introduction

The interactions between the continental or maritime surfaces and the atmosphere play a crucial role in the climate and have to be carefully monitored to understand the drifts currently being observed (Climate Change 2007: Synthesis report IPCC) in relation with global change. As it is a key signature of the surface energy budgets, the surface temperature (Ts) can be directly related to sensible and latent heat fluxes, and a number of methods have been proposed to use thermal infrared (TIR) remote sensing to monitor the surface conditions and develop practical applications in different fields: agriculture, hydrology, climatology… But researchers and users suffer a lack of adapted data and 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. Significant improvements in the modelling and monitoring of the surface/climate system, particularly at local scale, are now expected from the availability of new spaceborne observational techniques in the thermal infrared that provide both (i) high revisit capabilities and (ii) high spatial resolution. This is the goal of the MISTIGRI (**MI**cro **S**atellite for **T**hermal **I**nfrared **GR**ound surface **I**maging) mission initiated by CNES in collaboration with Spain, and designed to associate a resolution of 50m and a revisit of 1 or 2 days. After a two year phase 0, the project entered a phase A (2009-mid 2011).

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1. Scientific objectives

1.1. Monitoring of energy and water budgets of the continental biosphere

The energy and water fluxes over continental biosphere govern the status of vegetation and the biogeochemical cycles (CO_2 particularly). The specifications of MISTIGRI have been primarily defined to assess the rapid changes in land surface water status (after rainfall or irrigation) at the field scale. Two types of approaches relying on the use of models will be followed to estimate the evapotranspiration (ET). First simplified algorithms based on the analysis of the relationships between Ts and albedo (or NDVI) can provide direct estimates of ET from Ts (see reviews [1] and [2]). It requires further interpolation of ET maps between dates when TIR data is available to ensure a continuous monitoring of water status. The second approach is based on the use of bio-physical soil-vegetation-atmosphere transfer models (SVAT) associated to inversion [3] and assimilation procedures [4-6]. High revisit of MISTIGRI is expected to stimulate the development of TIR data assimilation. The expected main fields of application deal with agriculture, hydrology, biogeochemical cycles... Methodological progresses are also expected, among which the study of aggregation processes and scaling, the determination of emissivity and temperature-emissivity separation, and the study of directional anisotropy [7,8].

1.2. Monitoring of the urban environment

The climate of cities displays important spatial variability both at local scale (in relation with heights of buildings, orientation of streets…) and at larger scale (in relation with vocation of districts: settlement, industrial, commercial…). The use of a large panel of artificial materials with contrasted radiative surface properties, the reduction of vegetated areas (parks, gardens), and finally human activities (energy consumption..) also affect urban microclimates and differences with surrounding rural climate, resulting in the well-known urban heat island (UHI) phenomena. The urban remote sensing remained focused on the description of the UHI for a long time [9,10], but recent progress on modelling opens new perspectives. Progress has been made not only on surface energy budgets and fluxes [11,12] but also on the physics of the TIR signal itself: description of the directional anisotropy [13,14], radiative transfer and aggregation processes of temperature and emissivity, [15,16] among others. MISTIGRI should allow one to focus on the following applications: urban climatology and heat waves, urban hydrology [17], monitoring of urban vegetation, diffusion of pollutants and air quality, estimation of anthropogenic fluxes [18].

1.3. Monitoring of coastal and continental waters

Many additional 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. 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 to100 km scale- characterized by fronts, filaments which have a large impact on vertical transport of different properties (nutrients, CO_2…). 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 influence on air-sea fluxes as well as winds [19,20]. MISTIGRI will allow one to study such fronts displaying SST signatures not detected with current low resolution satellite data. A number of fields of applications are concerned: coastal oceanography, sea state, estuary hydrology, exchanges between the land and the coastal ocean, estimations of GHG fluxes at the air-sea interface, water quality, biological activity, marine services.

The high spatial resolution of the MISTIGRI data will also be used in a variety of applications dealing with continental waters (lakes and rivers), for instance study of confluence of rivers and lakes, monitoring of floods, thermal plumes of nuclear power plants… Surface water temperature of lakes has also been defined has Essential Climate Variable by GCOS and will be integrated in the future database (Hydrolare / Hydroweb) of the GTN-L list (Global Terrestrial Network for Lakes).

1.4. Strategy of the mission

The first aim of the MISTIGRI precursor mission is to demonstrate the interest of combining high revisit and spatial resolution for monitoring surface water status. As for Venμs, the MISTIGRI mission will tightly associate a spatial system with experimental sites monitored by scientific teams at ground (http://www.cesbio.ups-tlse.fr/fr/indexvenus.html). The large number of existing long term programmes and networks for monitoring climate, ecology, hydrology processes (FLUXNET, ICOS, LTER, GEWEX programmes, NEESPI…) and the persistence of the scientific questions addressed ensures that a large panel of sites will be available in the future.

