Effects of Phosphor Persistence on High-Speed Imaging of Transient Luminous Events

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***Abstract*— High-speed intensified cameras are commonly used to observe and study the transient luminous events known as sprite halos and sprite streamers occurring in the Earth's upper atmosphere in association with thunderstorm activity. In such observations, the phosphor persistence in the image intensifier, depending on its characteristic decay time, might lead to a significant distortion of the optical signals recorded by those cameras. In this paper, we analyze the observational data obtained using different camera systems to discuss the effects of phosphor persistence on high-speed video observations of sprites, and introduce a deconvolution technique to effectively reduce such effects. The discussed technique could also be used to enhance the high-speed images of other transient optical phenomena in the case when the phosphor persistence has a characteristic decay time that is comparable with the temporal resolution of the cameras required to resolve the phenomena.**

***Index Terms*— Deconvolution, high-speed imaging, phosphor persistence, plasma discharges, sprite streamers, transient luminous events.**

I. INTRODUCTION

SPRITES are large-scale transient luminous events induced by lightning electric fields in the Earth's upper atmosphere above active thunderstorms. The typical duration of these spectacular optical emissions is only a few milliseconds, and they usually start from the appearance of a brief descending diffuse glow, referred to as a sprite halo that sometimes remains subvisual, followed by fine-structured streamer filaments that propagate rapidly from ~80-km altitude down to ~40-km altitude at velocities in the range from $\sim 10^6$ to 5×10^7 m/s [1]. Video observations with high-speed intensified cameras are one of the primary means used in the recent years to study sprite dynamics [2], [3], as their rapid variation requires submillisecond temporal resolution and some dim features in sprites such as the halo emissions require high sensitivity in low-light conditions.

In the studies of such transient optical phenomena as sprites using high-speed intensified cameras, a critical feature of the observational system is the phosphor persistence in the image intensifier [4]. The characteristic decay time of the phosphor persistence in comparison with the temporal resolution of the high-speed cameras determines whether the phosphor persistence has significant effects on the recorded optical signals. If the characteristic decay time of the phosphor persistence is comparable with the temporal resolution of the camera, photons received by the intensifier during the exposure time of each frame are not fully released at the same period, such that the optical signals could be significantly distorted. Analysis of sprite images documented in the existing literature shows that in such a case, sprite halos are usually observed as a diffuse glow varying smoothly on a large spatial scale with no discernible small-scale structures [5], and that sprite streamers are observed as numerous long luminous filaments forming the tendril part of the sprites [2]. Similar effects of phosphor persistence have also been observed in the experimental studies of streamers in laboratory conditions [6], [7]. It is, on the other hand, well-known that the long luminous structures in the tendril part of sprites are in fact formed by bright, spatially compact, and fast moving streamer heads according to the numerical simulations using plasma fluid models [8], [9] and according to the most recent video observations using camera systems that have short phosphor persistence [1], [3]. Those most recent observations also show that sprite halos are not varying as smoothly as anticipated from the previous video observations, and that spatial structures are commonly present in the overall diffuse emissions of the halos, which are the optical manifestations of the pre-existing plasma irregularities in the D-region ionosphere [1], [10]. Halo structures, in fact, have been occasionally recorded in early observations with 1-ms temporal resolution [5], although they were not as clearly defined as the recently observed ones.

Long phosphor persistence is a limitation for the studies of transient optical phenomena using such high-speed intensified cameras as the one used in [2]. For some features in transient optical phenomena, such as the spatial structures in sprite halos [10], the effects of phosphor persistence can be reduced to a negligible level using a phosphor, if available, that has a characteristic decay time much shorter than the time scale of the halo dynamics. Nevertheless, as phosphors with shorter persistence have a lower quantum efficiency, consequently resulting in lower quality images, high-speed intensified cameras with long phosphor persistence are better

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options for sprite observations in some cases [11], [12]. More importantly, there will always be interesting features in transient optical phenomena, such as the branching of sprite streamers [1], that have time scales comparable with or even shorter than the characteristic decay time of the phosphor persistence in available camera systems. It is therefore important to be able to reduce the effects of phosphor persistence in other ways, for example, by postprocessing of digital images. The purpose of this paper is to present a deconvolution technique that can be used to effectively reduce such effects.

