LabVIEW Acquisition for Phosphor Thermography Data Reduction

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Abstract A new LabVIEW acquisition system for phosphor thermography data reduced ion was developed to replace the current 386-based system. The new system was based on a previously developed LabVIEW system. A system and a temperature calibration were performed and the results were expected based on the current system.

List of Symbols

E	= Energy, eV
F	= Logarithmic intensity function
I	= Intensity, W/m^2
R	= Camera digital response
T	= Temperature, K
a	= Response coefficient
c	= Speed of light, $2.98 * 10^8$ m/s^2
h	= Planck constant,
m	= Logarithmic intensity function coefficient
n	= Logarithmic intensity function coefficient
λ	= Photon wave length, m
δQ	= Luminance, $candela/m^2$
$\phi(T)$	= Intensity due to temperature
Δ	= Weighted logarithmic difference
η	= Ratio of fluorescence exponents

Subscripts

r	= Red
g	= Green

Two-color relative-intensity phosphor thermography is an experimental approach for obtaining global heat transfer on hypersonic wind tunnel models. With this method, a ceramic model is fabricated and coated with fluorescent phosphor crystals. Next, it is installed in the test section of a hypersonic wind tunnel, illuminated with UV light, and exposed to the heated flow of the facility. During a wind tunnel run, the model fluoresces with an intensity that is dependent on the local temperature on the surface, and intensity images are obtained using a color CCD camera. After a run, the intensity images are converted to temperature mappings via calibrations; and then, given temperature mappings at different times, heat transfer mappings are generated by solving the one-dimensional heat transfer equation at each point in an image. Phosphor thermography has proven itself as a quantitative approach, which can be rapidly applied to candidate vehicle concepts to help in the design of thermal protection systems (TPS).

The goal of the project is to modify existing LabVIEW to capture thermographic images, calibrate the system, and construct a lookup table (LUT) to display model surface temperature as viewed live. To complete the goals, an understanding of fluorescent and temperature theory is necessary, along with systems requirements and the procedures for systems calibration.

Fluorescence is a localized procedure of the absorption and emission of energy. It is dependent on the chemical make-up of the material used. It occurs when an energy source is introduced, which excites electrons, moving the electrons from the valance band to the conduction band. When the electron relaxes, and moves to a lower energy state, a photon will be emitted, which we see as light. The color of the light is based on the difference in the energy level that the electron travels. When the electron travels from a higher energy state to a lower energy state, the energy difference is the energy level of the emitted photon. The wavelength of the photon can be calculated based as:

$$\lambda = \frac{hc}{E} \qquad (1)$$

This wavelength determines the visibility, non-visibility, or color of the emitted light.

The emission intensity of thermographic phosphors is directly related to temperature. When these phosphors are subjected to heat, the electrons are thermally excited from the valence band, into an intermediate energy band. This creates a space conflict with the electrons coming from the conduction band. As a result, the intensity of the light will decrease. As the temperature is further increased, more electrons are excited from the valence to the intermediate energy levels, which reduce the space available for returning electrons. In the absence of the movement of electrons from the conduction band, the fluorescence cease, and the phosphor is quenched. Because the quenching temperature varies among the different types of phosphors, specific phosphors are more suited for specific temperature ranges.

Because of the temperature dependence of thermographic phosphors, they are well suited for use in wind tunnels for mapping of surface temperature on heat transfer models. Theoretically, give a constant incident ultraviolet (UV) illumination intensity, temperature can be determined on the model surfaces by examining the intensity of the phosphor emissions. Unfortunately, complicated model designs cause the incident light to not uniform. To overcome this problem, a relative intensity two-color method can be use. This method uses a phosphor mixture that emits two different colors of light. The ratio of the intensities is light independent and dependent on temperature. The relative intensities of the surface fluorescence can be given a value, which is a logarithmic function of the absolute intensity of each separate color[1]. For red/green, this can be shown as:

$$F_g = m * \log(I_g) + n_g \qquad (2)$$

$$F_r = m * \log(I_r) + n_r \qquad (3)$$

Subtracting Equation 3 from Equation 2:

$$F_{rg} = F_r - F_g = m * \log(I_r / I_g) + n_{rg} \qquad (4)$$

If the intensities can de shown as:

$$I_g = \phi_g(T) * I_{UV} \qquad (5)$$

$$I_g = \phi_g(T) * I_{UV} \qquad (6)$$

Substituting Equations 5 and 6 into Equation 4:

$$F_{rg} = F_r - F_g = m * \log(\phi_r(T) * I_{UV} / \phi_g(T) * I_{UV}) + n_{rg} \qquad (7)$$

reducing Equation 7:

$$F_{rg} = F_r - F_g = m * \log(\phi_r(T) / \phi_g(T)) + n_{rg} \qquad (8)$$

Since ϕ_r/ϕ_g is solely dependent on temperature, the dependence on UV light has been removed. Currently the phosphors used are ZnCdS:Ag,Ni, and $La_2O_2S:Eu^{3+}$. This gives a usable temperature range of 22-170^0 C[2], with ZnCdS:Ag,Ni for the lower portion of the temperature range.

