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(54) Title: A FAST SPECTRAL METHOD TO MEASURE EMISSIVITY IN A PARTIALLY-CONTROLLED ENVIRONMENT USING A FOCAL PLANE ARRAY INFRARED CAMERA

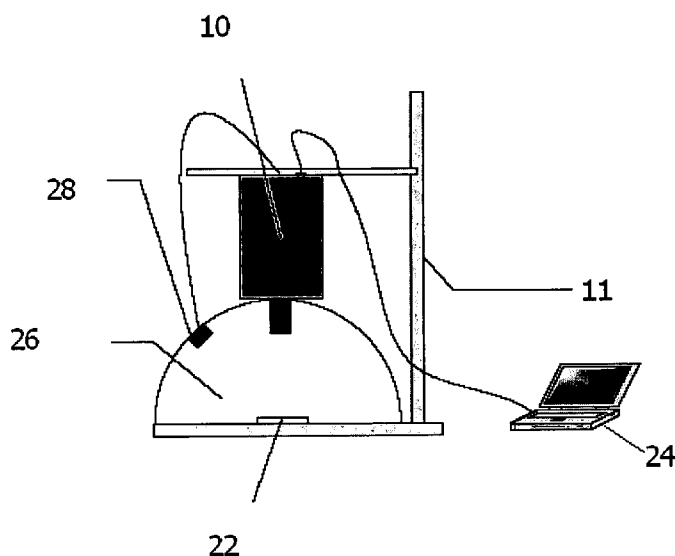


FIGURE 3

(57) Abstract: Provided are a system and a methodology of ascertaining the emissivity-corrected temperatures and the emissivity (ϵ) of an object or thermal scene (22) of interest. No prior knowledge of the emissivity of the object is required and no calibrating or reference body is required to decouple reflected radiation from emitted radiation. This methodology uses radiance expressions for two different bandwidths (filters 14, 16) and mathematically manipulates these expressions to remove emissivity to solve for the emissivity-corrected temperatures of the object (22'), and these temperatures are used to derive the emissivity of the object (22).



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**A FAST SPECTRAL METHOD TO MEASURE EMISSIVITY IN A
PARTIALLY-CONTROLLED ENVIRONMENT USING A
FOCAL PLANE ARRAY INFRARED CAMERA**

5 **FIELD OF THE INVENTION**

[0001] This invention generally relates to the remote or non-contact measurement of emissivity and/or temperature using infrared cameras, and more specifically to the remote measurement of emissivity and/or temperature that automatically compensate for radiation that is reflected by the object of interest.

10 **BACKGROUND OF THE INVENTION**

[0002] Infrared thermography or thermal imaging or thermal video is used in many industries. Thermographic cameras remotely detect radiation in the infrared range of the electromagnetic spectrum (about 0.9 μm to about 14 μm) and produce thermal images of that radiation. All objects emit infrared radiation based on their temperature in accordance with black body radiation law or Planck's Law. Thermography allows one to appreciate the variation in temperatures in an environment or an infrared scene with or without illumination, and see a thermal image of the infrared scene. Warmer objects, such as humans, other warm-blooded animals and other heat sources, appear brighter and stand out against cooler backgrounds, day or night. Historically, thermography has been used by militaries and security services. However, thermography can be applied in firefighting where an image can be produced through smokes, and in manufacturing where temperature distribution over a substrate, such as integrated circuit (IC) or printed circuit (PC) boards, can be measured.

25 [0003] A reliable, straight-forward and user-friendly emissivity correction device is in great demand in the micro-electronics industry. As integrated circuits and electronic chips become smaller, heat dissipation and heat management are becoming ever more important features in the development of a new chip generation. Miniaturization requires the ability to carefully control the heat dissipation locally and dynamically over the entire circuit or printed circuit board. Thus, the emissivity of the different components, discussed below, must be known to prevent the distortion of the absolute temperature measurement's process.

30 [0004] Measuring temperatures over a spatial distribution requires a focal plane array (FPA) infrared camera or similar media that are sensitive to infrared radiation.

35 However, an infrared camera doesn't measure only the temperature of a body. It

measures infrared energy radiated by objects, which includes emitted, reflected or even transmitted radiation. The emitted energy is the energy radiated or emitted by the objects as a function of their temperature, and is the energy intended to be measured. The transmitted energy is the radiation emitted by remote sources that passes through the objects to be measured. The reflected energy is the energy that reflects off the surface(s) of the objects to be measured from remote sources.

Transmitted or reflected energy need to be decoupled or compensated so that one can accurately measure the temperatures or accurately produce thermal images. All infrared thermography applications, as well as pyrometers, are based on this principle.

[0005] U.S. patent no. 7,439,510 to Bevan et al. (or US 2007/0152153) discloses disposing a calibrated reference patch having a known emissivity within the field of view (FOV) of the FPA infrared camera. The temperature of the calibrated referenced patch is measured by a contact probe. The calibrated reference patch is used to provide correction for the environmental radiation reflected off of the object to be measured. The '510 patent also discloses a method of double heating a reference black body to create calibration curves for the FPA infrared camera. Once the environmental radiation correction is known, it can be used to correct measurements taken from the rest of the object to be measured.

[0006] U.S. patent no. 5,868,496 to Spitzberg discloses using a calibration object of known emissivity, that has similar geometry as the object(s) to be measured, in place of the object to be measured. The temperature of the calibration object is maintained at a known temperature and its radiation is measured by the FPA IR camera. The difference between the temperature measured by the FPA IR camera and the known maintained temperature is directly related to the reflected and/or transmitted radiation.

Once this is known, the reflected and/or transmitted radiation can be estimated or compensated in the estimation process for later measurements.

[0007] Emissivity is the ratio of the energy radiated by any object to the radiated energy of a black body at the same temperature and under the same geometrical and spectral conditions. Emissivity ranges from 0.0 for a non-emitting object to 1.0 for a completely emitting or black body object. Since perfect black bodies do not exist, the infrared radiation of normal objects appears to be less than the true temperature, *e.g.*, a temperature measured by a thermocouple in contact with the object. The percentage of the temperature measured by infrared radiation to the true temperature is the emissivity. Knowledge of this emissivity parameter is important to obtain the

absolute object's temperature. The emissivity parameters of many materials are known and are listed on emissivity tables. Emissivity can vary depending on the frequency of the emission and the temperatures of the objects.

[0008] Emissivity compensation has been possible for FPA infrared cameras by entering known emissivity for different materials from emissivity tables. Emissivity can also be determined through calibration, by placing a test material of known emissivity in contact with the surface of the object to be measured with the FPA infrared camera to ensure that the test material and the object are at the same temperature. The temperature of the test material is measured with the FPA infrared camera. Then, the temperature of the object is measured and the emissivity of the object is varied until the FPA infrared camera reads the same as that of the test material.

[0009] Another known method for determining emissivity is to heat the sample to two different known temperatures. The sample's emissivity is the ratio of radiances given by Planck's law for these two temperatures. However, heating the sample may not be practical when the sample is a biological or chemical product.

[0010] A complex method of estimating emissivity is discussed in the '496 patent, which involves measuring radiation at multiple wavebands. The known measured power at each wavelength band is substituted into the known function of power with respect to emissivity, and compensated for the known background radiation. An expression for the emissivity of the surface as a function of temperature at each wavelength band is obtained. Measurements at a series of trial temperatures are obtained. These measurements are fitted by the least squares minimization curve to the model emissivity function. At each wavelength band, the model emissivity function is subtracted from the measured emissivity as a function of temperature. Then a constrained search over the predetermined range of temperatures is performed to determine the unknown constant coefficients required in the model expression to generate a least sum of squares of the difference functions at each wavelength .

[0011] Another known method for measuring emissivity is to assume that emissivity = (1-reflectivity). Narrow band laser beams are directed at the object at radiation bands, where emitted radiation is minimal, e.g., *visible range*, and the reflected energy at the laser's wavelength is measured. (See Background section of the '510 patent). Emissivity at these narrowed wavelengths is known. However, emissivity at non-visible wavelengths can be different than at the measured visible wavelengths and

emissivity has to be specifically measured. Other emissivity correction techniques are discussed in the Background section of the '510 patent. The '510 patent itself uses a two-color ratio thermometry method to measure temperatures, where a ratio of the radiance at two narrow frequencies is determined. The ratios are inserted into a ratio
5 look up table to obtain temperature readings.

