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# Derivation of an urban materials spectral library through emittance and reflectance spectroscopy

Simone Kotthaus [a,b,*], Thomas E.L. Smith [b], Martin J. Wooster [b,c], C.S.B. Grimmond [a,b]

[a] Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK
[b] King's College London, Department of Geography, The Strand, London WC2R 2LS, UK
[c] NERC National Centre for Earth Observation, UK

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ABSTRACT

Recent advances in thermal infrared remote sensing include the increased availability of airborne hyperspectral imagers (such as the Hyperspectral Thermal Emission Spectrometer, HyTES, or the Telops HyperCam and the Specim aisaOWL), and it is planned that an increased number spectral bands in the long-wave infrared (LWIR) region will soon be measured from space at reasonably high spatial resolution (by imagers such as HyspIRI). Detailed LWIR emissivity spectra are required to best interpret the observations from such systems. This includes the highly heterogeneous urban environment, whose construction materials are not yet particularly well represented in spectral libraries. Here, we present a new online spectral library of urban construction materials including LWIR emissivity spectra of 74 samples of impervious surfaces derived using measurements made by a portable Fourier Transform InfraRed (FTIR) spectrometer. FTIR emissivity measurements need to be carefully made, else they are prone to a series of errors relating to instrumental setup and radiometric calibration, which here relies on external blackbody sources. The performance of the laboratory-based emissivity measurement approach applied here, that in future can also be deployed in the field (e.g. to examine urban materials *in situ*), is evaluated herein. Our spectral library also contains matching short-wave (VIS–SWIR) reflectance spectra observed for each urban sample. This allows us to examine which characteristic (LWIR and) spectral signatures may in future best allow for the identification and discrimination of the various urban construction materials, that often overlap with respect to their chemical/mineralogical constituents. Hyperspectral or even strongly multi-spectral LWIR information appears especially useful, given that many urban materials are composed of minerals exhibiting notable reststrahlen/absorption effects in this spectral region. The final spectra and interpretations are included in the London Urban Micromet data Archive (LUMA; http://LondonClimate.info/LUMA/SLUM.html).



## 1. Introduction

Recent advances in thermal infrared remote sensing (Kuenzer and Dech, 2013) include a new generation of space- and airborne hyperspectral thermal sensors such as HyTES and HyspIRI (Abrams and Hook, 2013; Hook et al., 2013), and progress in ground-based techniques (methods and instruments) used both in the field and laboratory (Hecker et al., 2013). Spectrally detailed information across the long-wave infrared (LWIR) atmospheric window offers great potential to aid with a series of challenges of earth observation: it provides new insights and data for the development and application of algorithms aiming at the separation of surface temperature and surface emissivity effects in LWIR spectra and imagery (e.g. Peres et al., 2008) and for the subsequent use of these types of information in e.g. energy balance models (e.g. Xu et al., 2008), and also potentially aids the improved characterisation and classification of surface properties, material type, and surface change through the addition of LWIR information to that in the more commonly exploited VIS-to-SWIR solar reflected spectral regions (e.g. French et al., 2008).

However, current LWIR spectral library information such as that in the widely used ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) spectral library (Baldridge et al., 2009) does not adequately cover the immense diversity of urban materials

* Corresponding author at: Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK. Tel.: +44 (0)118 378 5419; fax: +44 (0)118 378 8905.
*E-mail address:* s.kotthaus@reading.ac.uk (S. Kotthaus).

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(Heiden et al., 2007), even though this will be crucial for the interpretation of hyperspectral remote sensing data gathered in such areas in the future. Urban surface properties have important implications for human health, sustainable design and climate change adaptation and hence present fundamental modelling parameters for related studies (Yang, 2011). In particular, the radiative response of impervious urban materials determines the radiation balance of incoming and outgoing long- and short-wave fluxes, and thereby urban climate conditions. Its significance recently received global media attention when solar radiation reflected by the curved façade[1] of a new skyscraper in the City of London was sometimes intense enough to create surface temperatures sufficient to melt particular plastic parts of nearby parked cars (Guardian, 2013). Spectral information covering the LWIR can also help to support surface temperature retrieval algorithms relevant to research concerned with urban climate and air quality. Relations between short-wave albedo and long-wave emissivity/surface temperature (Small, 2006) are of particular interest for urban climate studies concerned with human thermal comfort (Matzarakis et al., 2010) and/or building energy demand (Yaghoobian and Kleissl, 2012). The surface kinetic temperature (or even the surface brightness temperature directly, i.e. ignoring effects of emissivity) is often used to study the surface urban heat island phenomenon (Voogt and Oke, 2003), to model surface energy exchanges (Voogt and Grimmond, 2000; Xu et al., 2008), and to evaluate and improve urban canopy models (Kusaka et al., 2001).

