Review of Thermal Infrared Applications and Requirements for Future High-Resolution Sensors

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***Abstract*—High-resolution thermal infrared (TIR) remote sensing has a wide range of applications. In this paper, we describe the different applications and requirements identified in a literature review and during a consultation meeting with researcher experts in different fields. As a result, more than 30 applications were identified within three different fields: 1) land and solid Earth; 2) health and hazards; and 3) security and surveillance. A complete set of requirements (spatial, temporal, and radiometric resolution, algorithms used, and supporting data, among others) for each application is also provided. The results presented in this paper provide useful information to enhance the importance of high-resolution TIR data for civil applications and may serve as a reference document for future TIR mission concepts.**

***Index Terms*—Fuegosat, high resolution, land surface emissivity, land surface temperature, thermal infrared.**

I. Context: FSS

The Fuegosat Consolidation Element is part of the Earth Watch Programme approved by the European Space Agency (ESA) Council at the ministerial level in November 2001. The work plan for Fuegosat Consolidation Phase included two steps: the first step proposed to establish a mission architecture comprising nondedicated low Earth orbit (LEO) and geostationary Earth orbit (GEO) operational elements and dedicated infrared sensors, and the second step focused on the definition of an infrared element framework. Risk management related to natural hazards, including fire risk management, was recognized as highly relevant to the Global Monitoring for Environment and Security (GMES), which is now known as Copernicus. It was therefore proposed to implement an infrared element in the form of passenger payloads on all suitable Sentinel spacecraft. The target application was risk management related to natural hazards with a special focus on fire risk management. Sentinel infrared element accommodation studies were performed up to the preliminary concept review level. However, a reassessment of the mission requirements confirmed weaknesses in the traceability back to GMES/Copernicus operational service definitions, which was due to the nature of the original proposal. In particular, the fire monitoring capabilities could not be traced back to fast track or core service definitions. In parallel, the scope of high-resolution thermal infrared (TIR) observations was increased to include applications beyond fire monitoring as these were seen as relevant to Copernicus. Based on these findings, a program reorientation was defined, which included service definition, identification of new applications, user requirement consolidation, system definition, and associated technology activities.

In this framework, the Fuegosat Synthesis Study (FSS) project contributed to the identification of applications for high-resolution TIR remote sensing and the analysis of user requirements in three different topics: 1) land and solid Earth; 2) health and hazards; and 3) security and surveillance. The FSS project also included the matching of user requirements with derived concepts to identify and outline a set of potential mission scenarios and corresponding requirements. In this paper, we focus on the applications identified during the literature review and the requirements associated with each application.

II. Methodology

A. Literature Review

The methodology employed to identify the different applications and to extract the user requirements is based mainly on available project reports and particularly on papers published in international journals or proceedings presented at international symposia, i.e., these results were mainly obtained from a literature review. However, this approach was not adopted for the "security and surveillance"-related applications since these types of applications are not commonly published and divulged, and the literature review did not provide useful information; therefore, most of the applications and requirements were extracted from personal communications with military institutions. Note that only civilian "security and surveillance"-related applications were included in this paper.

B. Consolidation Review and Workshop

Applications and requirements identified during the literature review were consolidated after a consultation meeting

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with different international experts (identified researchers from different organizations). In this meeting, the different applications identified during the literature review were prioritized. The primary conclusion was that a spaceborne high-resolution TIR sensor(s) was required to address the different identified applications.

C. Prioritization of Applications

Performing a tradeoff consolidation analysis, one of the main emerging elements was that any future space mission based on TIR observations cannot concurrently and effectively satisfy all the requirements originating from the rather different applications. Therefore, it was considered that some applications may not be further considered, and for others, a priority ranking should be provided. For this purpose, three indexes were considered, and the sum of the three indexes was used as an indicator of application importance: 1) technological readiness index (TRI); 2) requirement sharing index (RSI); and 2) TIR user need index (TNI). Values of 1, 2, or 3 were assigned to each index.

The TRI refers to the operational maturity of the application and mainly takes into account the technical feasibility of the required spatial resolution, revisit time, and spectral configuration. Applications requiring moderate/low spatial resolutions and revisit times, and low spectral configurations (only 1 or 2 TIR bands) were considered with a high degree of technology readiness ($\mathrm{TRI} = 3$), whereas applications requiring high spectral–temporal–spatial data (e.g., multi-/hyperspectral TIR sensors with daily revisit time and spatial resolutions of few meters) were considered with a low degree of readiness ($\mathrm{TRI} = 1$).