2. Justification of resolution and revisit specifications

2.1. Spatial resolution

Several attempts made to disaggregate low resolution TIR imagery down to a few tens of metres [21-23], with the scope of exploiting the daily revisit of AVHRR, MODIS or Meteosat systems, revealed not robust enough to make such methods an alternative to direct satellite measurements. The choice of the spatial resolution of MISTIGRI is guided by two constraints.

First it must be compatible with the typical size of the ground units of the studied areas. Kustas et al. [24] showed that a resolution larger than about 100m makes difficult to discriminate the contribution of evapotranspiration of 2 crops, soybean and corn, in the Iowa plain where fields have a typical size of 100m x 100m. In the case of Texas high plains (~800m x 800m typical size) Agam et al. [21] found that a resolution ≤100m is optimal for agricultural applications. Garrigues et al. [25] 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 tan 100m'. Another guideline is provided by information obtained from administration in the Common Agriculture policy framework: in the case of a French typical hilly agricultural region (Gers department), 75% of the surface is made of plots ≥ 150x150m². We can also refer to the recent lobbying of users for requiring a TIR channel on Landsat LDCM at a 60m resolution (http://www.idwr.idaho.gov/GeographicInfo/Landsat/landsat-thermal-band.htm).

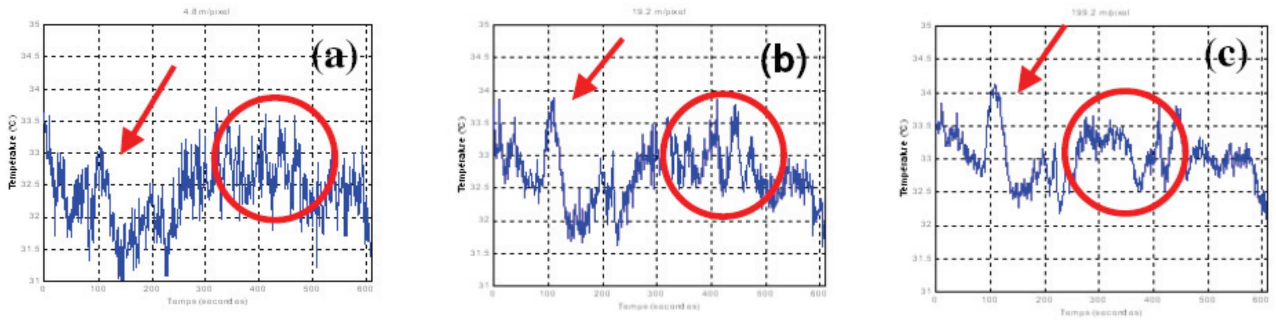

Figure 1. LST temporal evolution above a maritime pine stand in the South-West of France over a 600s period for 5 m (a), 19 m (b) and 200 m (c) aggregated pixel sizes (Le Bray INRA site, Aug. 1995, 16th, 1Hz acquisition frequency). Low frequency fluctuations related to convection in the PBL (arrow) are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

Second, in the TIR, the resolution must simultaneously cope with the turbulent nature of the LST which displays temporal fluctuations related to turbulence in the surface boundary layer (high frequencies) and in the convective planetary boundary layer (low frequencies). The first ones which correspond to turbulent structures of a few meters are smoothed by the spatial integration at the pixel scale (the so-called 'ergodicity') whereas the second ones (several hundreds meters size) cannot be reduced and contribute to the uncertainty on LST. Experiments above maritime pine stands using a helicopter-borne TIR camera [26] indicate that a resolution smaller than ~40m is not useful (Fig. 1). A confirmation of these results is expected in 2010 (i) from similar experiments over a large range of surfaces (from bare soils to cities) in the South of France, and (ii) from a numerical study using an improved version of the ARPS LES model developed at the Oklahoma University. To our knowledge similar results cannot be found in literature. In conclusion, the proposed resolution around 50m seems to be a good compromise between the two above-mentioned constraints. It is consistent with the 60 and 90m of Landsat ETM+ and ASTER. Moreover it is compatible with a reasonable swath (~25 km) at nadir.

2.2. Revisit

Users generally consider that one TIR cloudfree image must be available every five days for agriculture and water monitoring applications. Two 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 an hourly solar irradiance database from the INRA AGROCLIM network. It was performed on a 18 year-dataset (1992-2009) over 5 French stations corresponding to different locations and climates. A simple threshold criterion applied to the measured solar irradiance allowed to discriminate cloudless conditions; statistics were then made to evaluate the number of possible satellite acquisitions at different times of day, at different seasons, and to evaluate the impact of the revisit by sampling the database.
- The second study is based on the analysis of cloud masks MODIS products (2000-2008) for Europe, and similar statistics are proposed.

