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A technique for resolving the spectral response of a wide-band infrared measuring instrument from measurements without the need for a spectrally tuneable radiation source

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ABSTRACT

A technique is presented in which the spectral response of a wide-band infrared measuring instrument is obtained by means of calibration type measurements of a blackbody at various temperature settings and the application of a mathematical technique to these measurements. Successful application of the developed technique is enabled by Tikhonov regularization, which ensures a stable solution to the ill-posed problem of the Fredholm integral equation of the first kind describing the blackbody measurements made by the instrument. The quality of the solution strongly depends, however, on the accuracy of the measurements and the accuracy of the modelled spectrum in describing the emission from the blackbody source.

The technique is studied by means of an application to modelled results of instrument measurements, and is then applied to actual measurements made with an infrared camera. It is shown that the technique can, in the absence of specific manufacturer supplied information of the instrument and specialized equipment, be an alternative to the theoretical calculation of the instrument response spectrum or to an experimental determination of the instrument spectral response during which measurements are made of a spectrally tuneable radiation source like a blackbody and monochromator.

1. Introduction

In the field of radiometry, the infrared characteristics of an object of interest are inferred from radiation measurements done with calibrated instruments like cameras and spectrometers [1]. Such instruments, which are in common use in the military environment, usually function in one of the atmospheric windows in which attenuation by the atmospheric constituents allows a reasonable distance of propagation of the infrared radiation before total extinction. These windows, or spectral bands, are loosely defined as near-infrared (NIR, 0.75–1.4 μm), short-wave infrared (SWIR, 1.5–2.5 μm), medium-wave (or mid-wave) infrared (MWIR, 3–5 μm) and long-wave infrared (LWIR, 8–12 μm) [2]. The optical systems associated with these instruments, typically composed of lenses, reflective elements, windows, filters and anti-reflection coatings, need to be transparent (or fully reflective) to the infrared wavelengths within one (or several) of the mentioned spectral bands in order for the radiated energy from the object of interest to reach the detector. The detector itself needs to be designed and manufactured as to be sensitive in the required wavelength band.

In practice, no optical system is fully transparent at all wavelengths [3] within a spectral band, and the sensitivity of the widely used infrared photon detectors can also be assumed to have a non-flat spectral response to incoming radiation [4]. The response of the other main type of detectors in common use, i.e. thermal detectors, is generally wavelength independent [4], but spectral selectivity is also introduced to this type of detector whenever a surface coating with selective spectral absorptivity properties is applied to the detector. The combined effects of spectral selectivity in the optical system transmission and detector response result in the instrument, as a whole, having a non-flat spectral response to any radiation measured by it.

The influence of a non-flat instrument spectral response can largely be factored out by a calibration procedure. During this procedure an infrared source, like a blackbody with known Planck distributions of radiated energy at different temperature settings, is used as the object of interest to be measured by the instrument. The output signals of the instrument can then be correlated with the known temperature or radiance values of the blackbody being measured, so that the non-flat spectral instrument response is compensated for. In such a way, the instrument signal obtained from measuring a blackbody of unknown temperature can be inferred from the calibration information. However,

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for objects with non-blackbody spectra, such as spectrally selective emitters like gases, or grey bodies with constant emissivities smaller than one, the inferred temperature will most probably not agree with the object's thermodynamic temperature and is called the radiometric temperature (see [5] for the definitions of several types of radiometric temperatures). Moreover, for measurements during which the infrared signature of an object must be determined over a distance for which the atmospheric and other environmental contributions to the observed radiation is non-negligible, the measured radiation (and associated radiometric temperature), digress even more from the true value of that of the object of interest. In order to correctly model the radiance measured by the instrument, or to attempt to infer the source radiance value of the object of interest during data reduction by correcting for exogenous influences on the measurement, the instrument spectral response is required [6].

In general, the instrument spectral response can be determined by one of two methods:

- Theoretically by having information from the manufacturer in hand, like the detector responsivity as calculated from the spectral quantum efficiency of a photon detector [7], the spectral absorption of the surface of a thermal detector and the spectral transmission of the optical system and any filter or coating forming part of it.
- Purely experimentally with the use of a spectrally tuneable radiation source, like an infrared source and monochromator of some sort, capable of generating infrared radiance within a narrow wavelength band of which the centre frequency can be swept through the spectral wide-band (NIR, SWIR, MWIR or LWIR) in which the instrument operates, e.g. [8].

The first method typically, in practice, suffers from incomplete or unavailable information. Furthermore, the spectral information supplied by a manufacturer most likely consists only of typical values of quantum efficiency and transmission for a batch of detectors and optical systems, instead of the exact values of the specific component purchased.