The second parameter index, i.e., RSI, takes into account the possibility of generalizing the requirements of a given application, i.e., how much the specific requirements of that application can be shared with other applications. The more its requirements are shared by other applications, the higher the RSI. For example, if an application requires the same number of bands, spatial and temporal resolution and geographic coverage as others $\mathrm{RSI} = 3$ was assigned. Likewise, $\mathrm{RSI} = 2$ was assigned for a medium concordance level, and $\mathrm{RSI} = 1$ was assigned when requirements sharing was low.

The third and final element in the priority definition, i.e., the TNI, characterizes the significance/impact of the TIR measurements for the considered application. In this case, the question was: What is the added value of having TIR measurements available for that application (as well as other bands)? If TIR was considered crucial for that application, then it would receive a high ranking. Hence, applications that could not be addressed without TIR bands were considered $\mathrm{TNI} = 3$, whereas applications that could be addressed using other spectral ranges than TIR were considered $\mathrm{TNI} = 1$. Applications not completely requiring TIR bands but where TIR could provide complementary information were ranked as $\mathrm{TNI} = 2$.

Finally, the sum (S) of the three indexes was used to define the following priority levels (low, medium, and high).

$\mathrm{S} < 4$, Priority level: Low
$4 \leq \mathrm{S} \leq 6$, Priority level: Medium
$\mathrm{S} > 6$, Priority level: High

D. Requirements Tables

The applications and requirements identified during the study were summarized in form of tables, which list the major elements to be addressed in the user requirements review. These elements include: 1) application and source; 2) EO Level 2/3 product; 3) spatial resolution; 4) geographical coverage; 5) temporal resolution; 6) accuracy; 7) algorithms; 8) TIR spectral resolution; 9) other spectral ranges; and 10) supporting data. Despite the significance of these elements are clear for the remote sensing community, some of them require a clarification in the context of this paper.

The item "EO Level 2/3 product" refers to the main product(s) required to address the given application. The categorization of the processing levels may include some ambiguity depending on the criteria used to define the levels. For example, some differences can arise in the definition of levels in NASA and ESA products. The Committee on Earth Observation Satellites also provides a product-level definition, which is also partly based on NASA's definition. To avoid confusion, we preferred to use more general terms such as "geophysical variables" or even to provide the name of the particular geophysical variable, instead of providing the data level.

The item "spatial resolution" includes the optimal spatial resolution required to address a given application. It should be noted that requirements are provided for future missions. This implies that, in most cases, applications can be performed with more relaxed spatial resolutions, but users expect a better spatial resolution in the future.

In the case of the "TIR spectral resolution," we provide the required bands in the TIR range between 8 and 14 μm. For some applications (e.g., detection of hot temperature events) other spectral ranges such as the mid infrared (MIR, 3–5 μm) are preferable. However, since we focus on a TIR mission, we always provide in this item bands located in the range 8–14 μm. MIR bands are provided in the item "other spectral ranges," even if MIR bands are more important than the TIR bands.

III. Applications and Requirements

Here, the applications identified during this study, as well as the basic requirements, are presented. Applications were divided into three topics: 1) land and solid Earth; 2) health and hazards; and 3) security and surveillance. However, it was found that some applications could be included in more than one topic heading. Tables I–III present the user requirements for each application and topic, which are briefly discussed in the succeeding sections. It should be noted that describing the scientific background of the different applications is beyond the scope of this paper. However, literature references are given for each application, and some basic details are included in the requirements tables.

A. Land and Solid Earth

Applications included in the "land and solid earth" topic were volcano and fire monitoring, which are based on the detection of high-temperature events (HTE), and evapotranspiration (ET) retrieval and water stress detection, which relate to water