The solar irradiance-based analysis clearly shows that the 1 image per 5 day-period condition can be obtained with a two-day revisit only for a Mediterranean location, Avignon, and only during spring and summer (Fig. 2a,c). It also shows that acquisition times between 10 and 15 UT have no significant impact on the expected satellite data availability (Fig. 2b and 2d). More detailed analysis (i) considering interval between cloudless days and possible redundancies when consecutive, or (ii) crossing criteria of vegetation water stress with cloudiness are currently being done for SW France and Morocco sites: they confirm that the 2 day-revisit is not suited to fit requirements on data collection. The results obtained with MODIS at Europe scale confirm quite well those derived from the meteorological network data (Fig. 2e,f).

2.3. Spectral bands

In the thermal infrared, the baseline is a spectral configuration with 4 bands at 8.6, 9.1, 10.3 and 11.5 µm for obtaining surface radiometric temperature and emissivity using the TES algorithm [27]. Merging the first two bands into a single one at 8.8 µm for a better NeDT is possible and its interest for MISTIGRI is studied during the phase A.

In the Visible and Near Infrared (VNIR) range, 4 bands have been selected at 450, 670, 865 and 910 nm. They will have an improved resolution of about 20m. They will be used for different goals: improvement of the registration of TIR images, detection of low clouds, estimation of the integrated water vapor content, identification of land cover, obtaining a first guess of emissivity for TES, possible disaggregation of TIR data… Many of these objectives require VNIR imagery to be acquired simultaneously to TIR. For these reasons, using other satellites (Sentinel 2 for instance) cannot replace a VNIR instrument onboard.

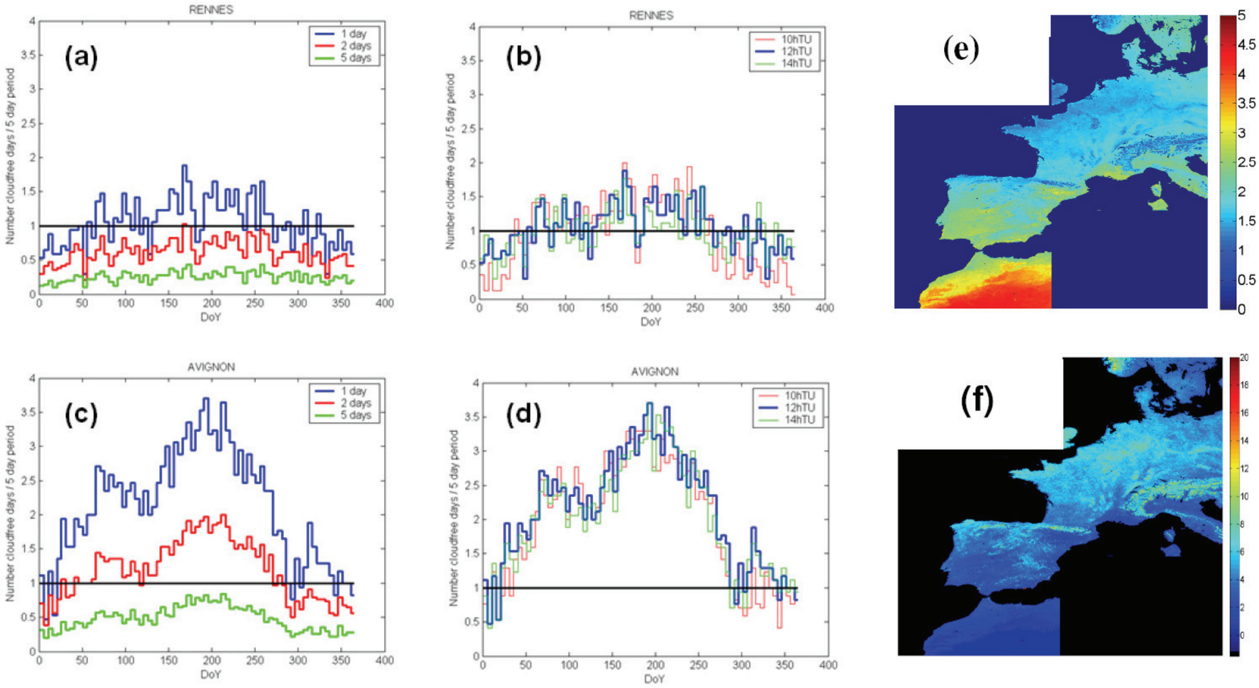

Figure 2. Impact of the revisit (1 or 2 days) on the availability of data by 5 days periods along the year (a: Rennes, c: Avignon). Impact on the acquisition time (b: Rennes, d: Avignon). [Yaxis:0-4°C, Xaxis DoY]. (e): number of cloudfree days per 5 day-periods over Europe for a 3 month spring period (March 1st - May 31st) derived from the analysis of a dataset of MODIS cloud masks (2000-2008), for 1 day-revisit. (f): Number of days between cloud-free data for the same dataset for 1day-revisit.

