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Thermal infra-red remote sensing for water stress estimation in agriculture

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Abstract. Thermal infrared images can be used to estimate vegetation water content of the plant and thus to locally adapt (precision agriculture) and globally adjust (sustainable management of water resources) irrigation water quantities. Thermal imaging cameras using micro-bolometer sensors loaded on light aerial vehicles are suitable to produce thermal images. These images are helpful for irrigation monitoring if they are: (i) coupled with simultaneous acquisition of images in the visible and near infrared bands; (ii) geometrically corrected to be superimposed with other images; and (iii) radiometrically corrected to take into account the drift of the thermal sensors and the effects of the atmosphere on the measured temperature.

Keywords. Thermal infrared images – Irrigation monitoring – Water stress – Remote sensing – Airborne images – Surface temperature – Vegetation.

Télédétection infrarouge thermique: application à la mesure du stress hydrique en agriculture

Résumé. *La thermographie infrarouge appliquée à la végétation permet d'estimer le contenu en eau de la plante et ainsi d'adapter des conduites d'irrigation différenciées (agriculture de précision) et précises (gestion raisonnée de la ressource en eau). Les caméras thermiques utilisant des détecteurs de type microbolomètre embarqués à bord d'aéronefs légers peuvent être utilisés pour réaliser des images thermiques. Ces images sont utilisables à des fins de conduite d'irrigation sous réserve : (i) d'être couplées à des acquisitions d'images dans le domaine du visible et du proche infrarouge ; (ii) d'être corrigées géométriquement pour être superposables aux autres données ; et (iii) d'être corrigées radiométriquement pour prendre en compte les dérives liées au capteur et les effets de l'atmosphère sur la température mesurée.*

Mots-clés. *Image thermique – Gestion de l'irrigation – Stress hydrique – Télédétection – Imagerie aérienne – Température de surface – Végétation.*

I – Introduction

Irrigation uses 70% of the water used worldwide. In a context of increasing food demand and scarcity of water resources, development of strategies to optimize water use in agriculture is a major challenge for sustainable development.

The rational management of water resources assumes a space and time optimization of water inputs across each plot. To achieve this objective the water needs of the crop must be determined. There are many methods to characterize, *in situ*, the water status of crops, however, they are often destructive and expensive.

Remote sensing data can provide a number of information on water status and health of crop and could assist in decision-making on irrigation. Recent developments (miniaturization) on light cameras in the visible and infrared bands and on vectors (satellites with high temporal repetitiveness, aerial light vectors) provide new ways of regular, non-destructive, monitoring of crops.

However, the use of remote sensing in agriculture is limited because of inadequacy of spatial, temporal and thematic products tailored to the needs of farmers.

To overcome these obstacles, Cemagref and CIRAD conduct applied research to develop technical solutions for original acquisition and processing of remotely sensed data. At the plot level, the solutions are based on ultra light aerial vehicles, equipped with low cost light sensors.

This paper shows geometric and radiometric preprocessing of data from uncooled thermal cameras to enable the integration of these data in spatial irrigation models.

II – Vegetation hydric stress

Producing one ton of crop needs about 100 tons of water. About 1% of the absorbed water is incorporated in the crop tissues, the rest is lost through transpiration (99%). This water is essential for the functioning of the plant and allows the regulation of leaf temperature and facilitates the absorption of nutrients through the roots.

Water requirements vary with the stage of plant growth and weather conditions (temperature and humidity, wind, etc.). The plant takes needed water from the ground. If there is a water deficit, in order to reduce water loss the plant closes its stomata. This will result in physiological changes (Fig. 1): (i) a decreased transpiration; (ii) a reduction in photosynthesis; (iii) an increase in leaf temperature.