[0012] However, the prior art does not contemplate fast measurements of emissivity within the whole field of view of its infrared cameras, spatially limited by the system's instantaneous field of view and with no specific knowledge of the object.

SUMMARY OF THE INVENTION

[0013] The invention is also directed to systems and a methodologies of ascertaining the emissivity-corrected temperatures and the emissivity of an object or thermal scene of interest. No prior knowledge of the emissivity of the object is required and no calibrating or reference body is required to decouple reflected radiation from emitted
15 radiation. The inventive systems and methodologies uses radiance expressions for two different bandwidths and mathematically manipulates these expressions to remove emissivity to solve for the emissivity-corrected temperatures of the object, and these temperatures are used to derive the emissivity of the object.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] In the accompanying drawings, which form a part of the specification and are to be read in conjunction therewith and in which like reference numerals are used to indicate like parts in the various views:

[0015] FIG. 1 is a schematic flow chart showing -providing process steps in
25 accordance with an embodiment of the invention;

[0016] FIG. 2 is a partially exploded view of a device that executes the method of FIG. 1;

[0017] FIG. 3 is an alternative of the device of FIG. 2;

[0018] FIGS. 4A-4B comprise a flowchart showing an operational sequence of an
30 embodiment of the invention; and

[0019] FIGS. 5A-5C comprise a flowchart showing an algorithm that performs the emissivity correction of an embodiment of the invention.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0020] Embodiments of the invention are directed to a novel, fast methodology of measuring emissivity and temperatures in a semi-controlled environment using an infrared sensor, an infrared thermometer (pyrometer) or a FPA infrared camera without contacting the objects to be measured. The methodology employs a spectral selection embedded in these IR devices including FPA infrared cameras and a dedicated algorithm to define the emissivity of objects in a thermal scene. The methodology does not require specific knowledge of the objects nor reference point(s) in the thermal scene. The method also uses two bands of wavelengths; however, the ratio of the two radiances at these wavelengths is not ascertained and no ratio lookup table is used to determined temperature or emissivity.

[0021] Referring to FIGS. 1 and 2, the device that executes the methodology is shown. FPA infrared camera 10 has a filter wheel 12, which comprises at least two filters 14, 16. Filters 14 and 16 are colored to impose a desirable frequency bandwidth on the radiation entering the infrared camera 10. The bandwidths of filters 14, 16 are different from each other, and preferred bandwidths are discussed below. Filter wheel 12 also has unoccupied slots 18, which can receive additional filters having different frequency bandwidths. Since the measured temperatures are associated with the frequencies of the emitted radiation, the additional filters provide wider ranges of temperature measurements. Filter wheel 12 is rotatable to select the preferred filter. Infrared camera 10 also has an optical lens 20 which can focus the radiation through filters 14 or 16 to the FPA, which is located internally within infrared camera 10 and to computer (CPU) or camera PC controller 24. As shown, lens 20 is positioned between the filters and thermal scene 22; however, the present invention is not so limited. Filters 14, 16 can be placed between lens 20 and thermal scene 22. Computer 24 displays an emissivity corrected thermal scene 22' on its screen. Suitable infrared cameras 10 include, but are not limited to, FLIRTM ATS SC5000 or SC7000, commercially available from FLIR Systems, Inc. Other infrared cameras, infrared FLAs, pyrometers, and infrared sensors can be used to measure temperatures and emissivities.

[0022] Referring to FIG. 3, the thermal environment can optionally be at least partially controlled by deploying screens or a shield 26 around thermal scene 22, such as a dome 26, to separate out stray radiation from the environment. In this embodiment, infrared camera 10 can be mounted on stand 11 with its optical lens 20 focused on thermal scene 22. Temperature gauge 28, such as a thermocouple or

thermistor, can be attached to the inner surface of shield 26 to measure the temperature of the surface of shield 26. The inner surface of shield 26 can also be coated with a flat or matte black coating or material of known emissivity or the emissivity can be measured by infrared camera 10 using any of the techniques discussed above. Hence, the temperature and the emissivity of the environment are known.

[0023] The operational sequence of an embodiment of the invention is illustrated in FIGS. 4A-4B. After the system is started, the information relating to the object to be measured (*e.g.*, thermal scene 22), such as the area of the object and the distance from the optical lens 20, is entered into computer 24 by the user in step 100. After step 1, the object's solid angle G is calculated by computer 24. In step 105, the temperature range of the object to be measured is entered by the user. For example, for integrated circuits or printed circuit boards illustrated in FIG. 2, the temperature range should be between about 50°C to about 100°C. Computer 24 can select or recommend the wavelength bands for filters 14, 16 depending on the temperature range of the thermal scene.

[0024] In the next sequence, the filter wheel 12 is rotated to one of the filters 14, 16 in step 110 and the detector saturation is checked, *i.e.*, to assure that any peak in the temperature scene does not exceed the camera's temperature range. Detector saturation can be caused by the radiation reflected off of the object to be measured or by the temperature range exceeding the temperature rating of the infrared camera 10, among other factors. If the detector saturation condition exists, then a warning message appears for the user to make adjustment to remove the saturation. In step 115, the other filter 16, 14 is checked for detector saturation.

[0025] After the detector saturation conditions are checked, the external or background temperature is entered by the user in step 120. In the embodiment shown in FIG. 3, the external or background temperature is the temperature measured by temperature gauge 26. In step 125, camera 10 takes N number of frames of the thermal scene 22 or object to be measured through one filter 14 or 16. As shown in FIG. 4, twenty-five (25) frames are recorded; however, any number of frames can be used. Computer 24 then calculates the mean temperature of the thermal scene 22 through that filter. In step 130, filter wheel 12 is rotated to the other filter 16 or 14, and in step 135 another N number of frame through that filter are recorded, and the second mean temperature is calculated. In step 140 a fast emissivity map (FEM)

algorithm, described in detailed below, is applied to each pixel in the FPA. The time delay between the acquisition with filter #1 and the acquisition with filter #2 should be as short as possible, *e.g.*, less than 1.0 second. Preferably, the time delay should be linked to the dynamic of the thermal scene. When the thermal scene is relatively

5 stable, the time delay between acquisition can be longer, and when the thermal scene's temperatures change more rapidly, the time delay should be shorter.

Thereafter, the filter wheel 12 is optionally turned to an open window 18.

Alternatively, two cameras 10, one with filter 14 and the other with filter 16 can be used to record the temperatures of the thermal scene simultaneously to provide two

10 contemporaneous temperatures.

[0026] Each pixel in the two-dimensional array FPA with its location designated as (i,j), now has recorded a radiation from a corresponding portion on thermal scene 22, which needs to have its emissivity corrected by the FEM algorithm, as discussed below.

15 **[0027]** As used herein in connection with the FEM algorithm, the following symbols have the following definitions:

Symbols	Definition
G	Solid angle from camera 10 to thermal scene 22
T_{bckg}	Background or external temperature °C.
$T_{\#1}$	Temperature measured by camera 10 with filter #1 (filter 14)
$T_{\#2}$	Temperature measured by camera 10 with filter #2 (filter 16)
h	Planck constant (6.63×10^{-34} W·s ² or J·s)
k	Boltzman constant (1.38×10^{-23} J/K)
C	speed of light (3.00×10^8 m/s) in vacuum
$\lambda_1, \Delta\lambda_1$	Mean wavelength of filter #1 (filter 14), and range of the bandwidth of filter #1, respectively.
$\lambda_2, \Delta\lambda_2$	Mean wavelength of filter #2 (filter 16), and range of the bandwidth of filter #2, respectively.
ϵ	Emissivity of the ambient radiation, <i>e.g.</i> , emissivity of shield 26. ϵ has a default value of 1.0
$R_{\text{bckg}\#1}(i,j)$	Radiance of the background at T_{bckg} over the $\Delta\lambda_1$ of filter 1 at pixel (i,j) in the FPA.