II. Analytical Analysis

In high-speed imaging of transient optical phenomena, when the optical emissions reach the observational system, they need to pass through the image intensifier before being received by the image sensor of the camera. An image intensifier usually consists of a sealed tube containing a photocathode, a microchannel plate, and a phosphor screen [13]. The main function of the image intensifier is the multiplication of the incoming photons (i.e., the amplification of the incoming optical signal), which enables the camera to take images at extremely low light conditions and/or at extremely short exposure times. In the amplification process, the incoming photons first meet the photocathode of the image intensifier, and produce photoelectrons by collisional ionization. The microchannel plate of the intensifier multiplies the incoming electrons from the photocathode, and then the energy of the multiplied electrons from the microchannel plate is converted back into photons by the phosphor screen of the intensifier. During this process, the phosphor screen may have significant persistence effect, depending on its characteristic decay time, and thus could greatly affect the signals received by the image sensor.

The impulse response of the phosphor screen is assumed as

$$g(t) = \frac{1}{\tau}\exp\left[-\frac{t}{\tau}\right] \quad (1)$$

where τ = half-life/ln(2) is the characteristic decay time of the phosphor persistence, and half-life represents the half-life of the phosphor persistence. For an input signal $I_{\rm in}(t)$ originated from the optical phenomenon and received by the phosphor screen, the distorted signal $I_{\rm out}(t)$ output from the phosphor screen is the convolution of the original signal $I_{\rm in}(t)$ and the impulse response of the system $g(t)$

$$I_{\rm out}(t) = \frac{1}{\tau}\int_0^t I_{\rm in}(t')\exp\left[-\frac{t-t'}{\tau}\right]dt' \quad (2)$$

which is also the optical signal received by the image sensor and recorded as individual images by the camera.

A reverse process can be applied to recover the original signal $I_{\rm in}(t)$ from the distorted signal $I_{\rm out}(t)$ recorded in the high-speed video images using a deconvolution technique. Based on the convolution theorem, the original signal $I_{\rm in}(t)$ can be recovered as

$$I_{\rm in}(t) = \mathscr{F}^{-1}\left[\frac{\mathscr{F}\{I_{\rm out}(t)\}}{\mathscr{F}\{g(t)\}}\right] \quad (3)$$

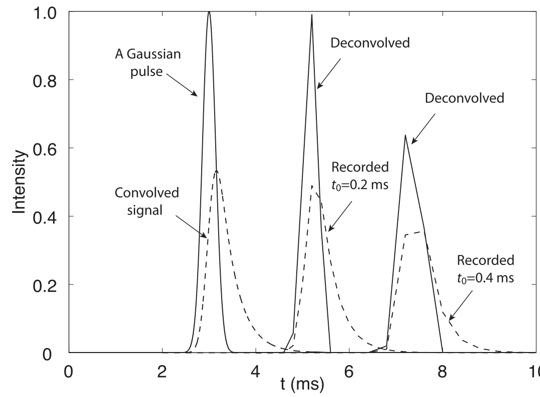

Fig. 1. shows the results in two of our tests: the Gaussian pulse, the distorted signal due to phosphor persistence, the signals recorded by a camera with an exposure time t_0=0.2 ms or 0.4 ms, and the deconvolved signals.

where $\mathscr{F}$ represents the operation of Fourier transform. The above deconvolution technique can be easily implemented using fast Fourier transform. The accuracy of the recovered signal $I_{\rm in}(t)$ depends on the quality of the recorded signal $I_{\rm out}(t)$ and the accuracy of the phosphor decay model $g(t)$.

The phosphor decay model shown by (1) is a simple model proposed based on the available information in [2]. A more complicated and more accurate $g(t)$ could lead to more accurate results. Concerning the impact of the quality of the recorded signal $I_{\rm out}(t)$, the relation between two different timescales determines whether the deconvolution technique can be used to effectively recover the original signal from a video observation of transient luminous events: the duration σ_0 of the transient luminous event and the temporal resolution t_0 of the camera which in our analysis is assumed to be equal to its exposure time. To investigate the impact of these two timescales on the effectiveness of our algorithm, we use the following Gaussian pulse as an original signal and recover the pulse after it being distorted by a phosphor and recorded by a camera:

$$I(t) = I_0\exp\left(-\frac{t^2}{\sigma_0^2}\right). \quad (4)$$

Fig. 1 shows the results in two of our tests: the Gaussian pulse, the distorted signal due to phosphor persistence, the signals recorded by a camera with an exposure time t_0 = 0.2 or 0.4 ms, and the deconvolved signals. We find in those tests that the deconvolution technique can effectively recover the original signal in the cases when $t_0 \leq \sigma_0$, namely, the temporal resolution of the camera needs to be sufficiently high to resolve the transient luminous events in order to achieve an effective recovery of the original signal. We also find that even if the characteristic decay time τ of the phosphor persistence is much longer than the above two timescales (i.e., $t_0 \leq \sigma_0 \ll \tau$), the original signal can still be effectively recovered. Note that a descriptive model has been suggested for recovering continuous, rather than pulsed, excitation in [13].