TABLE I
SUMMARY OF USER REQUIREMENTS FOR LAND AND SOLID EARTH APPLICATIONS

Application [Source]	EO Level 2/3 Product	Spatial resolution	Geographical coverage	Temporal resolution	Accuracy	Algorithms	TIR spectral resolution	Other spectral ranges	Supporting data
Eruption clouds *[Corradini et al. 2008, Picchiani et al. 2011, Prata et al. 1989]*	Geophysical variables (Gases and particle concentrations)	1-3 km	Large 1000 – 2000 km	3-4 hours		Statistical, Brightness Temperature Difference (BTD)	Two bands (10 – 12 μm)	UV-VIS	Physical models
Tropospheric Plumes *[Pugnaghi et al. 2006, Realmuto et al. 1986]*	Geophysical variables (Gases and particle concentrations)	30-100 m	Medium 100 – 500 km	daily		Look-Up Table, Radiative Transfer Model	Multispectral (≥ 3 bands in 8-12 μm)	UV-VIS	Physical models, DEM
Hot spots and active lava flows *[Wright et al. 2002]*	Geophysical variables (Normalized Thermal Index)	10 - 50 m	Small 60-100 km	daily	< 1 K	Threshold	11μm	4μm -	Deformation maps - DEM
Post eruptive studies on lava flows *[Harris et al. 2003, Oppenheimer 1998]*	Geophysical variables (Extrusion rates, distribution maps)	10 – 50 m	Small 100 – 200 km	15 days	< 1 K	Threshold	11μm	SWIR-MIR - SAR	DEM
Detection of fires [*CEOS 2003; Zhukov et al. 2006*]	Geophysical variables (LST)	100 m	Global	15 minutes	Not critical (hot spots are at least 200 K higher than background)	Temperature threshold from a single image	Multispectral (≥ 3 bands in 8-12 μm)	SWIR (1.5-2.5 μm) MIR (3-5 μm)	Atmospheric constituents for atm correction
Estimation of fire risk [*CEOS 2003*]	Geophysical variables (Vegetation Index)	30 m	Global	Daily - Weekly	2% (usual accuracy of NDVI estimations)	Multitemporal: Vegetation Condition Index (VCI)	-	VNIR (Red,Green, NIR@0.8μm)	-
Estimation of burnt area [*CEOS 2003; Giglio et al. 2009*]	Geophysical variables (Vegetation Index)	30 m	Global	Daily - Weekly	2% (usual accuracy of NDVI estimations)	Multitemporal: comparison of reflectance or vegetation index with time series	-	VNIR (Red,Green, NIR@0.8μm)	-
Detection of earthquakes – LST [*Tronin 2000, Tramutoli et al. 2005, Saraf & Choudhury 2005*]	LST	0.5 – 5 km	200km - global	daily	< 1 K	Split-window method; Temperature and Emissivity Separation (TES) method	Two bands (10 – 12 μm); Multispectral (≥ 3 bands in 8-12 μm)	VNIR (Red, NIR@0.8μm)	atmospheric water vapor content; Atmospheric constituents for atm correction
Detection of earthquakes - Emissivity [*Tronin 2000, Tramutoli et al. 2005, Saraf & Choudhury 2005*]	emissivity	0.5 – 5 km	200km - global	Weekly - monthly	< 0.01	Threshold method; TES	Multispectral (≥ 3 bands in 8-12 μm)	VNIR (Red, NIR@0.8μm)	Atmospheric constituents for atm correction
Detection of coal mine fires [*J. Zhang et al. 2004, C. Kuenzer et al. 2007, X. Zhang et al. 2004*]	Geophysical variables (LST)	1 - 100 m	Local to Regional	Daily-Monthly	Not critical (hot spots are 20 K higher than background)	Temperature threshold from a single image	1 broad-band (8-12 μm) Multispectral (≥ 3 bands in 8-12 μm)	VNIR (Red,Green, NIR@0.8μm) MIR (3-5 μm)	In-situ temperature to select the threshold is recommendable
Delineation of potential coal fires and coal fire risk areas [*Gao et al. 2006, Gao et al. 2009*]	Land cover	100 m	Local to Regional	Monthly	-	Classification techniques from a single image	Multispectral (≥ 3 bands in 8-12 μm)	VNIR (Red,Green, NIR@0.8μm) SWIR (1.5-2.5 μm)	-
Detection of water stress in crops [*Sepulcre-Cantó et al. 2006, Sepulcre-Cantó et al. 2007*]	Level 3 (classifications, consider also visible, near infrared and meteorological data)	2 - 7 m	Local	Daily	1 K	Temperature threshold, classifications techniques	Two bands (10-12 μm)	VNIR	Meteorological data (air temperature)
Detection of water stress in forest [*Vidal & Dvaux-Ros 1995, Duchemin et al. 1999*]	Land cover	100 m	Local to Regional	Daily-Monthly	1 K	Temperature threshold, classifications techniques	Two bands (10-12 μm)	VNIR	Meteorological data (air temperature)
Detection of evapotranspiration in crops [*Sobrino et al. 2005 Sobrino et al. 2008*]	Level 3 (classifications, consider also visible, near infrared and meteorological data)	1 - 10 m	Local	Instantaneous-Daily	1 K	Energy Balance Models	Two bands (10-12 μm)	VNIR	Meteorological data (Air temperature, relative humidity)
Detection of evapotranspiration in River, Basin [*Sánchez et al. 2007, Jia et al. 2009*]	Level 3 (classifications, consider also visible, near infrared and meteorological data)	100 m	Local to Regional	Daily-Monthly	1 K	Energy Balance Models	Two bands (10-12 μm)	VNIR	Meteorological data (Air temperature, relative humidity, precipitation)
Detection of evapotranspiration in continents [*Fisher et al. 2008*]	Level 3 (classifications, consider also visible, near infrared and meteorological data)	1 km	Continental-Global	Daily-Monthly	1 K	Energy Balance Models	Two bands (10-12 μm)	VNIR	Meteorological data (Air temperature, relative humidity, precipitation)
Growing Degree Day estimations [*Vancutsem et al. 2010, Hassan et al. 2007a*]	Level-3 Land surface temperature; Vegetation Index (NDVI)	20-1000m	Local scale	Daily/Sub-daily	1-2 K	Multivariate Statistical correlation	Two bands (10 – 12 μm) for Split-Window; Multispectral (≥ 3 bands in 8-12 μm) for TES	VNIR for NDVI 0.63 – 0.69 μm 0.76 – 0.90 μm	Weather station network & Land cover map