$R_{\text{bckg}\#2}(i,j)$	Radiance of the background at T_{bckg} over the $\Delta\lambda_2$ of filter 2 at pixel (i,j) in the FPA.
$R_{\#1}(i,j)$	Radiance at mean $T_{\#1}$ over the $\Delta\lambda_1$ of filter 1 at pixel (i,j) in the FPA.
$R_{\#2}(i,j)$	Radiance at mean $T_{\#2}$ over the $\Delta\lambda_2$ of filter 2 at pixel (i,j) in the FPA.
T_{abs}	Analytical temperature, which is the root of the polynomial ($B-A=0$) $T_{\text{abs}} > \text{maximum}(T_{\#1}, T_{\#2})$. T_{abs} is solved numerical approximation to the order of at least 10^{-6} . T_{abs} is the emissivity corrected temperature.
$R_{\text{abs}\#1}$	Radiance at T_{abs} over the $\Delta\lambda_1$ of filter #1 at pixel (i,j) in the FPA.
$R_{\text{abs}\#2}$	Radiance at T_{abs} over the $\Delta\lambda_2$ of filter #2 at pixel (i,j) in the FPA.
ϵ_1	Emissivity at the frequency range of filter #1 with the background or reflected radiation removed.
ϵ_2	Emissivity at the frequency range of filter #2 with the background or reflected radiation removed.
ϵ_{scene}	The average of ϵ_1 and ϵ_2 and the emissivity of the scene at pixel (i,j) .

[0028] As used herein, the radiance (e.g., $R_{\text{bckg}\#1}(i,j)$, $R_{\#1}(i,j)$, etc.) is the integration of Planck's law at the relevant temperature over the frequency range of the filter, $\Delta\lambda$. Hence, radiance has the following general form in an embodiment of the invention.

$$\text{Radiance (R)} = \frac{2 \cdot \pi \cdot h \cdot c^2 \cdot \lambda_m^{-5}}{\text{Exp}(h \cdot c / \lambda_m \cdot k \cdot T_m) - 1} \cdot \Delta\lambda_m,$$

- 5 where the subscript (m) denotes either filter #1 or filter #2, or background condition when used with frequency or frequency range (λ , $\Delta\lambda$), and denotes mean or measured temperature when used with T. For example, the terms λ_1 , $\Delta\lambda_1$, $T_{\#1}$, denote the mean wavelength, bandwidth and measured temperature, respectively, of filter #1 (i.e., $m = 1$), respectively. λ , $\Delta\lambda$ can be any range within the infrared region and preferably in
- 10 the near infrared region, and embodiments of the invention are not limited to any

particular frequency(ies). One of ordinary skill in the art can select the proper λ 's, $\Delta\lambda$'s for any applications.

[0029] Without being limited to any particular theory, the inventors have determined a methodology to remove the reflected radiation from the measured radiation from the object to be measured without having to insert a reference body having similar shape as the object to be measured or to include a reference patch on the thermal scene, as taught by the prior art and discussed above. In other words, novel means for compensating for the reflected radiation without using a reference or calibrated body in the thermal scene are provided below.

[0030] In the inventive methodology, the object to be measured, *e.g.*, thermal scene 22 as an IC circuit or PC board illustrated in FIG. 2, has a finite dimension and is opaque, so that transmitted radiation is minimized or preferably eliminated. Such object shall have a spatial surface temperature distribution $T(i,j)$, where (i,j) represents the spatial coordinates of a given pixel on the FPA that corresponding location on the object to be measured.

[0031] For each pixel, camera 10, preferably calibrated using the manufacturer's procedure, through one filter 14, 16 provides a temperature measurement, $T_{\#1}$ and $T_{\#2}$. Using the general radiance equation above, radiance $R_{\#1}$ and $R_{\#2}$ can be computed.

The specific forms of $R_{\#1}$ and $R_{\#2}$ are provided below (as equations 3 and 4) with all the equations derived for this methodology.

[0032] Assuming that the object to be measured is a lambertian object, *i.e.*, the radiance by the object is independent of the direction of observation, especially for small angular variations, then the radiated intensity (I) is:

$$I = R \cdot S / \pi \text{ (Watts),}$$

where S is the object's two dimensional surface as seen by camera 10. The camera's irradiance value (E) is:

$$E = (R \cdot S) / (\pi \cdot d^2) \text{ (Watts/m}^2\text{),}$$

where d is the average distance from the camera 10 to the object to be measured, and

$S / (\pi \cdot d^2)$ is defined as G, the object's solid angle. Furthermore, the object to be measured (*e.g.*, thermal scene 22) is placed in a given environment. This environment is characterized by a temperature, T_{bckg} , and Θ , which is an experimental parameter and can be expressed as,

$$\Theta = \epsilon \cdot \kappa,$$

where ϵ is the background emissivity, discussed above, and κ (Gr. kappa) is an experimental correction factor related to atmospheric transmission. κ is used to experimentally correct the background emissivity. In other words, the background emissivity can be measured experimentally to correct, if necessary, the ϵ factor.

- 5 [0033] As discussed above, an acceptable approximation for reflected radiation is $(1 - \epsilon)$. Hence, radiance R for the first filter (and similarly for the second filter) can be written as:

$$R_{\#1} = \epsilon \cdot (\text{radiance related to emitted radiation for } \Delta\lambda_1) + G \cdot (1 - \epsilon) \cdot \Theta \cdot (\text{radiance related to reflected radiation from the background for } \Delta\lambda_1).$$

- 10 Of course, the emitted radiation portion is multiplied by the emissivity factor to take into account non-black body emission. The reflected radiation portion is multiplied by the solid angle G to take into account of the size of the object to be measured relative to its environment, and by Θ to take into account the background emissivity. $R_{\#1}$ can be written mathematically as:

$$R_{\#1} = \underbrace{\epsilon \cdot \frac{2\pi \cdot h \cdot c^2 \cdot \lambda_1^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_1 \cdot k \cdot T_{\#1}}\right) - 1} \cdot \Delta\lambda_1}_{\text{Planck law for } \Delta\lambda_1 \text{ spectral band and related to the object emission}} + G \cdot (1 - \epsilon) \cdot \underbrace{\Theta \cdot \frac{2\pi \cdot h \cdot c^2 \cdot \lambda_1^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_1 \cdot k \cdot T_{\text{bckg}}}\right) - 1} \cdot \Delta\lambda_1}_{\text{Planck law for } \Delta\lambda_1 \text{ spectral band and related to the background emission}}$$

15

$R_{\#1}$ can be simplified or written in short hand as

$$R_{\#1} = \epsilon \cdot R(T, F_{\#1}) + G \cdot (1 - \epsilon) \cdot \Theta \cdot R_{\text{bckg}\#1},$$

where, $R(T, F_{\#1})$ is the shorthand for radiance at the temperature measured by and wavelengths of filter #1, and $R_{\text{bckg}\#1}$ is the background radiance measured by filter #1, as defined above. Similarly,

20

$$R_{\#2} = \epsilon \cdot R(T, F_{\#2}) + G \cdot (1 - \epsilon) \cdot \Theta \cdot R_{\text{bckg}\#2},$$

[0034] Since the frequency ranges of the first and second filters (*i.e.*, filters 14 and 16) are relatively narrow, another acceptable assumption is that the emissivity ϵ , while a function of frequency, is substantially constant over the frequency ranges of both filters. This assumption has been employed successfully with two-color pyrometers.

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[0035] An advantage of embodiments of the invention is that since the equations for $R_{\#1}$ and $R_{\#2}$ contain the emissivity factor ϵ of the object to be measured, when these two equations are solved for the temperature, this temperature is emissivity corrected.