The current acquisition system consists of 386 computers running software specifically written for thermography image acquisition. The software is written to a specific hardware configuration, which consist of outdated image grabbing cards that are hard to procure. If there is a problem with the hardware or if it becomes inoperable, the complete software system becomes ineffective. The proposed solution is to create a new phosphor thermography data acquisition/reduction/analysis process with the ability to use multiple hardware configurations. The proposed system will consist of off the shelf personal computers running the Windows98/2000 environment. This system consists of Pentiums with 1Gb of Random Access Memory (RAM). These systems are equipped with an image acquisition card and have LabVIEW installed. Images are obtained with a state of the art video CCD camera. The acquisition program will utilize the Graphic User Interface (GUI) program LabVIEW 6i and NI-IMAQ/Vision. The data reduction is completed on a UNIX based system running the GUI program IHEAT.

The initial setup of the computer system was completed without problems. The image acquisition card was not factory installed and had to be installed in the lab. The hardware drivers sent with the cards were made for Windows 9x/NT, which were not compatible with Windows 2000. Windows 2000 would recognize the cards, but they failed to install properly. This compatibility issue was later solved with new driver being received from the suppliers' specific for Windows 2000. One of the major problems with the image acquisition cards and Windows 2000 was the cards use of the computer's RAM. The image acquisition has 4 Mb synchronous graphic RAM (SGRAM) on board frame storage and the capability to use the computer's RAM. When the cards were initially installed, the default memory size of 4 Mb was used. This allowed for the viewing of video and minor frame capturing. However, when multi-frame frame capturing was required, the system locked up, and had to be rebooted. To fix this problem, an additional 500 Mb of RAM was allocated for the image acquisition usage, but when the computer was rebooted, the computer would not load the operating system. Through trail and error, the memory size of 200 Mb was to be best size for computer operation and image acquisition. This allows approximately 250 frames captures to be stored in memory, and allow for video operation. The image acquisition cards are multi channel, which allows multi-camera usage.

The original LabVIEW module or Virtual Instrument (VI) was written using LabVIEW 5 on a Windows 98 system. The main VI consists of many subVI, each that performs a separate function with in the main. This allows for the reuse of VI elsewhere. The sequence of events for the main VI is broken down into three phases. The phases are

1. The Initialization – This includes the initialization and board setup of the image acquisition card. Phosphor batch default and user's preference are setup during this phase. Red, Green, and Blue (RGB) gains are setup from a save preference file. A blank IMAQ image for each of the colors (RBG) and one for a thermal plain is created. The temperature LUT is found and read. The initialization completion information or any errors encountered are print out to a system status screen.
2. The Main portion of the VI. The image is displayed on the screen in the palette and color plane specified by the user. Any adjustment to the RGB gains are completed and saved into a lookup file by phosphor batch. User preferences are also set here. Any type of image acquisition is completed in this phase. Acquisition may be completed on a schedule, which is based on frame number. The image acquisition utilized a 30 frame per second schedule. The saving of acquired images is completed in this phase.
3. When image acquisition is completed and the user exits the VI, the buffer is cleared and the IMAQ images are destroyed, freeing memory. The image acquisition card is closed and the any sub VIs are closed prior to or as the being closed.

This original module was updated using LabVIEW 6i for Windows 2000. This mostly was the replacement of separate LabVIEW VIs with updated ones and the adding of features. The major changes were in the ability to adjust the black and white gain settings of the RGB components of the image acquisition cards. In the original VI, the result from any adjustments was barely noticeable. Upon initialization a second set of IMAQ, images were created. These images were used for the ability to load an image from file, and compare live images against saved images. A stopwatch was added. A VI was added that saves run information in a file, writing any errors that occurred and any user information that is desired. Live image pixel value information was added, allowing the user to choose a point of the image and to see the resulting average value of the pixel. The average is the average of the four pixel values take each 300 ms.