TABLE I
(*Continued.*) SUMMARY OF USER REQUIREMENTS FOR LAND AND SOLID EARTH APPLICATIONS

Growing Degree Day mapping [*Mikkelsen & Olesen 1984, Blair et al. 2002, Hassan et al. 2007b*]	Level-3 LST & Land cover maps	20-1000m	Regional to local scale	Daily/Sub-daily	1-2 K	Multivariate Statistical correlation & Spatial Analysis using Computational approach	Two bands (10 – 12 μm) for Split-Window; Multispectral (≥ 3 bands in 8-12 μm) for TES	VNIR for NDVI 0.63 – 0.69 μm 0.76 – 0.90 μm	Weather station network & Land cover map
Cooling Degree Day Estimations [*Stathopoulou et al. 2006*]	Level-3 Land surface temperature	20-1000m	Local scale	Daily/Sub-daily	1-2 K	Method proposed by Stathopoulou et al (2006)	Two bands (10 – 12 μm) for Split-Window; Multispectral (≥ 3 bands in 8-12 μm) for TES	VNIR for NDVI 0.63 – 0.69 μm 0.76 – 0.90 μm	Weather station network & Land cover map

TABLE II
SUMMARY OF USER REQUIREMENTS FOR HEALTH AND HAZARDS APPLICATIONS

Application [Source]	EO Level 2/3 Product	Spatial resolution	Geographical coverage	Temporal resolution	Accuracy	Algorithms	TIR spectral resolution	Other spectral ranges	Supporting data
UHI - Vegetation maps *[UHI Proj, 2009]*	Maps	10-100 m	Local-Regional	monthly		Multivariate statistical	Two bands (10 – 12 μm)	Multispectral	Land cover maps
UHI - Land cover/Land use *[UHI Proj, 2009]*	Maps	10-100 m	Local-Regional	monthly		Multivariate statistical	Two bands (10 – 12 μm)	Multispectral-SAR	GIS
UHI - Building information *[UHI Proj, 2009]*	Temperature	1 - 10 m	Local	monthly	1 – 2 K	LST	Two bands (10 – 12 μm)	SAR	City maps
UHI - Air Quality *[UHI Proj, 2009]*	Temperature	20 m – 1km	Local-Regional	Daily-monthly		Statistical		UV-VIS	Atmo models
Air pollution [*Bowman et al. 2006; Barret et al. 2005*]	Radiance	100 m	Local- Regional	Daily (at noon)	-	Inversion techniques from IR sounding measurements	Hyperspectral (3-15 μm) FTIR spectroscopy	-	-
Differentiate between urban and industrial zone [*Kato & Yamaguchi 2007*]	Storage heat flux	100 m	Local	Monthly	LST: 1.5 K Emissivity: 0.015	TES for LST/ε and energy balance	Multispectral (≥ 3 bands in 8-12 μm)	VNIR data for albedo	Meteorological data and surface roughness
Oil spill detection [*Shcherbak et al. 2008, Tseng & Chiu 1994*]	Temperature	100m-1Km	Local-Regional	Few hours	1 K	Temperature threshold (LST from split-window)	Two bands (10 – 12 μm)	Combination between VNIR and RADAR	
Plume detection [*Chrysoulakis 2002, Chrysoulakis & Cartalis 2003, Chrysoulakis et al. 2005*]	Temperature CLD	100m-1Km	Local	Few hours	1 K	Classification and temperature threshold (LST from split-window)	Two bands (10 – 12 μm)	VNIR for NDVI 0.63 – 0.69 μm 0.76 – 0.90 μm	
Prediction of floods [*Billa et al. 2006, Feidas et al. 2000, Morales et al. 2003*]	Level 3 (classifications, consider also visible and near-infrared)	500m - 1km	Regional	Daily	-	Temperature threshold, classifications techniques	Two bands (10-12 μm)	VNIR or Passive microwave	Lighting information from long-range network
Monitoring of floods [*Roshier et al. 2004, Lakshmi et al. 2001*]	Level 3 (thresholds)	1m - 1 km	Local to regional	Daily (Noon-Midnight)	1 K	Temperature threshold from a single image	Multispectral (≥ 3 bands in 8-12 μm)	-	-
Mapping malaria potential regions [*Green & Hay 2002, Gemperli et al. 2004, Rahman et al. 2006*]	Level-3 Land surface temperature; Vegetation Index (NDVI)	100-1000 m	Continental to regional scale	Daily/sub-daily	< 2K	Split-window	Two bands (10 – 12 μm)	VNIR for NDVI	Meteorological data
Arthropod vector ecology and disease distribution [*Marj et al. 2008, Gemperli et al. 2004*]	Level-3 LST & Land cover maps	100-1000 m	Continental to regional scale	10 days composite/sub-daily	< 2K	Split-window	Two bands (10 – 12 μm)	VNIR for NDVI	Meteorological data
Mapping cholera potential regions [*Gil et al. 2004, Lobitz et al. 2000, Emch et al. 2008*]	Level-3 ; SST and Chlorophyll concentrations	100-1000 m	Continental to regional scale	Daily/sub-daily	< 1K	Split-window	Two bands (10 – 12 μm)	VNIR (blue and green channels for chlorophyll)	Meteorological data
Mapping meningitis outbreak [*Gemperli et al. 2004*]	Level-3 ; LST and Dust Blown map	100-5000 m	Continental to regional scale	Daily/sub-daily	< 2K	Split-window	Two bands (10 – 12 μm)	VNIR for NDVI	Meteorological data
Asbestos-cement detection over non-accesible areas [*Bassani et al. 2007*]	Level-2 (radiance) Level 3 Emissivity at high spatial level	3-20 m	Local scale	Monthly/daily	Not critical, only relative values are used	Temperature and Emissivity Separation algorithms	Hyperspectral (with a band in 9.44 μm)	VNIR for visual inspection recommendable	Laboratory analysis, mineralogical composition, in-situ measurements