III. Observations of Sprite Streamers

We first compare the images of sprite streamers obtained using camera systems with significantly different

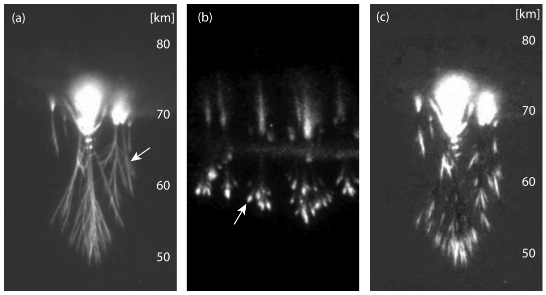

Fig. 2. High-speed video images of sprite events observed using two different camera systems (see the text), respectively. (a) On August 13, 2005 at 03:12:32.0 UT. (b) On July 4, 2008 at 08:13:59.6 UT. (c) Same video frame as (a) after implementing deconvolution.

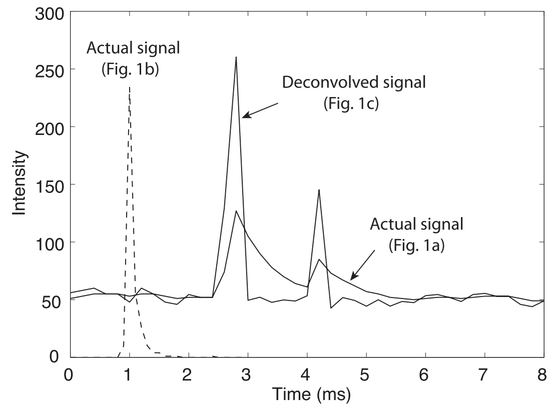

Fig. 3. Solid line: temporal variation of the actual signal recorded by camera and the corresponding signal recovered using the deconvolution technique in one sample pixel shown by an arrow in Fig. 2(a). Dashed line: temporal variation of the actual signal in a sample pixel shown by an arrow in Fig. 2(b).

phosphor persistence. The camera system used to record the sprite event shown in Fig. 2(a) was a Vision Research Phantom 7.1 monochrome high-speed imager coupled to an ITT Gen III image intensifier with a spectral response from 450 to 900 nm. The phosphor persistence of this intensifier was measured with controlled sources to have a half-life between 0.35 ms (for dim features) and 0.70 ms (for bright features), and the gamma setting of the camera is not known. The phosphor decay time depends on the brightness for each pixel including those unsaturated ones, and the exact relation between the brightness and decay time is also unknown due to lack of precise tests of the intensifier. Note that, a half-life of 0.35 ms is comparable with the temporal resolution of the camera and the typical timescale of sprite events (a few milliseconds). The frame rate of the camera is 5000 frames/s corresponding to a temporal resolution of 0.2 ms [2]. The sprite observation shown in Fig. 2(b) was made with a Phantom 7.1 camera, with a Video Scope International VS4-1845 HS image intensifier that has a short phosphor persistence of 1 μs. The frame rate of the camera is 10 000 frames/s corresponding to a temporal resolution of 0.1 ms. The two camera systems have only a slight difference of a factor of two in their temporal resolutions. However, the sprite elements recorded by the camera system with long phosphor persistence exhibit continuous filamentary structures in their lower parts, as shown in Fig. 2(a), which, in fact, are formed by the smearing of the emissions from compact streamer heads moving with high speeds, similar to those clearly resolved by the camera system with short phosphor persistence in Fig. 2(b).

The deconvolution technique presented in the previous section can be used to recover the structures of the sprite streamers shown in Fig. 2(a), which suffer significant distortion from the long phosphor persistence of the image intensifier. Fig. 2(c) shows the optical emissions at the same moment of time as in Fig. 2(a) after implementing deconvolution. Note that in the process of deconvolution, the half-life of the phosphor persistence in the image intensifier is assumed to be 0.35 ms (for dim features, see Section II), as the sprite streamers are considered to be dim features when compared with the bright sprite cores presented at ~70-km altitudes in Fig. 2(a). The streamer heads shown in Fig. 2(c) appear to be similar to those shown in Fig. 2(b), with only slightly longer lengths in their propagation direction due to longer exposure time of the high-speed camera in this case.