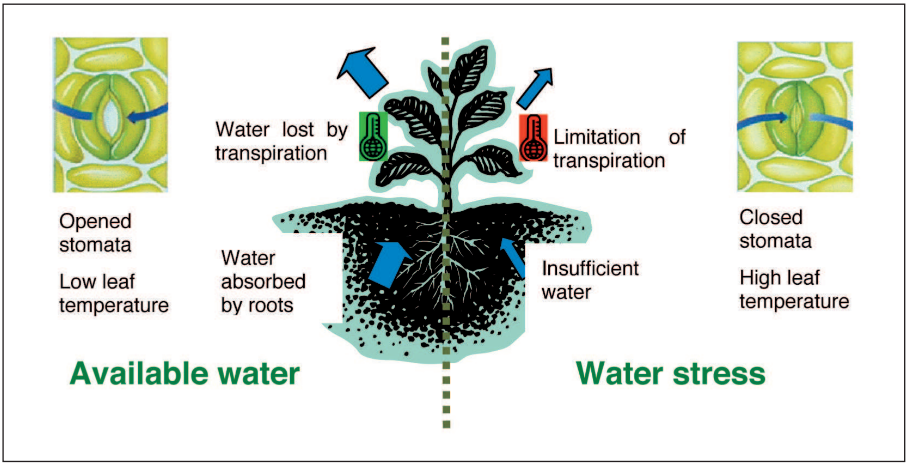

Fig. 1. Plant response to water stress.

According to its intensity, water stress can result in loss of quality. Significant water deficits can lead to irreversible changes leading to a significant drop in yield.

III – Remote sensing images of vegetation

1. Visible, near and middle infrared bands

When sunlight comes into contact with an object, it can be reflected by the surface of the object, absorbed or transmitted to lower levels. The spectral signature of an object is the expression of the reflectance (ratio of the radiance reflected by the object from the incident radiation, expressed in %) as a function of wavelength.

The common characteristic of all vegetation is to have a low reflectance curve in the visible (due to strong absorption by leaf pigments), high in the near infrared (spectral region sensitive to the amount of biomass) and through the medium infrared (mainly influenced by the water content of the canopy) (Fig. 2). Mineral surfaces (rocks, bare soil ...) have a spectral signature which increases from blue to near infrared. Water absorbs all infrared radiations.

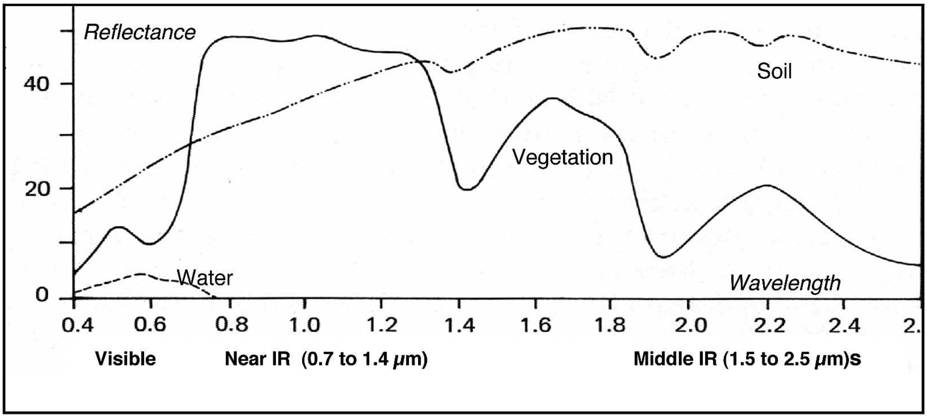

Fig. 2. Typical spectral signature of soil, vegetation and water (Lilliesand and Kieffer, 1987).

On a plot, the reflectance is a combination of spectral signatures of soil and vegetation, which depends on the amount of leaves. Vegetation indices based on combinations of spectral bands in the visible and near infrared, are useful to estimate the amount of vegetation from the images. One of the most common indices :NDVI (Normalized Difference Vegetation Index) is calculated from reflectance in the red and near infrared bands : NDVI = (R-NIR)/(R+NIR) (Fig. 3).

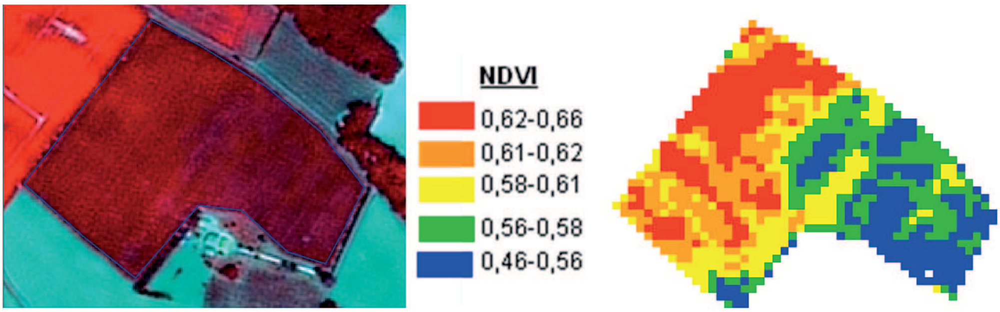

Fig. 3. Example of a 2009 SPOT image and NDVI values (Telerieg project - ANPN plot - Gers, France).