TABLE III
SUMMARY OF USER REQUIREMENTS FOR SECURITY AND SURVEILLANCE APPLICATIONS

Application [Source]	EO Level 2/3 Product	Spatial resolution	Geographical coverage	Temporal resolution	Accuracy	Algorithms	TIR spectral resolution	Other spectral ranges	Supporting data
Detection of minefields and landmines [Maathuis & van Genderen 2004]	Geophysical variable: LST	2–8 cm (landmines) 1-5 m (minefields)	Local	Overpass time: sunrise, sunset	<0.5ºC	Split-window (SW); Temperature and Emissivity Separation (TES)	Two bands (10 – 12 μm); Multispectral (≥ 3 bands in 8 – 12 μm)	VNIR (Red, NIR@0.8μm)	Emissivity, water vapor content
Border security [Personal Interview]	TOA Brightness Temperature	~15m	Europe + N Africa to 5ºN	1-2 days	Detection			SAR	DEM
Object monitoring and detection [Personal Interview]	TOA Brightness Temperature	~10m	Local		Detection	Two dimensional MRTD* models	1 band: 0.8 - 2.5 μm	SAR	DEM
Ship & port monitoring: Piracy/drug smuggling/illegal Immigration [Personal Interview]	TOA Brightness Temperature	~15m	Lat.: 60º N to 35º S Lon. 70º W to 70º E		Detection	Two dimensional MRTD* models	1 band: 0.8 - 2.5 μm	SAR, VIS	Automatic Identification System (AIS)
Industrial/power plant monitoring [Wu et al. 2007, Tang et al. 2003]	Geophysical variable: LST	10-15m			1-2 K	TES, models, statistics	Spectrometry	UV/VIS/NIR	Sonde measurements
Trafficability (off-road soil moisture content) [Personal Interview]	Geophysical variable: LST	30m			1-2 K	Target Translation Method (TTM)	Two bands (10 – 12 μm)	SAR	DEM, reanalysis, surface emissivity

(*) Minimum Resolvable Temperature Difference

management issues. Other secondary applications included the role of TIR data in earthquake events, detection of coal mine fires, and growing degree days. Requirements for all these applications are summarized in Table I.

1) Volcano Monitoring: Volcanic eruptions pose serious hazards to sensitive ecosystems, transportation, and communication networks and to populated regions. Knowing the mineralogy of a rock or alluvial surface is critically important to geologists trying to interpret the geologic, climatic, or volcanic history of the surface. Spectroscopy and remote sensing in the TIR region has lagged behind that of other wavelength regions for numerous reasons. However, the utility of TIR remote sensing for geology and mineralogy has become clear in the past decades and numerous air- and space-based instruments (in LEO and GEO) have become available. Volcano monitoring, particularly during the eruption phase, requires a high temporal resolution, and typically, volcanologists use GEO-based data sacrificing spatial resolution for temporal resolution. Another feature of volcano monitoring is that by, its very nature, the location of the volcano is known, which for spaceborne system definition is important.