Another advantage is that emissivity can also be solved. Mathematical manipulations of the equations for $R_{\#1}$ and $R_{\#2}$ are as follows:

[0036] The equation for $R_{\#1}$ and $R_{\#2}$ can be rewritten as follows by isolating ε :

$$R_{\#1} = \varepsilon \cdot (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1}) + (G \cdot \Theta \cdot R_{\text{bckg}\#1})$$

$$R_{\#2} = \varepsilon \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}) + (G \cdot \Theta \cdot R_{\text{bckg}\#2})$$

and further isolating ε to the right hand side of the two equations yields

$$R_{\#1} - (G \cdot \Theta \cdot R_{\text{bckg}\#1}) = \varepsilon \cdot (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1}) \quad (A1)$$

$$R_{\#2} - (G \cdot \Theta \cdot R_{\text{bckg}\#2}) = \varepsilon \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}) \quad (A2)$$

[0037] One preferred way to solve the equations A1 and A2 is to solve both for $R_{\#1}$ and $R_{\#2}$ and set them equal to each other. In other words, the radiance from thermal scene should be substantially the same from both filters.

$$R_{\#1} = (G \cdot \Theta \cdot R_{\text{bckg}\#1}) + \varepsilon \cdot (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1})$$

$$R_{\#2} = (G \cdot \Theta \cdot R_{\text{bckg}\#2}) + \varepsilon \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}), \text{ or}$$

$$(G \cdot \Theta \cdot R_{\text{bckg}\#1}) + \varepsilon \cdot (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1}) = (G \cdot \Theta \cdot R_{\text{bckg}\#2}) + \varepsilon \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}) \quad (A3)$$

[0038] Equation A3 can be solved by assuming or estimating an emissivity value and through trial and error assign a temperature value that satisfies equation A3.

Alternatively, emissivity can be measured using any of the techniques discussed above. Hence, in accordance with a preferred embodiment of the present invention, emissivities and temperatures can be accurately measured without using a calibrated patch or a reference body to compensate for reflected radiation.

[0039] Another preferred way to solve equations A1 and A2 is by presuming that ε is constant over the narrow frequency ranges of filters 14 and 16, by dividing these two equations, ε can be eliminated therefrom (at least for now):

$$\frac{R_{\#1} - (G \cdot \Theta \cdot R_{\text{bckg}\#1})}{R_{\#2} - (G \cdot \Theta \cdot R_{\text{bckg}\#2})} = \frac{(R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1})}{(R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2})} \quad (A4)$$

Multiplying both sides of equation A4 by the denominator of the right hand side yields:

$$\frac{R_{\#1} - (G \cdot \Theta \cdot R_{\text{bckg}\#1})}{R_{\#2} - (G \cdot \Theta \cdot R_{\text{bckg}\#2})} \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}) = (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1})$$

Setting this equation to equal to zero yields:

$$R_{\#1} - (G \cdot \Theta \cdot R_{\text{bckg}\#1}) \cdot (R(T, F_{\#2}) - G \cdot \Theta \cdot R_{\text{bckg}\#2}) - (R(T, F_{\#1}) - G \cdot \Theta \cdot R_{\text{bckg}\#1}) \cdot (R_{\#2} - (G \cdot \Theta \cdot R_{\text{bckg}\#2})) = 0$$

$$\left\{ \frac{R_{\#2} - (G \cdot \Theta \cdot R_{\text{bckg}\#2})}{R_{\#1} - G \cdot \Theta \cdot R_{\text{bckg}\#1}} \right\} \cdot [R_{(T, F\#2)} - G \cdot \Theta \cdot R_{\text{bckg}\#2}] - [R_{(T, F\#1)} - G \cdot \Theta \cdot R_{\text{bckg}\#1}] = 0$$

Temperature is the only remaining variable in this equation. This equation is a polynomial and can be grouped as:

$$\underbrace{\left\{ \frac{R_{\#1} - G \cdot \Theta \cdot R_{\text{bckg}\#1}}{R_{\#2} - G \cdot \Theta \cdot R_{\text{bckg}\#2}} \right\} \cdot [R_{(T, F\#2)} - G \cdot \Theta \cdot R_{\text{bckg}\#2}]}_B - \underbrace{[R_{(T, F\#1)} - G \cdot \Theta \cdot R_{\text{bckg}\#1}]}_A = 0$$

[0040] The polynomial equation ($B - A = 0$) can be solved for the emissivity-corrected

- 5 temperature, T_{abs} , or absolute or real temperature, which is a root of this polynomial. A preferred way to solve for T_{abs} is by standard polynomial algorithm, or by trial and error. In other words, values for T_{abs} are inserted into the polynomial until the resultant reaches approximately zero. Preferably, this equation is solved until $B - A \leq 10^{-6}$. T_{abs} is generally greater than both $T_{\#1}$ and $T_{\#2}$.

- 10 **[0041]** Once T_{abs} is determined, radiance R is determined for each filter's frequency ranges using T_{abs} . At this time, emissivity ϵ , as measured with each filter is solved, since, emissivity ϵ , is the ratio of the actual emitted energy by a body to the emitted energy of a black body, as shown in equations 8 and 9, below.

- 15 **[0042]** Since emissivity was assumed to be constant over the narrow frequency ranges for both filters, and since the calculated emissivity values from both filters are slightly different from each other, the final emissivity or the emissivity for the thermal scene 22 for each pixel is calculated as the average emissivity values from both filters.

[0043] The specific equations used in the fast emissivity map (FEM) algorithm and explained above are listed below:

Factor	Eq. No.	Formula
$R_{\text{bckg}\#1}(i,j)$	1	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_1^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_1 \cdot k \cdot T_{\text{bckg}}}\right) - 1} \cdot \Delta\lambda_1$
$R_{\text{bckg}\#2}(i,j)$	2	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_2^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_2 \cdot k \cdot T_{\text{bckg}}}\right) - 1} \cdot \Delta\lambda_2$
$R_{\#1}(i,j)$	3	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_1^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_1 \cdot k \cdot T_{\#1}}\right) - 1} \cdot \Delta\lambda_1$

$R_{\#2}(i,j)$	4	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_2^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_2 \cdot k \cdot T_{\#2}}\right) - 1} \cdot \Delta\lambda_2$
T_{abs}	5	B-A = 0, where T is the sole variable. Solve for T until $B-A \leq 10^{-6}$
$R_{\text{abs}\#1}$	6	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_1^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_1 \cdot k \cdot T_{\text{abs}}}\right) - 1} \cdot \Delta\lambda_1$
$R_{\text{abs}\#2}$	7	$\frac{2\pi \cdot h \cdot c^2 \cdot \lambda_2^{-5}}{\exp\left(\frac{h \cdot c}{\lambda_2 \cdot k \cdot T_{\text{abs}}}\right) - 1} \cdot \Delta\lambda_2$
ε_1	8	$\varepsilon_1(T_{\text{abs}}, R_{\#1}, R_{\text{bckg}\#1}) = \frac{(R_{\#1} - \varepsilon' \cdot R_{\text{bckg}\#1})}{(R_{\text{abs}\#1} - R_{\text{bckg}\#1})}$ All of the terms on the right hand side are known.
ε_2	9	$\varepsilon_2(T_{\text{abs}}, R_{\#1}, R_{\text{bckg}\#1}) = \frac{(R_{\#2} - \varepsilon' \cdot R_{\text{bckg}\#2})}{(R_{\text{abs}\#2} - R_{\text{bckg}\#2})}$ All of the terms on the right hand side are known.
$\varepsilon_{\text{scene}}$	10	$\varepsilon_{\text{scene}} = \frac{(\varepsilon_1 + \varepsilon_2)}{2}$

[0044] With the preferred methodology described above, FIGS. 5A-5C illustrate the algorithm of the FEM, as described above. In step 200, the background radiance R_{bckg} is calculated using inputs T_{bckg} , $\varepsilon_{\text{bckg}}$, λ and $\Delta\lambda$ for each pixel for each filter using equations 1 and 2. In step 205, the radiance of the object to be measured $R_{\#m}$ is calculated using the mean temperature, λ and $\Delta\lambda$ for each pixel for each filter as inputs using equations 3 and 4. Then in step 210, T_{abs} is calculated using inputs $R_{\#1}$, $R_{\#2}$, R_{bckg} and $\varepsilon_{\text{bckg}}$ for each pixel using equation 5. In steps 215 and 220, R_{abs} values are calculated for each pixel for each filter, using equations 6 and 7, respectively. In step 225, the emissivity measured by each pixel is calculated with background radiance R_{bckg} , emitted radiance $R_{\#m}$, λ and $\Delta\lambda$ for each pixel for each filter using equations 8 and 9. Finally, in step 230 the emissivity of thermal scene at each pixel is determined using equation 10.