Once the acquisition system was completed, a system calibration needed to be conducted. This checks the system to see if there are any abnormalities and allows for the required adjustments prior to using the system in the wind tunnels. The two test completed were the system calibration test and the oven test. The system calibration checks the camera response to light. This procedure was conducted using an integrating sphere. The integrating sphere produces white light, in which the output can be adjusted using an adjustable shutter and a control box, which displays the light intensity. The sphere was connected to AC power that has been passed through a transformer to maintain a constant 120 volts AC sine wave. The camera's lens was placed 18" from the opening of the sphere. The camera was adjusted level and so that the image center was located at the center of the opening of the sphere. With all ambient light sources turned off, the integrating sphere was turned on, with the shutter closed. The control box is then adjusted to 0 Candela/m^2. An image is captured and saved as a tagged image file format (TIFF). The shutter is then opened and the intensity is adjusted to 5 Candela/m^2, while capturing an image at one Candela/m^2 increments. After reaching 5 Candela/m^2, the intensity is adjusted to 135 Candela/m^2, capturing an image at each 5 Candela/m^2 increment. The intensity is then reduced to zero, while capturing images at 115, 100, 75, and 50 Candela/m^2, respectfully. The images are then processed through IHEAT, a UNIX based image-processing tool, looking at the red and green component. The average value or the region of interest is calculated and a fourth order fit is performed to get the luminance for each color component, using Equations 5 and 6.

$$\delta Q_r = a_{0,r} + a_{1,r}R_r + a_{2,r}R_r^2 + a_{3,r}R_r^3 + a_{4,r}R_r^4 \qquad (9)$$

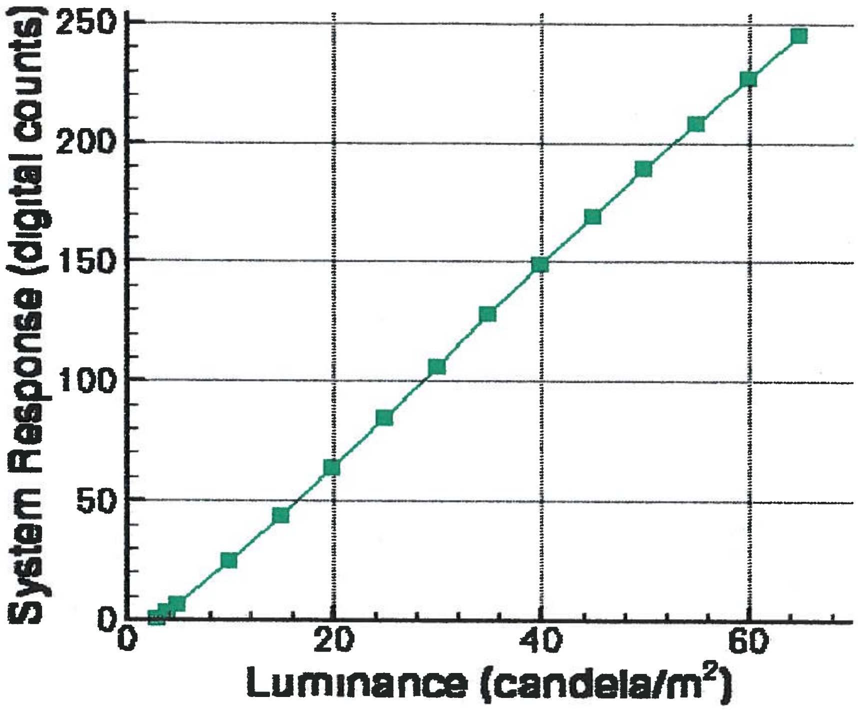
$$\delta Q_g = a_{0,g} + a_{1,g}R_g + a_{2,g}R_g^2 + a_{3,g}R_g^3 + a_{4,g}R_g^4 \qquad (10)$$

The coefficients are recorded for later use in the creation of LUT. The expected result should be a somewhat linear system response, with the green component reaching the 255 digital count before the red component. In the system calibration performed on the LabVIEW system, the green component was more or less linear from 0 to 65 Candela/m^2, when somewhere between 65 and 70 Candela/m^2 the green component reached 255 (figure 1a). The red component was also more to less linear, and reached 255 at approximately 135 Candela/m^2 (figure 1b). The response from both the green and red components was as expected. If the outcome is not as expected, the gains may adjust, either through the software, preferably, or through the camera control box.