2) Fire Monitoring: Fires are a major security hazard in numerous countries around the world and affect urban and rural areas alike. Here, the term "fire" will be dedicated to any wild fire occurring in the natural environment, including farmland fires [7]. Wildland fire is any nonstructural fire. This is different to a controlled fire, which can be set on purpose by professionals on vegetated areas such as forests, savannahs, or Mediterranean vegetation. In Europe, the Southern countries (Portugal, Spain, France, Italy, and Greece) are the most affected by fires, with an average of almost 50 000 fires between 1980 and 2008, corresponding to an average annual burnt area of more than 480 000 hectares [27]. The total cost of fires can be estimated at around 1% of the global gross domestic product [60], including the costs of direct and indirect fire losses, the cost of fire-fighting organizations, the cost of fire insurance administration and the cost of fire protection for buildings.

Fires are typically characterized by parameters such as emission plume extent, temperature, and fire radiative power. Most *in situ* daytime fire sightings result from the observation of smoke generated by fuel combustion, whereas most nighttime sightings result from high and unusual luminosity of the burning areas. The high temperature of the burning areas makes the fires detectable from space under clear-sky conditions.

3) Water Management: Detection of water stress and ET retrieval are key applications for water management purposes. Thermal infrared remote sensing has been recognized for a long time as one of the most feasible means to detect and evaluate water stress and to quantify ET over large areas in a spatially distributed manner.

Water stress is considered to be a major environmental factor limiting plant productivity worldwide. Water stress develops in plants when evaporative losses cannot be sustained by extracting water from the soil by the roots.

ET describes the loss of water from the Earth's surface to the atmosphere by the combined processes of evaporation from surface and transpiration from vegetation. ET depends on the presence of water and is regulated by the availability of energy, which is needed to convert liquid water to water vapor and to transport vapor from the land surface to the atmosphere. Physiological regulations also occur in plants through mechanisms controlling water extraction by the roots, water transport in plant tissue, and water release to the atmosphere via the stomata at the leaf surface (in direct relation with the mechanisms of CO_2 assimilation and photosynthesis).

4) Other Applications: Other applications using TIR remotely sensed data were also identified within the "land and solid Earth" topic. Examples include earthquake monitoring, coal mine fire monitoring, and growing degree days. However, during the consolidation process of the study, these applications were considered medium to low priority compared with the other applications stated earlier. This does not mean, however, that these applications are not important, but within the scope of this review and its focus on high resolution, these applications were not considered to be main drivers.

B. *Health and Hazards*

The last two decades have witnessed an increasing use of remote sensing for understanding the geophysical phenomena underlying natural hazards. The scientific knowledge gained along with the ability to disseminate timely geospatial information together with demographic and socioeconomic data contributes to comprehensive risk mitigation planning and improved disaster response. Observations from Earth-orbiting satellites are complementary to local and regional airborne observations and to traditional *in situ* field measurements and ground-based sensor networks. The contributions of satellite remote sensing to Earth science, ranging from high-resolution topography (using e.g., interferometric SAR, lidar, and digital photogrammetry) and geodesy to passive multispectral thermal sensors, such as ASTER or MODIS and active microwave imaging, have transformed the discipline. This transformation has resulted in a rapidly growing field of applied research that is increasingly able to provide geospatial information products fulfilling the operational needs of multihazard decision support tools and systems. Policy makers and emergency managers/responders from many levels, e.g., international, federal, state, regional and local jurisdictions, use these tools and systems to generate scenarios, devise mitigation plans, and implement effective response measures.

In this topic, two major applications are considered: the urban heat island (UHI) effect and epidemiology. Other applications such as industrial risks, coastal inundations, and asbestos–cement detection are also identified and presented. Requirements for all these applications are provided in Table II. Note that fire risk could be also considered a "health and hazard" application, but it was included in the "land and solid Earth" applications.