3. Proposed mission architecture

The mission architecture briefly presented hereafter is the result of technical studies and trade-off led by CNES with the support of TAS (Thales Alenia Space). For details, the reader can refer to papers [28,29].

3.1. Instrumental concepts

The TIR instrument is based on the use of a 640 x 480 uncooled microbolometer array with a pixel pitch of 25 µm developed by a French company ULIS. The requirement for the swath is 25km at least. The thermal time constant of microbolometers introduces a constraint to the satellite operation by making necessary a sampling time longer than the time constant in order to achieve a good MTF and linearity performances. This Time Delay Integration (TDI) acquisition mode requires a satellite slow down obtained by rotating the platform (varying the pitch angle) during the acquisition of the image. The possibility of implementing a ‘supermode’ to over-sample the scene by tilting the two-dimension detector array at 45° with respect to the satellite along-track direction is currently being studied [28]. NEDT values between 0.2 and 0.5K at 290K are expected.

An onboard calibration will be done using two internal blackbodies at 283 K and 313 K. This solution (instead of blackbodies placed at the entrance of the instrument) allows to reduce volume and to keep compatibility with the existing CNES MYRIADE platform. The goal is an absolute accuracy of 1K.

The VNIR instrument will be based on classical 1D CCD arrays.

3.2. Mistigri satellite main features

The MISTIGRI spacecraft architecture is based on the last version of the standard MYRIADE platform which allows fulfilling the mission needs with a large margin. MYRIADE is a multi-purpose flight proven platform developed by CNES in partnership with industry. It enables a total satellite mass of at least 200kg compatible with different launchers (Soyuz, Vega, Dnepr, Rockot, PSLV, Falcon 1E).

3.3. Orbit choice and acquisition capacity

The 1 day-revisit specification imposes a one day repeat cycle orbit at an altitude of 561 km. The case of the 720 km (2 day-revisit) has also been examined, but it would require a constellation of 2 satellites shifted by one day to fulfil the 1 day-revisit specification. Coverage and acquisition capacity are depending on the orbit choice.

The coverage capacity (or accessibility) is defined by the ground area that can be seen by the satellite within the roll depointing limit (across track) of 30°. In case of a 720 km altitude, the day time coverage is pretty satisfactory: 73% at the equator latitude and up to 100 % from the 43° latitude. In the case of a 560 km altitude however, the coverage drops to only 42 % at 45° latitude.

The acquisition of the sites is obtained by rotating the platform, across or along track. The acquisition capacity is therefore limited by the time duration needed to achieve this rotation and by the image duration, taking into account a slow down ratio. As a consequence of the agility needs, the standard MYRIADE reaction wheels are to be replaced by more powerful wheels. A study performed at CNES has demonstrated the possibility to acquire imagery on sites in the most difficult case study of the orbit over western Europe including sites in Spain and France both sides of the track. Assuming sites spread over the land surfaces, a rough extension of this study leads to a total acquisition capacity of about 1200 different sites in the world in case of the 720 km altitude and about 500 sites (less of the half of 1200 sites) in case of 560 km altitude.

The scientific data produced by the TIR and VNIR instruments are stored in the 16 Gbits Myriade Mass Memory and downloaded to a X band ground station located on a northern site. This location allows a large visibility duration of about 100 mn per day, enabling to download up to 100 Gbits every day at the 16,8 Mbits/sec rate.

A Payload Data Ground Segment (PDGS) based on the Venµs Scientific Mission Ground Segment will be developed. PDGS encompasses three main functions: the image data processing, the image quality monitoring, and the products distribution.

4. Conclusion

The studies conducted in phase 0 and beginning of phase A with the support of CNES for refining the mission specifications, and the preliminary instrumental design proposed by TAS confirm the feasibility of the MISTIGRI mission. Most of the MISTIGRI system elements involved in the base line have a strong heritage, which should significantly reduce program costs, and technical and schedule risks. Infra-red cameras based on microbolometers were developed at CNES for CALIPSO and IASI projects, and MISTIGRI can also rely on the experience of the Venµs project, which will ease the design of the ground segment and of the processing chains. On a scientific point of view, MISTIGRI benefits from recent methodological developments around the TIR (understanding of the signal, surface models…) that open new perspectives for using the TIR data to respond to the demand pushed by environmental questions.

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