The second method can be considered as the preferred method, since any manufacturing deviation from the design norm is automatically apprehended in the measurements. The problem here might be the lack of the appropriate, specialized, and usually costly, equipment. Also, due to the nature of a narrow band radiation source, the amount of radiation energy decreases as the resolution (determined by the width of the tuneable narrow wavelength band) increases, which might present instrument dependent problems related to inadequate sensitivity.

The goal of the research reported on in this article is to present a promising alternative method to the two mentioned traditional methods for determining the spectral response of an infrared measuring instrument. The main idea behind this method is to use only a blackbody, which is a standard piece of equipment in any infrared laboratory, and a very low temperature object for calibration type measurements from which the instrument spectral response can be retrieved after applying an appropriate mathematical technique.

In Section 2.1 the mathematical technique is developed by starting from the basic measurement equation for calibration type measurements. The technique is considered novel in the sense that it demonstrates that it is in principle possible to obtain the instrument spectral response of a wide-band instrument from measurements of a blackbody without the use of a monochromator. However, although the spectral response recovery is in principle possible, it does come with complications arising from the instability of the solution. Fortunately, an attempt can be made to stabilize this type of unstable solution arising from the inversion of ill-conditioned matrices; to this effect, the regularization method of Tikhonov is introduced. After introduction of this stabilization method, the technique is applied in Section 2.2 to synthetically generated measurements, i.e. measurement results with no measurement errors but with unstable solutions. The behaviour of the technique with the mentioned regularization method is then demonstrated by an investigation into its dependency on the controllable aspects, i.e. controllable parameters, used during the process of obtaining a solution, followed by a discussion of the findings in Section 2.3.

Section 3.1 presents the spectral response of a real instrument, a MWIR camera, as obtained from the two earlier mentioned traditional methods. In order to utilize the proposed technique for obtaining the camera spectral response, it is showed in Section 3.2 how a realistic model of the signal output from the instrument should be constructed before attempting to resolve its spectral responsivity. This model is considered sufficiently generic to be applicable to a wide range of infrared (IR) camera models. The measurement setup of the calibration type measurements is then also described in detail to enable any interested party to replicate these types of measurements. It is then shown that, although it is in principle possible to resolve the spectral response of an instrument by the proposed technique as illustrated in Section 2, a high degree of accuracy are required in the measurements and in the knowledge of the observed object radiance spectrum. The purely experimentally determined camera spectral response (second method described above), considered as an absolute reference, is then used to compare the solutions obtained from the proposed technique against and also to obtain an indication of the required degree of measurement accuracy for the technique to be applied successfully.

Section 4 summarizes the research done and the findings and limitations when applying the proposed technique, with some reflections on possible future research and other applications.

2. Technique for resolving the instrument spectral response

2.1. Theory

The measurement of an object by an ideal instrument, without any exogenous influences, can be described by the measurement equation (cf. [9])

$$s = \int_{\lambda_a}^{\lambda_b} L_{obj}(\lambda)\Re_L(\lambda)d\lambda, \tag{1}$$

where s (units of [V] or [A]) is the signal obtained from the instrument as a result of the observed object having a wavelength (λ) dependent radiance $L_{obj}(\lambda)[\mathrm{W{\cdot}m^{-2}{\cdot}sr^{-1}{\cdot}\mu m^{-1}}]$. The wavelengths λ_a and λ_b demarcate the spectral band in which the instrument is sensitive to radiation, and $\Re_L(\lambda)$ is the spectral radiance responsivity of the instrument, which is the ratio of the output of the instrument to that of the spectral radiance of the observed object (units of [(V or A)/(W·m^{-2}·sr^{-1}·μm^{-1})]). The responsivity can be written as

$$\Re_L(\lambda) = \Re_L(\lambda_o)r(\lambda) = C_{L2s}r(\lambda), \tag{2}$$

where $C_{L2s} \equiv \Re_L(\lambda_0)$ is the spectral responsivity at the wavelength at which $\Re_L$ obtains its maximum value, i.e. at wavelength λ_o, so that $r(\lambda) = \Re_L(\lambda)/C_{L2s}$ forms the normalized spectral responsivity, which are often used in these type of measurement equations (see e.g. [10–12]). C_{L2s} forms a wavelength independent conversion factor (and therefore removable from under the integration sign in Eq. (1)), which both scales the calculated radiance back to the correct level and also converts it into instrument signal units (L to s), whenever the normalized spectral responsivity $r$is used in the measurement equation as is shown later in Eq. (4). The use of r introduces a simplification in the notation used in the technique under development, with $r$containing only the essence of the desired information to be retrieved– the shape of the spectral response and not so much the absolute level of this spectrum.

The object radiance, $L_{obj}(\lambda)$, describes all contributions from all sources of radiance reaching the instrument, but in the rest of this section it will be considered to consist only of a blackbody, described by Planck's law