2. Thermal infrared band

Every object emits energy proportionally to the fourth power of its surface temperature (Stefan-Boltzmann law). The amount of energy emitted depends on the wavelength, the wavelength where the emission is maximum is greater as the temperature decreases. For most of the land surface-vegetation (between –20 and 50°C), this maximum corresponds to a wavelength near 10 microns (Fig. 4).

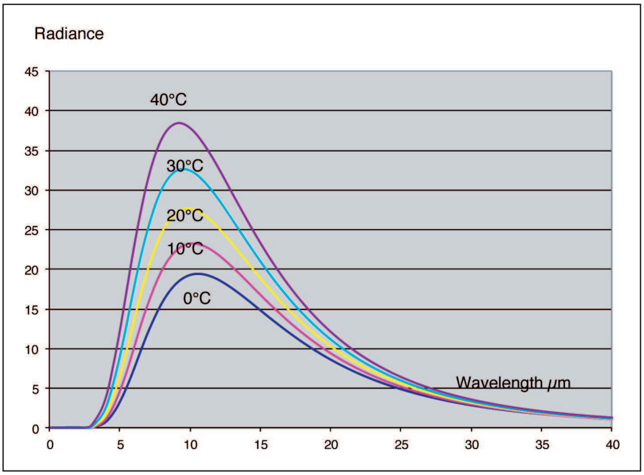

Fig. 4. Black body radiance – Plank Law.

For an ideal black body, it is possible, by measuring the emitted energy in a range of wavelength, to find the surface temperature of the body. However, natural surfaces behave like a gray body with emissivity that varies with the nature of the object. Vegetation cover have an emissivity between 0.95 and 0.99, higher when they are rich in chlorophyll and water (with an average of 0.98, meaning that the surface emits 98% of the energy emitted by blackbody at the same temperature).

Between 8 and 12 microns, solar radiation is negligible and the atmosphere is quite transparent. The measurement of radiation emitted by the Earth's surface in this spectral range and the knowledge of the emissivity of objects allows to estimate the surface temperature of vegetation.

If in addition if the air temperature is known (e.g. a weather station nearby), then the difference between surface temperature of the canopy and air temperature provides a good indicator of the water status of the plant (Fig. 5):

(i) If there is available water, due to transpiration, the plant temperature decreases and the difference between air temperature and canopy temperature increases;

(ii) During periods of water stress, the crop limits its transpiration using stomata regulation and the temperature of the plant increases.

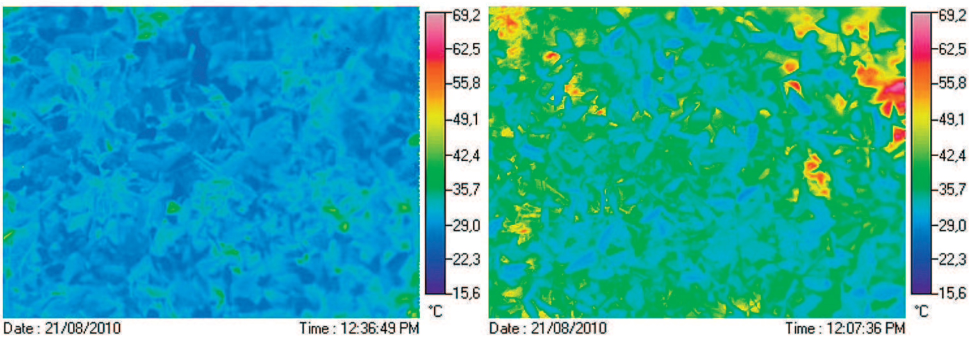

Fig. 5. Example of thermal images on soya bean plot - irrigated (left) and rainfed (right) part of the plot Telerieg project 2010- Experimental plot of Cemagref - Montpellier – France.