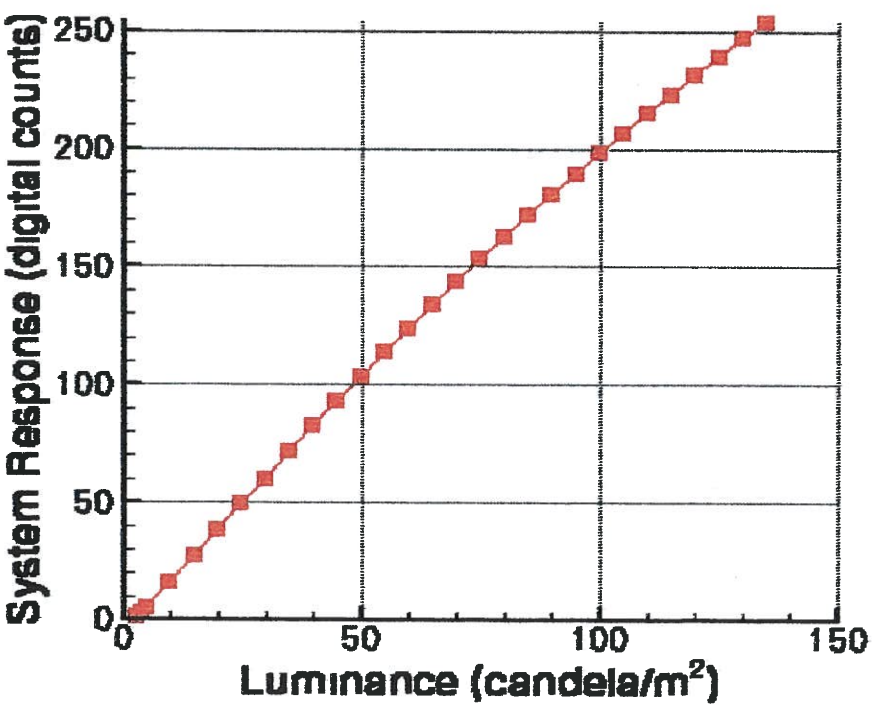
The next step in the testing of the LabVIEW system was the oven calibration. A sample plate, which is a thin fused silica ceramic plate 7.5 x 7.5 cm and .15 cm thick and coated with a phosphor, is placed horizontally on a shelf in a programmable convection oven that is fitted with thermocouple on the back wall. Air is blown into the oven through the sidewalls to create a uniform temperature distribution. Ultra violet (UV) light is shown through a 0.2 x 0.2 m window in the front door of the oven and adjusted so a wide range of fluorescence is observed. The oven is programmed to start at room temperature and increase the oven temperature to 170° C, at 10°C increments, and then return to room temperature. Each increment takes 6 minutes, with 2 minutes for the oven to increase to the desire temperature and then 4 minutes for the sample to soak at the desire temperature. With all ambient lights sources turned off, an image is taken at the end of each soak period. The images are then reduced in IHEAT, looking at the red and green components and averaging the response count values at each pixel within a region of interest. The region of interest is drawn to get as much data as possible, without including any irregular edge data. The component's luminance is calculated using Equations 5 and 6 by using the component responses. Δ, Log ($\delta Q_r/\delta Qg$), is calculated and graphed (Figure 2)

The next step is the creation of a lookup table, or converting red and green component values to temperature, for use in temperature mapping. A 256 X 256 array is created. This array corresponds to all possible combinations for the value of the red and green components. Two new luminance (δQ_r, δQ_g) arrays are created for all red and green component count values, using the coefficients found in the system calibration. The arrays are used to determine temperature based on red and green components intensities. The table created coincides with the color spectrum (Figure 3).

The use of LabVIEW for two-color relative-intensity phosphor thermography is sensible and has many advantages over the old system. It allows for varied hardware and software configuration, giving the ability to upgrade or replace hardware as problems arise or as components are upgrade and improved, without major program rewrite. The LabVIEW program allows for easy update and performs tasked that previously required separate software. The program has the ability to capture both individual images and multi images through an acquisition schedule, and then save them both on the acquisition computer and the individual's computer, using FTP add-on. In both the system calibration and in the temperature calibrations, the LabVIEW system performed as expected, based on the previous system.