[0045] While it is apparent that the illustrative embodiments of the invention disclosed herein fulfill the objectives stated above, it is appreciated that numerous

modifications and other embodiments may be devised by those skilled in the art. One such modification is that the inventive methods described and claimed herein is suitable for pyrometers or IR temperature probes. Therefore, it will be understood that the appended claims are intended to cover all such modifications and

5 embodiments, which would come within the spirit and scope of the invention.

CLAIMS

We claim:

- 5 1. A system for measuring radiation emitted by an object (22) remotely comprising:
an infrared sensor (10),
a first filter (14) having a first mean wavelength and a second filter (16)
having a second mean wavelength different than the first mean wavelength,
10 a lens (20) for directing the radiation emitted by the object (22) to the infrared sensor, and
a means including a central processing unit (CPU) for compensating for the reflected radiation from the object without using a reference or calibrated body.
- 15 2. A system for measuring radiation emitted by an object (22) remotely comprising:
an infrared sensor (10),
a first filter (14) having a first mean wavelength and a second filter (16)
having a second mean wavelength different than the first mean wavelength,
20 a lens (20) for directing the radiation emitted by the object (22) to the infrared sensor, and
a central processing unit (CPU) that compensates for the reflected radiation from the object without using a reference or calibrated body.
- 25 3. The system of claim 1 or 2 further comprising a shield (26) positioned around the object.
4. The system of claim 1 or 2, wherein the infrared sensor (10) comprises an infrared camera (10) having a focal plane array.
- 30 5. The system of claim 1 or 2, wherein the infrared sensor (10) comprises a pyrometer.
6. The system of claim 1 or 2, wherein the CPU (24) comprises a computer (24).

7. The system of claim 3, wherein the CPU (24) is included in the infrared camera (10).
- 5 8. The system of claim 1, wherein the means for compensating for the reflected radiation comprises a means for inputting an emissivity and a means for solving radiance equations acquired from each filter for a compensated temperature of the object.
- 10 9. The system of claim 8, wherein the emissivity is measured.
10. The system of claim 1, wherein the means for compensating for the reflected radiation comprises a means for solving for a compensated temperature of the object from a combined equation prepared by manipulating radiance equations acquired
15 from each filter to remove emissivity.
11. The system of claim 10, wherein the means for compensating for the reflected radiation further comprises a means for calculating an emissivity of the object using the compensated temperature of the object.
- 20 12. The system of claim 2, wherein the CPU calculates a compensated temperature of the object from a combined equation prepared by manipulating radiance equations from each filter.
- 25 13. The system of claim 12, wherein the CPU further calculates an emissivity of the object using the compensated temperature of the object.
14. A method for processing radiation emitted by an object comprising:
a. acquiring a first thermal reading of the object with a first filter (step 6),
30 b. acquiring a second thermal reading of said object with a second filter (step 8), wherein a mean wavelength of the second filter is different than a mean wavelength of the first filter,
c. providing an expression (step 104) based on (i) a first radiance expression over a bandwidth of the first filter, wherein the first radiance expression

includes an emissivity of the object, (ii) a second radiance expression over a bandwidth of the second filter, wherein the second radiance expression includes the emissivity of the object and (iii) manipulating the first radiance expression and the second radiance expression to remove the emissivity, and

- 5 d. transforming the thermal readings to a corrected temperature of the object by solving the expression.

15. The method of claim 14, further including a step (e) of solving for the emissivity of the object (step 110) using the corrected temperature.

10

16. The method of claim 14, wherein step (c) is performed on a central processing unit (CPU).

17. The method of claim 14, wherein the expression comprises a polynomial.

15

18. The method of claim 14 further comprising the step of providing an infrared sensor.

19. The method of claim 18, wherein the infrared sensor comprises an infrared camera with a focal plane array (FPA).

20

20. The method of claim 19, wherein steps (a)-(d) are conducted for each pixel in the FPA.

25 21. The method of claim 18, wherein the infrared sensor comprises a pyrometer.

22. The method of claim 14, wherein the corrected temperature produced by steps (a)-(d) excludes radiation reflected from the object.

30 23. A method for processing radiation emitted by an object comprising:
 a. acquiring a first thermal reading of the object with a first filter (step 6),
 b. acquiring a second thermal reading of the object with a second filter (step 8), wherein a mean wavelength of the second filter is different than a mean wavelength of the first filter,

c. providing a first radiance expression over a bandwidth of the first filter (step 102), wherein the first radiance includes an emissivity of the object,

d. providing a second radiance expression over a bandwidth of the second filter (step 102), wherein the second radiance includes the emissivity of the object,

5 e. combining the first radiance expression and the second radiance expression to remove the emissivity (step 104),

f. rearranging the expression of step (f) into a polynomial,

g. solving the polynomial of step (g) to acquire a corrected temperature of the object.

10

24. The method of claim 23, comprising:

h. computing a first corrected radiance over the bandwidth of the first filter using the corrected temperature (step 106),

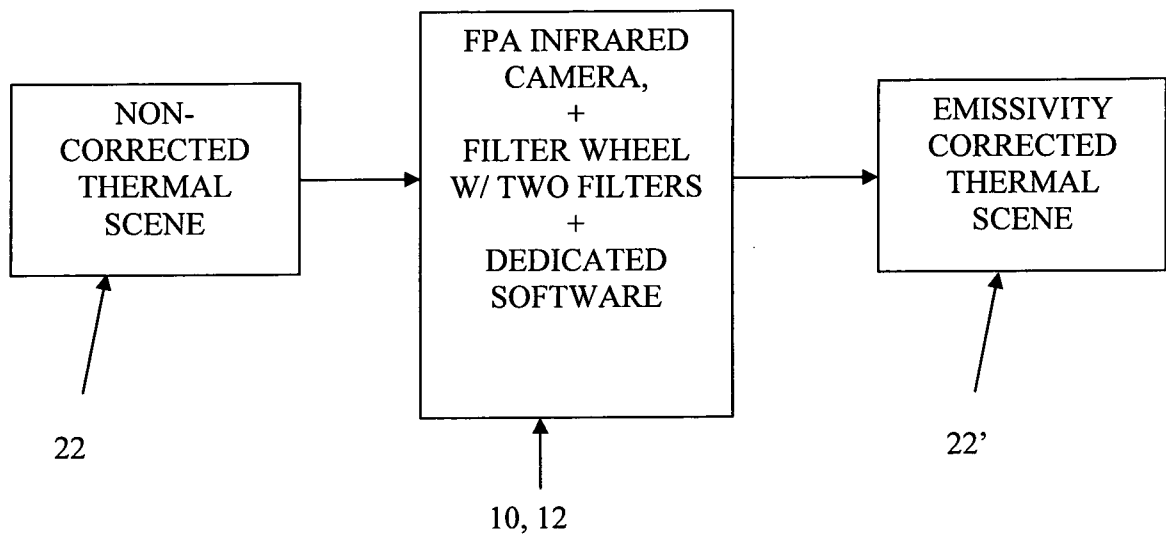
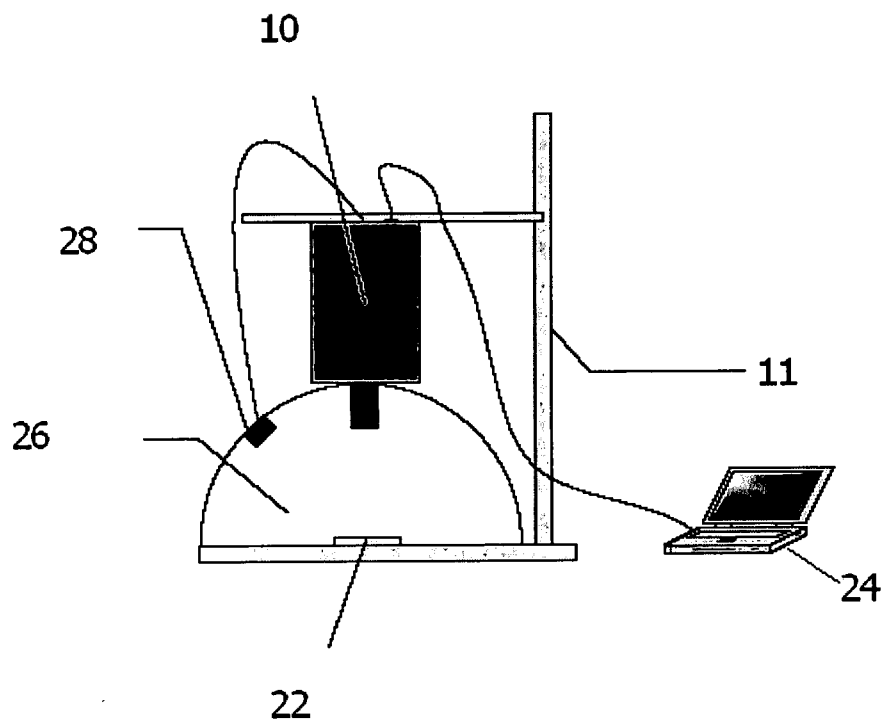
15 i. computing a second corrected radiance over the bandwidth of the second filter using the corrected temperature (step 106), and

j. computing a first corrected emissivity over the bandwidth of the first filter and computing a second corrected emissivity over the bandwidth of the second filter (step 110).