1) UHI: Thermal remote sensing has been used over urban areas to assess UHI effects, to perform land cover classifications, and as input for models of urban surface atmosphere exchange. The main surface parameter to be extracted from thermal remote sensing is the so-called land surface temperature (LST) or simply surface temperature, which is of primary importance to the study of urban climatology. LST modulates the air temperature of the lowest layers of the urban atmosphere, and it is central to the understanding of the energy balance of the surface. LST helps to determine the internal climates of buildings and is fundamental to energy exchanges, which affect the comfort and well being of city dwellers. Surface and atmospheric modifications due to urbanization generally lead to a modified thermal climate that is warmer than the surrounding nonurbanized areas, particularly at night. This phenomenon is known as the UHI. UHIs have long been studied by ground-based observations taken from fixed thermometer networks or by traverses with thermometers mounted on vehicles. With the advent of thermal remote sensing technology, remote observation of UHIs became possible from satellite and aircraft platforms and has provided new avenues for studying their causes through the combination of thermal remote sensing and urban micrometeorology [59]. Since thermal remote sensors observe the spatial patterns of thermal radiance at the surface, the term surface UHI (SUHI) is usually employed to distinguish between UHI (when air temperature is considered) and SUHI (when LST is considered). For this field, most information was extracted from an UHI project funded by ESA under the DUE program (http://www.urbanheatisland.info).

2) Epidemiology: There is a growing international consciousness about the importance of the epidemiology of diseases. It is recognized that improved up-to-date information about the environment where infectious diseases occur will help epidemiologists to study, understand, and predict threats to human health and hazards. Spaceborne Earth observation opens up new opportunities to predict and help combat epidemic outbreaks, as well as to join the search for the origin of pathogens. In fact, several diseases can be analyzed using factors that have been determined through remote sensing data; a detailed list of them was studied by Beck *et al.* [3] and referenced therein.

Remote sensing data creates an important opportunity to evaluate risk areas and determine the spatial distribution of some epidemic or vector outbreaks, which affect human health. In fact, since the 1970s, remote sensing improvements have contributed to health science. Some free or low-cost environmental and meteorological data sets (e.g., low-resolution images) have been used to assess epidemic risks at global, regional, and local levels. Therefore, remote sensing data can provide valuable information for determining risk factors and mapping risk areas; these can then be integrated into models, which are based on ecological analyses [25].

3) Other Applications: Other operational contexts in the framework of "health and hazards" applications can benefit from TIR remote sensing. Among them, industrial risks, coastal inundation, and the detection of asbestos–cement were considered. However, these applications were considered as lower priority within the context of this paper.

C. *Security and Surveillance*

Applications and user requirements for security-and-surveillance-related issues are currently only vaguely defined within the public forum. This is obviously because this domain is closely linked with military and politically sensitive applications. In addition, these applications require primarily very high spatial resolution TIR data, and less emphasis is given to spectral configurations or algorithms to extract geophysical quantities. Operational TIR systems at very high resolution are rarely accessible to the scientific community, and therefore, the available knowledge in the scientific community is limited. This fact implies that a review of peer-reviewed literature (as considered for "solid Earth" and "health and hazards" applications) is limited at best, and this was reflected in the list of applications and user requirements (only limited information could be obtained from international journals).

TABLE IV
SUMMARY OF TIR REMOTE SENSING APPLICATIONS AFTER THE CONSOLIDATION REVIEW. A PRIORITY LEVEL (HIGH, MEDIUM, LOW) HAS BEEN ASSIGNED TO EACH APPLICATION USING THE INDICES (TR, RS, TIR) PRESENTED IN SECTION II-C

Topic	Subtopic	Application	TR	RS	TIR	Priority
Land & Solid Earth	Volcanoes	Eruption clouds-ash	1	2	3	Medium
		Degassing plumes	2	2	3	High
		Hot spots and active lava flows	2	2	3	High
	Fires	Detection of fires	1	2	3	Medium
		Estimation of fire risk	3	2	2	High
		Estimation of burnt area	3	2	1	Medium
	Water management	Detection of water stress in crops (tree crops)	1	1	3	Medium
		Detection of water stress in crops (typical crops)	2	3	3	High
		Detection of water stress in forest	2	3	3	High
		Detection of evapotranspiration in crops (tree crops)	1	1	3	Medium
		Detection of evapotranspiration in crops (typical crops)	2	3	3	High
		Detection of evapotranspiration in River Basin	3	3	3	High
		Detection of evapotranspiration in continents	2	2	3	Medium
	Coal mine fires	Detection of coal mine fires	2	2	3	High
		Delineation of potential coal fires and coal fire risk areas	3	1	1	Medium
	Geology	Soil composition	2	2	3	High
Health & Hazards	Urban Heat Island	Vegetation maps	2	3	2	High
		Land cover/Land Use	2	3	2	High
		Building Information	1	1	3	Medium
		Air Quality	2	2	2	Medium
	Industrial risks	Air pollution	1	1	3	Medium
		Differentiate between urban and industrial zone	3	3	2	High
		Oil spill detection	1	1	1	Low
		Plume detection	1	1	2	Medium
	Coastal inundations	Prediction of floods	1	1	1	Low
		Monitoring of floods	2	2	1	Medium
		Asbestos-cement detection over non-accesible areas	1	1	1	Low
Security & Surveillance		Detection of minefields	1	1	1	Low
		Border Security	1	2	2	Medium
		Target activity monitoring	1	2	2	Medium
	Ship/Port monitoring	Piracy/drug smuggling/Illegal Immigration	2	2	1	Medium
		Industrial/power plant monitoring	2	2	1	Medium
		Trafficability (off-road soil moisture content)	2	2	1	Medium