To approximate water stress with thermal data, one of the most widely used index is the Crop Water Stress Index (CWSI) (Idso *et al.* 1981) which takes into consideration the temperature of the plant, air temperature and relative humidity. CSWI is convenient for fully coverage crops. For crops like orchards, surface temperature measurement is a composite of soil temperature and canopy temperature. To find the temperature of the plant, the culture coverage must be computed, usually derived from a vegetation index (Lebourgeois 2009). The measure will be especially significant if the air temperature is high (i.e. hot weather at noon or early afternoon) and without strong wind.

Current satellites carrying sensors in the thermal infrared band, as ASTER (Advanced Spaceborne Thermal Emission Terra and Reflection Radiometer) or Landsat ETM + (Landsat Enhanced Thematic Mapper Plus) are of limited use for precise irrigation control because:

(i) Spatial resolution is insufficient (ASTER 90m, Landsat 60m);

(ii) The image acquisition is early in the morning (9 to 10 am in solar time) and water stress on crops does not result in significant differences in temperature;

(iii) The temporal resolution is low (one image every 16 days for Landsat) and should be synchronous with a clear sky.

Due to these limitations thermal satellite images are not useful at plot scale for precise irrigation monitoring. Aerial images are today more convenient, waiting for more efficient future satellites.

IV – Image acquisition devices

Many aircrafts can be used for low altitude image acquisition: small helicopter, ultralight aircraft (ULA), or unmanned aerial vehicles (UAV) (Fig. 6).

Fig. 6. Examples of aircrafts - UAV (hexacopter, Telerieg project) and ULA.

Onboard sensors include commercial visible and near infrared cameras (NIR cameras are modified commercial visible cameras) and thermal cameras (Figs 7 and 8).

During Telerieg project visible cameras (like Sony A 850 with 50 mm lens) and 320*240 pixels (like FLIR B20) thermal cameras were used.

The flight altitude was determined by the spatial resolution required. this resolution varies according to the sensors (Table 1). In the case of orchard a spatial resolution of 30 cm in the thermal band is necessary so that individual trees are visible on the images. For continuous crops, like durum wheat, a lower resolution can be used.

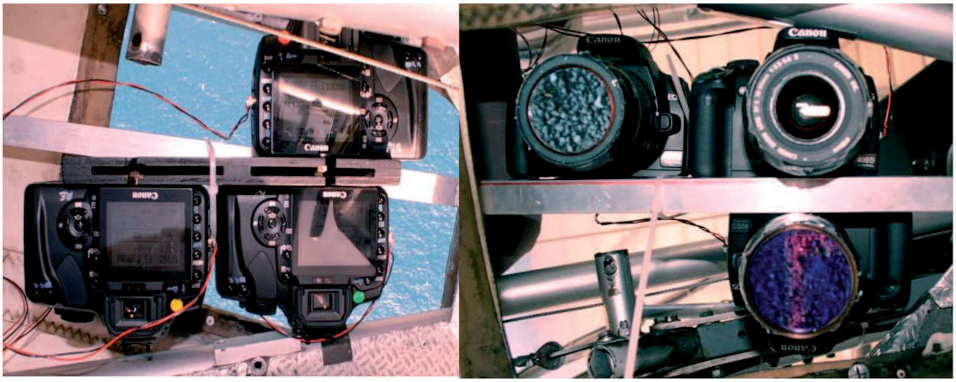

Fig. 7. Examples of visible and modified near infrared cameras on an ULA.

Fig. 8. Examples of thermal camera with remote screen control on ULA - small thermal camera for UAV.

Table 1. Resolution of images

Flight altitude over canopy	900 m (durum wheat)	300 m (apple orchard)
Visible and NIR resolution	10 cm	3 cm
Thermal resolution	1 m	30 cm
Swath	340 m	100 m

V – Thermal images preprocessing

1. Geometric correction

Images acquired using thermal cameras could have large geometric distorsions. In order to use these images for the calculation of indices of water stress it is necessary to correct the images geometrically (Fig. 9). Several approaches are detailed in Pierrot Desseligny *et al.* (2008).

In order to reference the thermal, visible and NIR images in a geographic information system (using an appropriate projection system) identifiable points whose coordinates are well known in the field are needed (The navigation systems used on ULA or UAV do not allow a very precise positioning of the images).