20 25. The method of claim 24, comprising:

k. computing an average emissivity of the two corrected emissivities (step 112).

26. The method of claim 23, wherein the corrected temperature produced by steps
25 (a)-(g) excludes radiation reflected from the object.

**FIGURE 1****FIGURE 3**

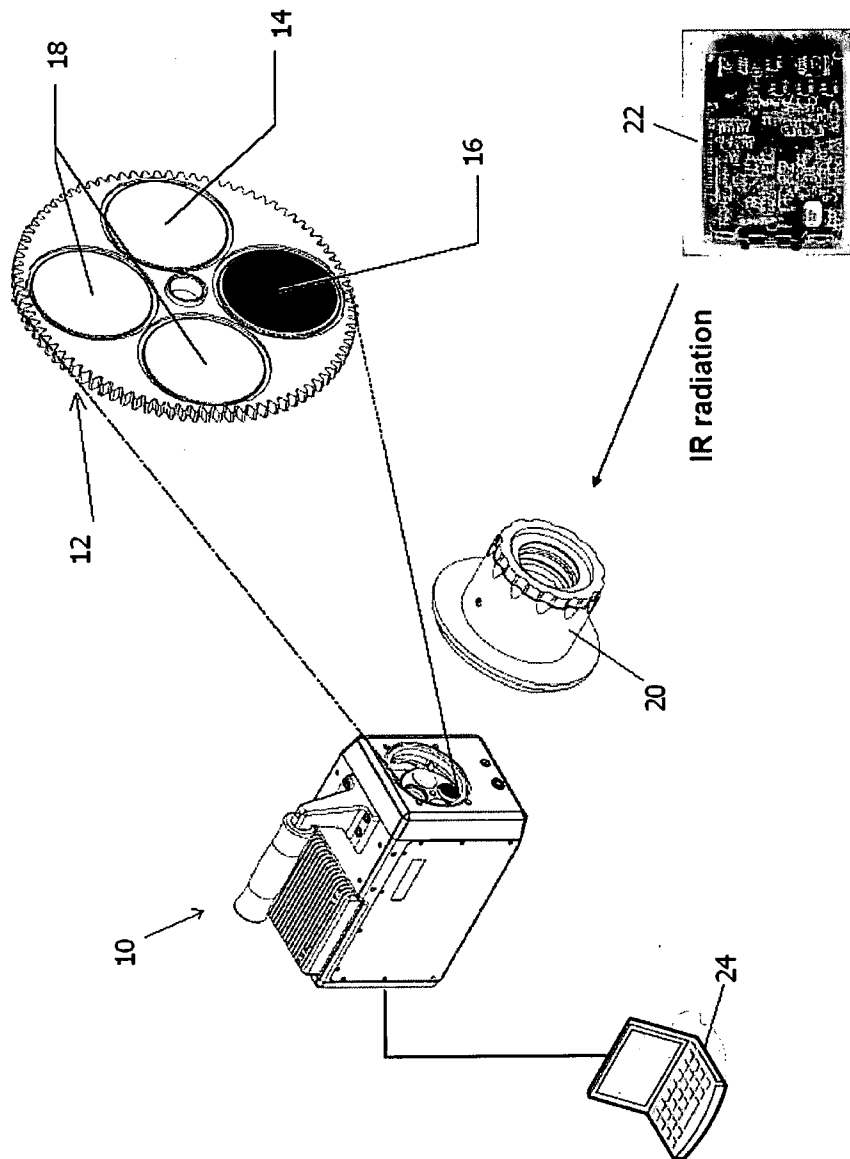


FIGURE 2

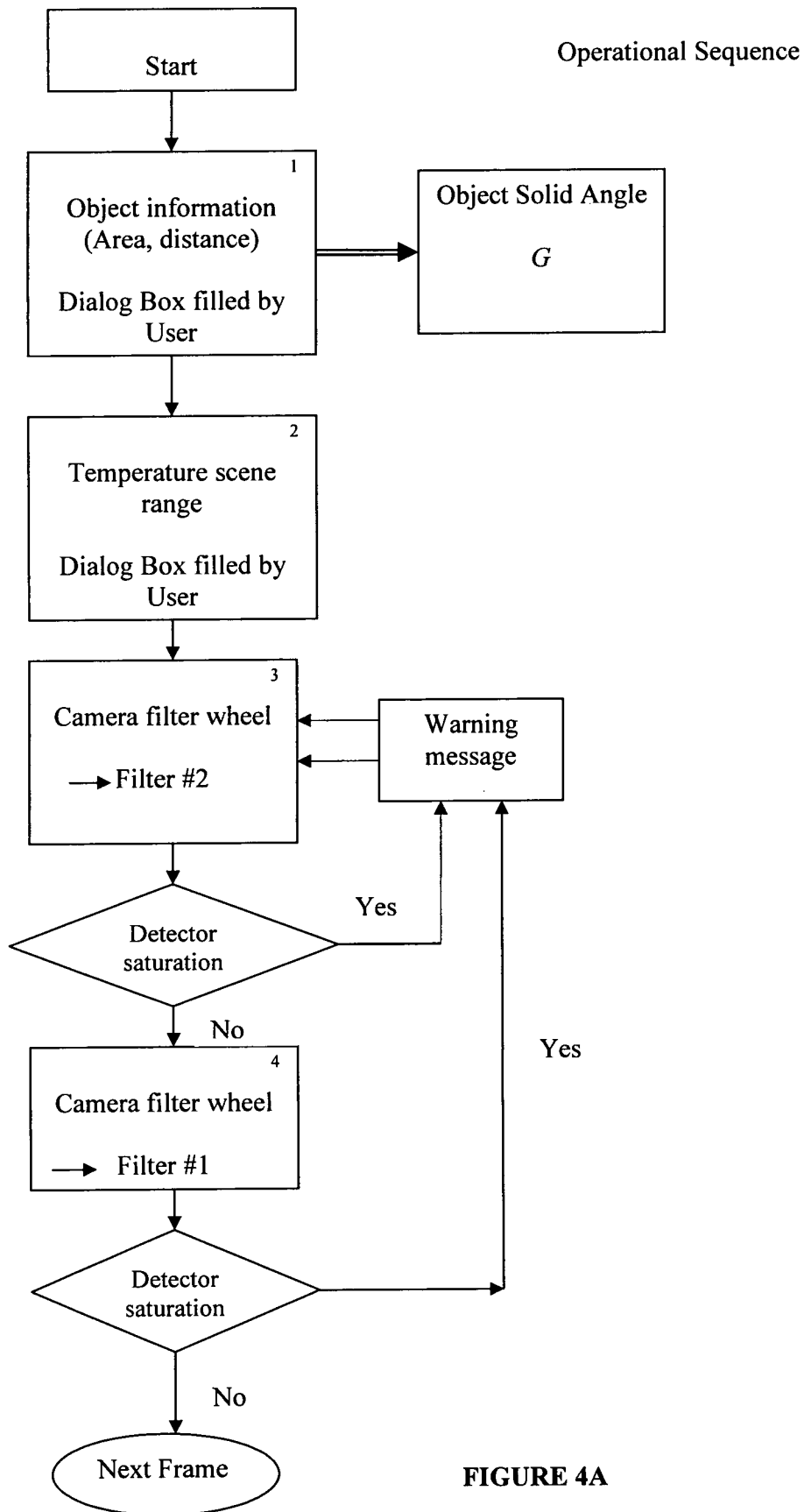


FIGURE 4A

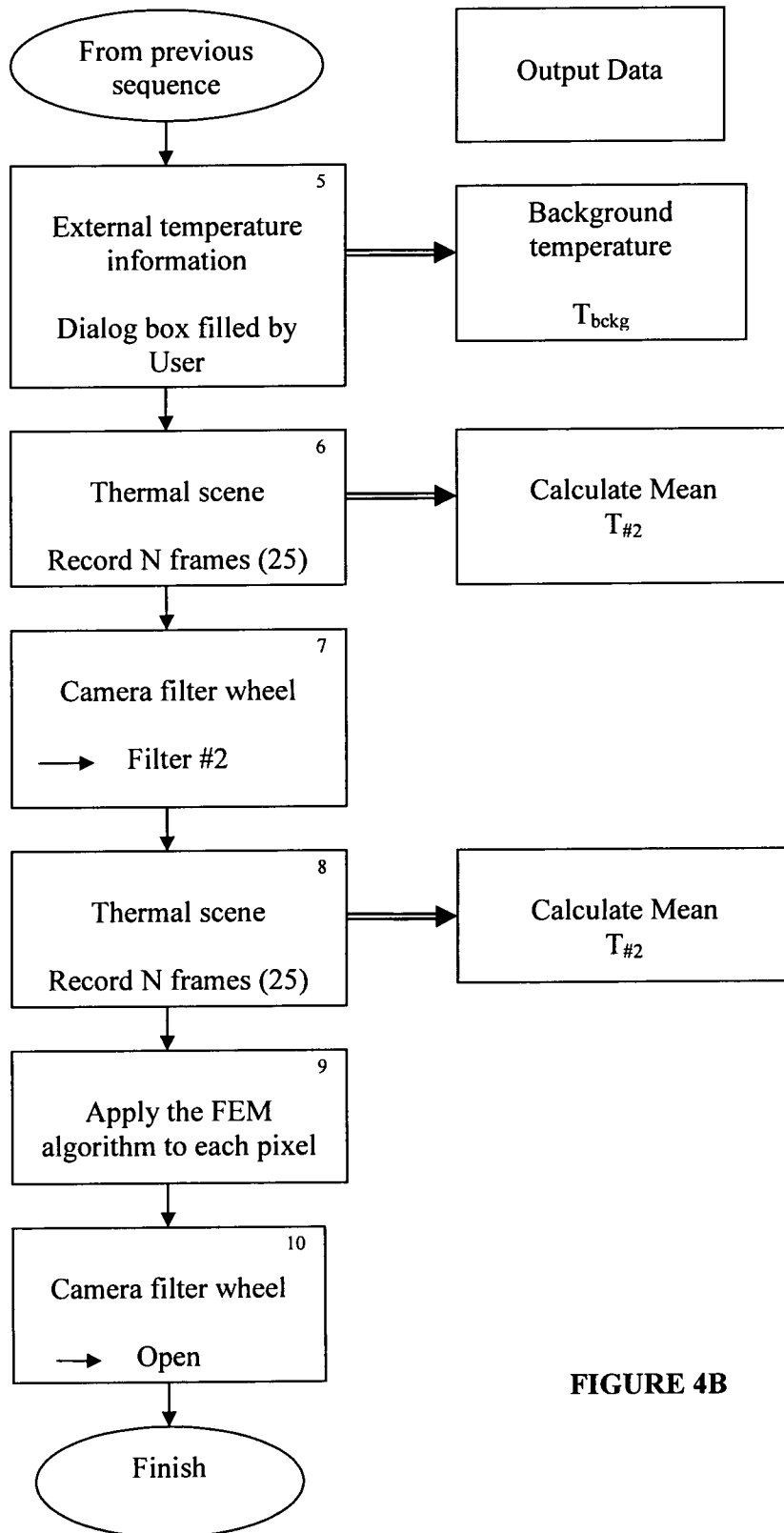