This paper aims to support such work by developing a new urban materials spectral library covering both the LWIR and VIS–SWIR atmospheric windows, and by elucidating the methods and uncertainties inherent in the production of such a database using, respectively, Fourier Transform InfraRed (FTIR) and grating-based spectrometry. Some background information is provided to underline the motivation of this study (Section 2). Then, the applied spectroscopy methods are introduced (Section 3), providing details on radiometric calibration, background correction and the separation of emissivity and temperature. Investigations of the thermal properties of reference radiation sources (that provide the basis for the radiometric calibration) permit uncertainties arising from the methodology to be quantified. A framework for laboratory-based FTIR emissivity observations is developed (similarly applicable outdoors) and spectra of the different material-classes are analysed (Section 4). Finally, uncertainties of the FTIR spectroscopy observations are summarised and implications of the results for remote sensing of impervious urban materials are considered (Section 5).

## 2. Motivation

Current spectral libraries provide information on a wide variety of materials (e.g. MODIS spectral library, Moderate Resolution Imaging Spectroradiometer, Wan et al., 1994; US Geological Survey, USGS, Clark et al., 2007; ASTER, Baldridge et al., 2009), however, their coverage of impervious urban materials remains limited, especially in the LWIR spectral region (e.g. see Table 1).

Urban spectral libraries have been developed from airborne and/or ground truth observations for example in: Tel-Aviv, Israel (Ben-Dor et al., 2001 using library spectra of Price, 1995), Potsdam and Dresden, Germany (Heiden et al., 2001; Roessner et al., 2001; Heiden et al., 2007), Bonn, Germany (Franke et al., 2009) and Santa Barbara, USA (Herold et al., 2004; Herold, 2007), with increasing interest in the LWIR spectral response of anthropogenic materials. Only a few studies include *in situ* measurements of the same surfaces covering short and long wavelengths (e.g. Kerekes et al., 2008).

[1] Note: this façade was glass which is not a focus of this study.

Cities are very complex spatially, given their three-dimensional structure and immense heterogeneity. But also temporally conditions are changing at fast rates compared to many more 'natural' environments, due to human movements, re-construction (new developments replacing old structures) or technological advances in manufacturing techniques (making new construction materials available). The latter may be used to reduce costs or to yield novel architectural benefits (e.g. flexibility of PVC), but increasingly the environmental aspects of materials and surfaces are being considered in the context of climate change mitigation. Highly reflecting materials are deployed to reduce absorption of solar energy at the surface, which can help to cool urban areas (Akbari et al., 2009). Furthermore, with the need to reduce life-cycle carbon emissions (e.g. DCLG, 2013) there is demand to replace materials (e.g. demand for carbon–neutral cement, Damtoft et al., 2008). Knowledge about chemical compositions and radiative properties of both novel and older construction materials is required to ensure that their dynamic impacts are incorporated into our understanding of the ever-changing urban environment. Applications in a research context range from the characterisation of sites where atmospheric quantities are measured and modelled *in situ* to improved interpretation of airborne or satellite remote sensing data.

As many materials have distinct spectral absorption features in the visible to short-wave infrared (VIS–SWIR) region of the electromagnetic spectrum, multi- or hyper-spectral information across the these wavelengths is applicable to a variety of environmental research questions (e.g. Clark, 1999). Amongst others, they provide a basis for the land cover classification of natural materials, such as soil types (Rossel et al., 2006), vegetation (Adam et al., 2010), and also anthropogenic materials (Townshend et al., 1991). This requires some *a priori* knowledge of the materials' spectral characteristics (Heiden et al., 2001), usually obtained from "ground truth" field spectroscopy, often carried out simultaneously with air-/space-borne data acquisition, and/or from spectral libraries. Urban applications of such classifications (Weng, 2012) cover a wide range of purposes; such as mapping of urbanisation (Deng et al., 2009), identification of impervious surface cover for the quantification of flood risk (Schueler, 1994), assessment of concrete quality (Brook and Ben-Dor, 2011), and evaluation of road network conditions (Herold et al., 2003; Pascucci et al., 2008).

Some materials however, pose a challenge to land cover classification algorithms based on VIS–SWIR information because they lack distinct features in this spectral region. Roberts et al. (2012) suggest that urban land cover classification (e.g. differentiation between bare soil and asphalt) could be significantly improved by including hyperspectral LWIR data, emphasising the great potential of a comprehensive LWIR spectral library. This is because many materials are featureless at shorter wavelengths (e.g. mineral composites, Cloutis et al., 2008), but reveal clear absorption and reststrahlen bands in the LWIR region. The *reststrahlen* (German, 'residual rays') effect describes reflection of radiation in a certain absorption band due to changes of the refractive index within the medium. In combination with absorption features, the related wavebands ('reststrahlen bands') allow conclusions to be drawn about the material's molecular structure.

In addition to the benefits to land cover classification, spectral LWIR emissivity is valuable because it relates outgoing radiance, or a body's 'brightness temperature', to its actual surface kinetic temperature (Gillespie et al., 1998), often termed the land surface temperature (LST; Tomlinson et al., 2011). All LWIR remote sensing approaches aimed at surface kinetic temperature/LST estimation require a method to partition the measured radiance into its contributions from the kinetic temperature of the surface and its emissivity. Several such temperature–emissivity–separation (TES) algorithms have been developed (e.g. Gillespie et al., 1998; Dash