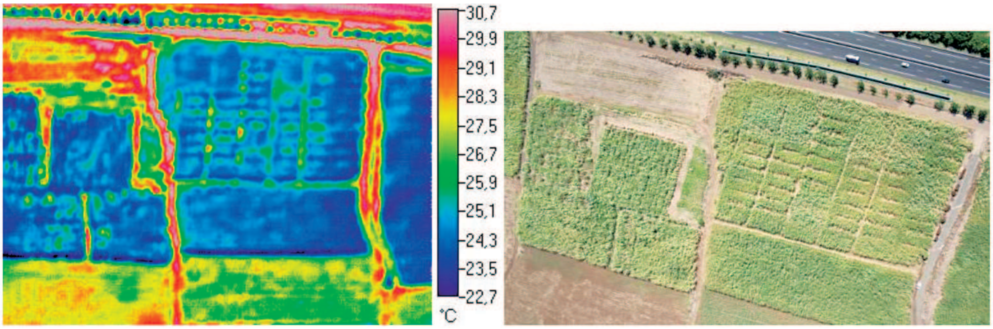

Fig. 9. Examples of thermal and visible images before geometric correction.

In order to have points visible in thermal images as in visible images, specific targets were used: a composition of an aluminium plate (noticeable in thermal image due to a very low emissivity) with a fine reflective cross sign (for visible and NIR images. Targets were positioned with a centimetre precision using a differential GPS system (Joliveau 2011) (Fig. 10).

Fig. 10. Aluminium targets – Position measurement – Targets seen as cold points on thermal image.

2. Radiometric correction

The thermal image is obtained through a matrix of uncooled microbolometers. Each individual microbolometer has a signal-noise ratio of about one celcius degree. This uncertainty is (just) consistent with the objectives of accuracy desired for use in agronomy (Pinter *et al.*, 1990).

Moreover the thermal radiance emitted by the crop is modified by the atmosphere between the crop and the sensor. The atmosphere: (i) reduces the original signal (by absorption and diffusion); and (ii) add its own signal (linked to the atmosphere temperature and contents)

In order to evaluate the atmosphere effects several images were taken of the same plot at several altitude. The next figure shows how the atmosphere (cooler than the soil) reduces the apparent measured temperature (Fig. 11).

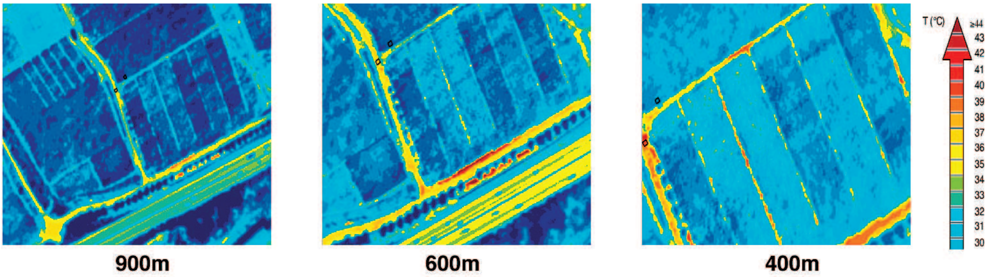

Fig. 11. Same plot at different altitudes.

As the hydric stress of vegetation is computed using a difference between air temperature and crop temperature the atmosphere effect needs to be corrected so that the crop temperature could be retrieved.

The correction of these effects can be made from measurements of *in situ* targets located in the studied area (e.g. using cold and hot targets to interpolate a range of temperature) and large enough to cover several pixels of the image. Targets‘ temperature are measured from the ground during the aircraft acquisition and used to correct images for atmospheric effects.

Several targets were tested during the Telerieg project. Due to a low emissivity EPS (polystyrene) is appropriate to simulate a cold surface, hot surfaces are generally existing (bare soils, roads, etc.) or can be simulated using dark materials (like black plastic sheeting) (Fig. 12).