Most of the openly available information includes applications using handheld thermal cameras or unmanned aerial vehicles, with spatial resolutions on the order of centimeters. One sensor identified was the Multispectral Thermal Imager (MTI) sensor, developed at Los Alamos National Laboratory (Sandia National Laboratory). This sensor has a spatial resolution of 5 m in the visible bands and 20 m in the thermal bands. MTI is an American quasi-military reconnaissance sensor on a spacecraft launched in March 2000. The program was cosponsored by the American Department of Energy, Office of Nonproliferation and National Security. The 587-kg spacecraft carried visible and infrared sensors in 15 spectral bands to spot cooling ponds adjacent to nuclear reactors and dust content associated with uranium ore processing [51]. The collected data also has spin-off benefits for civilian research involving atmospheric ozone measurement, water vapor content, etc.

The Copernicus initiative (www.copernicus.eu) also includes some preoperational security services. G-MOSAIC (http://www.gmes-gmosaic.eu) and LIMES (http://www.fp6-limes.eu) are two examples. These already completed projects combined Earth observation technologies with communication and positioning technologies, addressing different domains, such as maritime surveillance, infrastructure surveillance, providing support to peace-keeping, etc. However, the applications found within these projects relied on high-resolution visible and near-infrared (VNIR) imagery (e.g., IKONOS, QUICKBIRD) and SAR data: No user needs related to high-resolution TIR data were identified. This is likely because no TIR sensor with high resolution and revisit time is currently available.

Different applications were suggested by the military organizations consulted by the study team, and from these meetings, basic user needs were identified. As stated earlier, since information was provided through personal communication, a strong justification of the identified user needs cannot be provided in some cases. It should be noted that the International Society for Optics and Photonics (SPIE) organizes the Security+Defence conferences and publish the proceedings of these conferences. Despite this valuable information for the "security and surveillance" topic, the study team had no access to this documentation, and it was not consulted during this study. The main user requirements came from the European Union Satellite Centre, which supports the decision-making of the Common European Security and Defence Policy. Identified user needs for "security and surveillance" applications are provided in Table III.

IV. CONCLUSION

The review performed in the framework of the FSS identified several high-resolution thermal remote sensing applications and requirements spanning three different topics: land and solid Earth, health and hazards, and security and surveillance. Results presented were extracted from literature, although in the case of the "security and surveillance" topic information from personal communication was also incorporated. Main applications in the land and solid Earth topic including volcano and fire monitoring, as well as detection of water stress and retrieval of ET for water management purposes, lead to the identification of about 20 applications. In the case of the health and hazards topic, the main applications identified were UHIs and epidemiology, leading to the identification of more than ten different applications. Applications related to the security and surveillance topic was based on limited information found in the literature, and only a few applications were identified. After the consolidation review, some applications were discarded, and requirements were iterated. A priority level was also assigned to each application. The final list of applications and associated priority levels compiled within the context of this review is presented in Table IV.

There is a clear perception that a high-resolution TIR mission with a near daily revisit would have significant consensus among the various user communities since existing high-resolution TIR sensors (e.g., Landsat/TM-ETM-TIRS, Terra/ASTER) do not meet most of the user requirements. This finding is also reflected by recent and past studies and proposals such as MicroSatellite for Thermal InfraRed Ground Surface Imaging (MISTIGRI) and the Thermal Infrared Explorer (TIREX). MISTIGRI is a Centre National D'Études Spatiales (CNES) microsatellite project carrying a TIR sensor suite in cooperation with Spain. TIREX was a proposal presented in 2010 to the ESA's call for Earth Explorer Opportunity Missions, which was finally deselected for Phase A. The originality of MISTRIGRI and TIREX was to combine a high spatial resolution ($\sim$50 m) with high revisit capabilities of one or two days over selected sites. Another related initiative is the NASA Jet Propulsion Laboratory Hyperspectral Infrared Imager (HyspIRI) mission (https://hyspiri.jpl.nasa.gov/).

In summary, a number of high-resolution TIR applications ($\sim$40) were analyzed and technical requirements for a potential TIR sensor were identified. The results presented in this paper can serve as a reference for the design of a future high-resolution TIR sensor, which would bridge the currently existing gap between high spatial and temporal resolution TIR data.

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