(a) Green Component's System Response vs. Luminance



(b) Red Component's System Response vs. Luminance

Figure 1 System Calibration Reponses

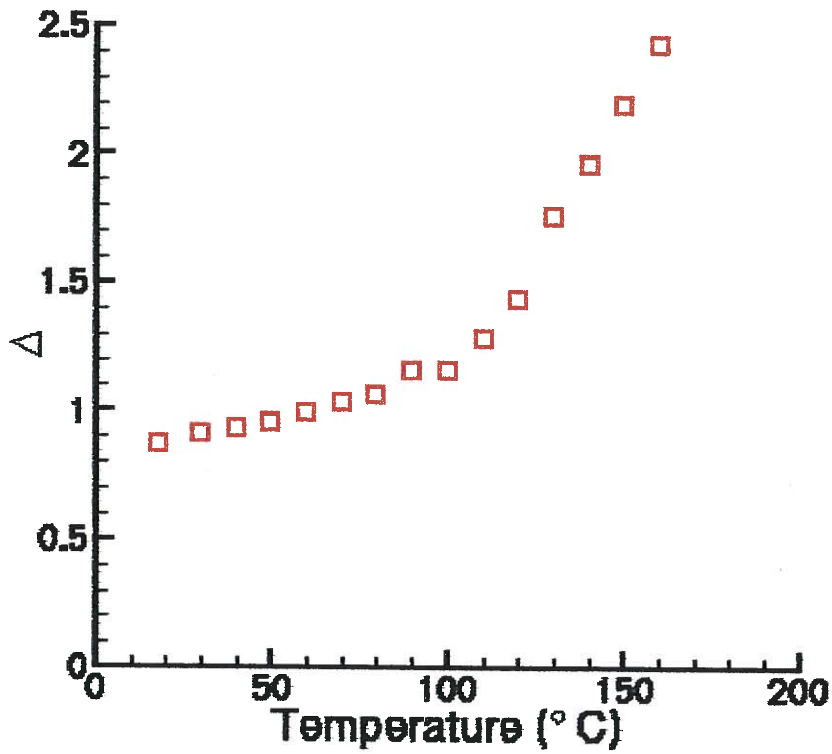
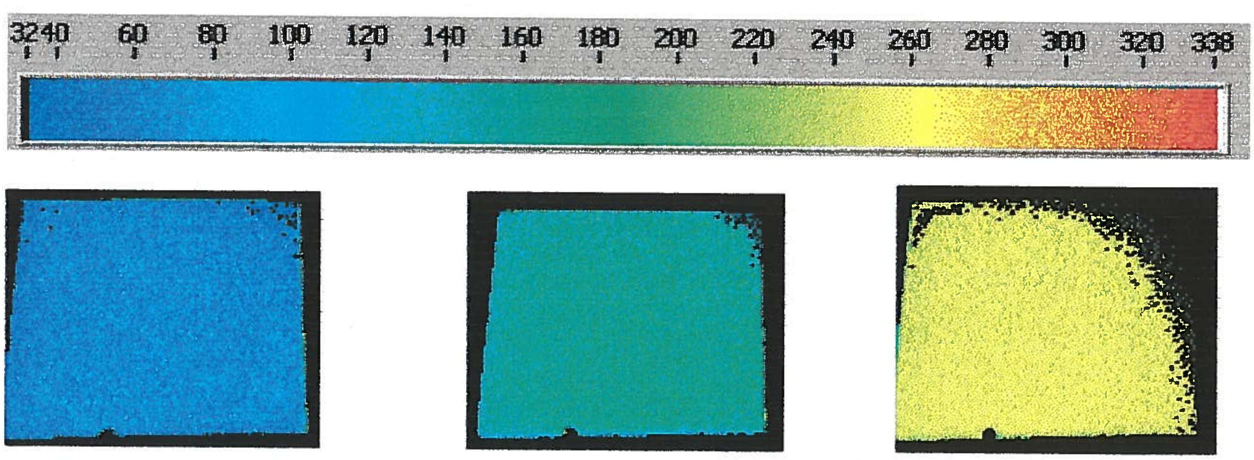


Figure 2 (Δ –Curve)



a. (18° C/ 65° F) **b. (70° C/ 156° F)** **c. (120° C/ 242° F)**

Figure 3 (Computer Images using Temperature Look-up Table)

References

[1] Merski, N.R, "A Relative-Intensity Two-Color Phosphor Thermography System", NASA TM 104123, Sept 91

[2] Merski, N.R, "Global Aeroheating Wind Tunnel Measurements Using Improved Two-Color Phosphor Thermography Method", Journal of Spacecraft and Rockets, Vol. 36, No. 2, Mar-Apr 99, pp 160-170