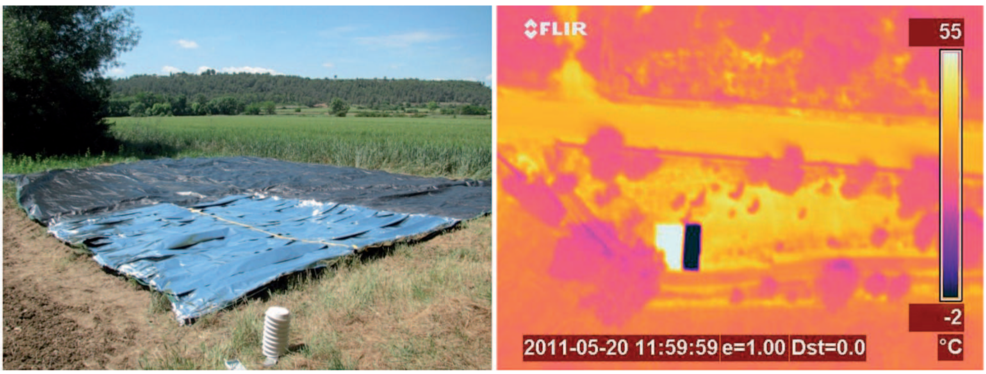

Fig. 12. Example of cold and hot targets on the field and in the thermal image.

This approach with hot and cold targets is efficient but costly, imposing a field operator with a thermal sensor during the aerial acquisition.

As an alternative, the use of radiative transfer models is interesting but requires the use of detailed atmospheric profiles (temperature, humidity, pressure, aerosols and gas molecules) (Jacob *et al.*, 2004). These data are often unavailable or do not coincide in time or space for local use.

To overcome this lack of data, a temperature and humidity sensors, connected to a data logger, was installed on the aircraft. This system allows to log a simplified profile atmospheric temperature / humidity during the phases of ascent and descent of the aircraft. This approach is convenient if the aerial data uses a UAV taking off from the plot.

These data were then used in a radiative transfer model developed by ONERA (MATISSE Advanced Earth Modeling for Imaging and Simulation of the Scenes and their Environment) (Simoneau *et al.*, 2001).

Using atmospheric profile and MATISSE software a first correction could be applied to overcome the atmosphere effect in the image according to the flight altitude (Marti, 2011) (Fig. 13).

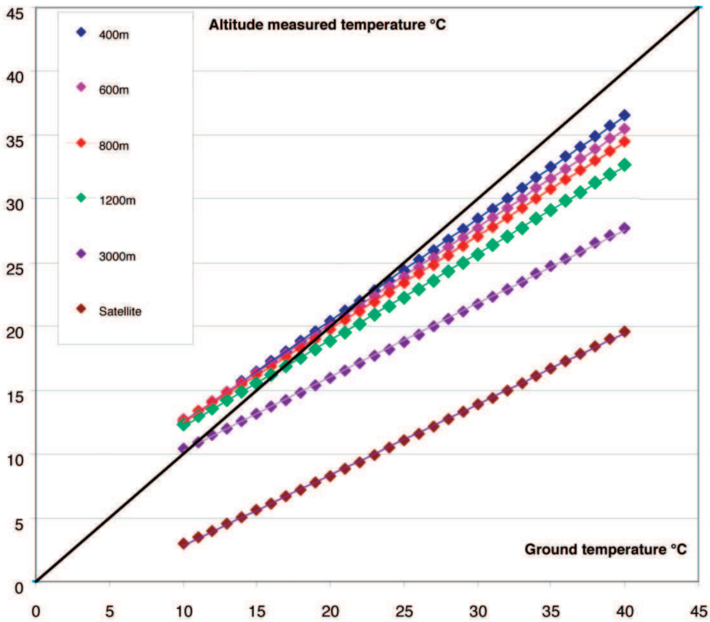

Fig. 13. Example of temperature correction using MATISSE.

VI – Conclusion

The development of uncooled thermal cameras can be considered as useful in airborne precision agriculture for irrigation monitoring and therefore for better management and conservation of water resources. Data preprocessing is still complicated and the results are at the limit of accuracy desired for operational use. Progress needs to be done (and are expected) on:

(i) Sensors such as improved thermal resolution.

(ii) Easier usability in radiative transfer models.

(iii) Physical / agronomic better determination of the relationship between the behavior of the vegetation and the signal measured in the thermal infrared.

In this objective, Cemagref and CIRAD continues this research today, with several scientific and operational partners in the South-western Europe (southern France, Spain, Portugal) thanks to the Telerieg project (Interreg IV-B SUDOE Programme).

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