FIGURE 4B

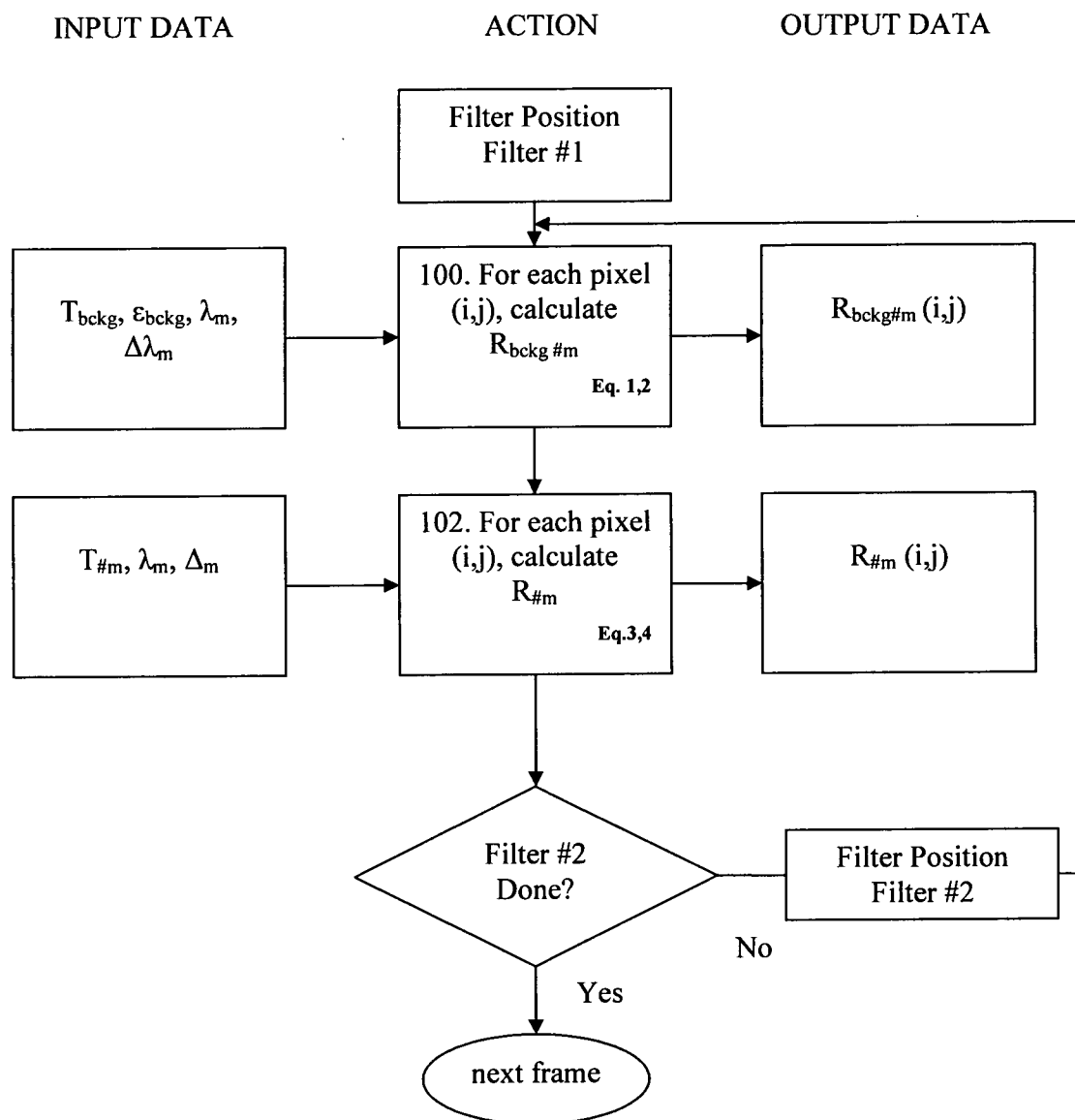


FIGURE 5A

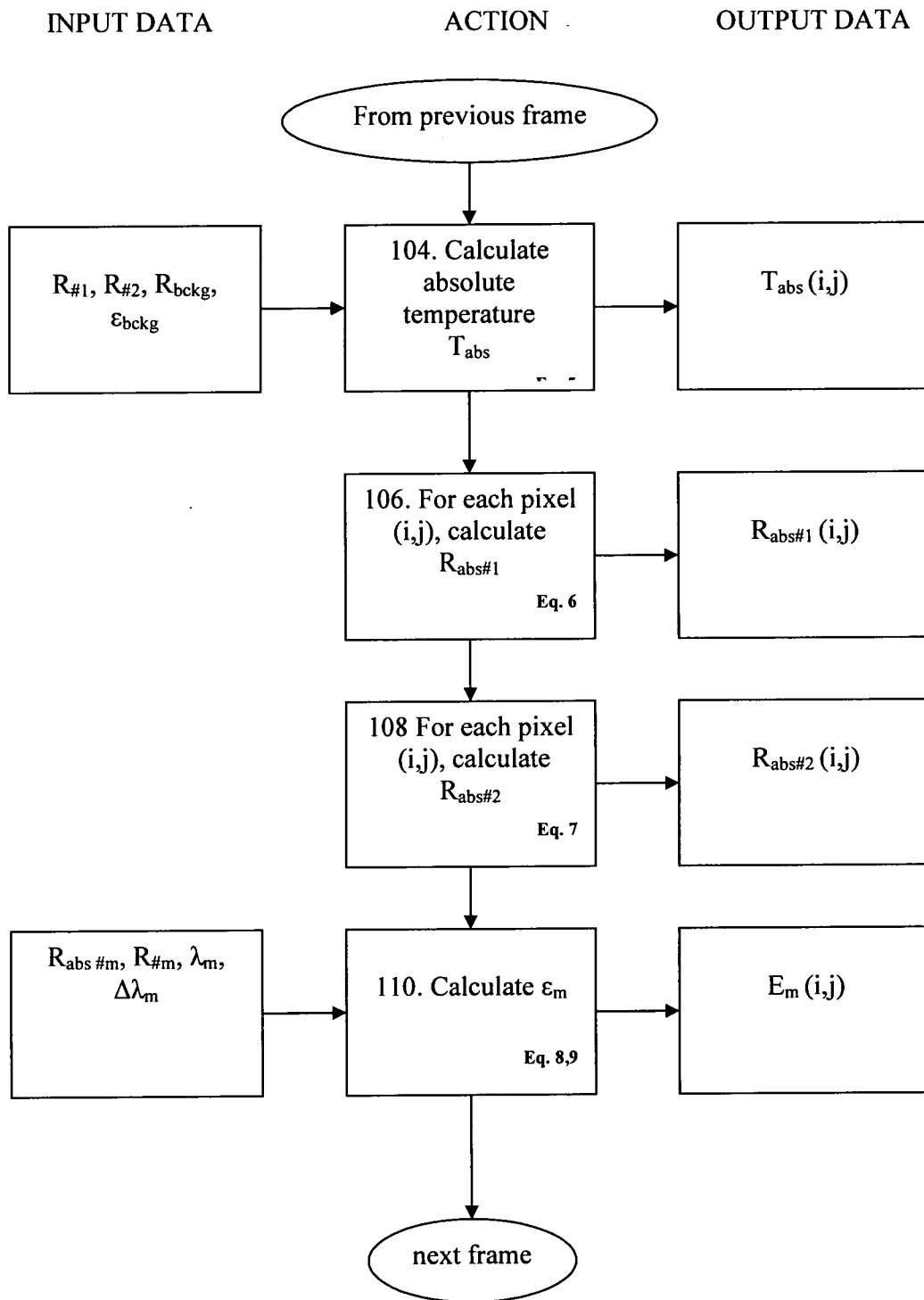
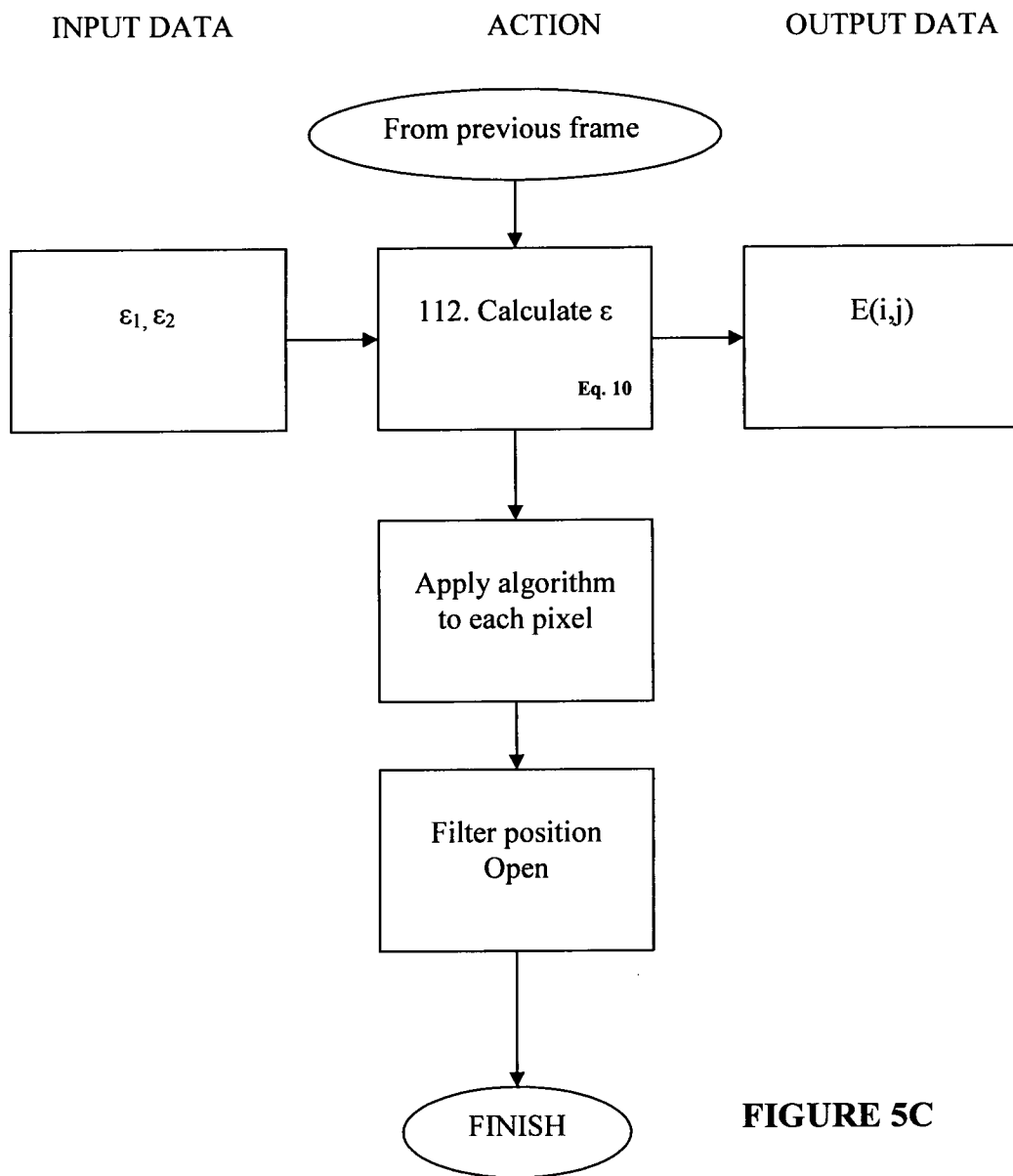


FIGURE 5B



INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2009/005630

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01J5/60

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 129 150 A (DEUTSCHE FORSCH LUFT RAUMFAHRT [DE]) 27 December 1984 (1984-12-27) page 9, line 3 - page 11, line 1; claims 1,2,6; figures 3,4,6-8 page 12, line 3 - page 14, line 21 page 15, line 36 - page 16, line 6 -----	1-26
A	EP 0 143 282 A (DEUTSCHE FORSCH LUFT RAUMFAHRT [DE]) 5 June 1985 (1985-06-05) page 14, line 12 - page 17, line 37 -----	14,23

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2009/005630

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