To further demonstrate the effectiveness of the deconvolution technique, we examine the temporal variation of the optical signal in individual pixels of the images where at least one streamer head propagates through. Representative results are shown in Fig. 3. Note that the approximate locations of the chosen sample pixels have been indicated by arrows in Fig. 2(a) and (b). The two solid lines correspond to the sprite event shown in Fig. 2(a). The actual signal recorded by the camera shows that two streamer heads pass through the sample pixel, and the level of optical emissions decays in ~1.5 ms back to the background value after reaching its peak intensity, which in relative linear units used in Fig. 3 is $\sim 127 - 50 = 77$ for the first streamer head. Note that the value 50 is the intensity of the background emissions, and the maximum intensity in a grayscale image is 255. By comparison, in the deconvolved signal, the level of optical emissions restores to the background value in 0.2 ms, which is the temporal resolution of the camera, and the peak intensity of the first streamer head is $\sim 255 - 50 = 205$. The peak intensity of the emissions from the second streamer (~95) is much lower because the center of the streamer head does not exactly pass through the chosen sample pixel. On the basis of the above comparison, it is apparent that long phosphor persistence leads to long relaxation time of the optical emissions and lowers the luminosity of the sprite streamers. It is interesting to note that the actual signal shown by the dashed line in Fig. 3, which was recorded by a camera with short phosphor persistence of 1 μs, shows that the emissions also restore to the background level in ~0.2 ms. This value is comparable with that of the deconvolved signal shown in Fig. 3, which indicates that the deconvolution technique can be used to effectively remove the effects of long phosphor persistence introduced by the image intensifier. Note that the assumption of a half-life of 0.35 ms is justified by the results of deconvolved signal presented in Fig. 3, which show that the level of emissions restores to the background value after the streamer heads passed through the pixel. It has been tested that if a longer half-life (e.g., $\geq$0.5 ms) is used, the level of emissions after the streamers passed through would be lower than the background value, which is unphysical.

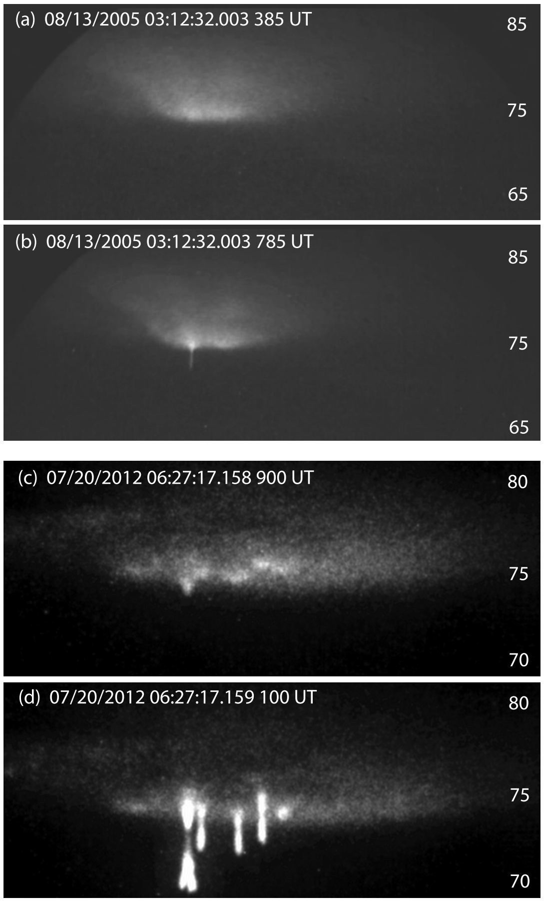

Fig. 4. (a) and (b) Halo emissions preceded those of the sprite streamers shown in Fig. 2(a). As noted in the text, the camera used to record this event has long phosphor persistence with a half-life of 0.35–0.70 ms. (c) and (d) Spatial structures in diffuse halo emissions observed on July 20, 2012 at 06:27:17:158 900 UT. Sprite streamers were initiated from those spatial halo structures at 06:27:17:159 100 UT. In this case, the camera has a short phosphor persistence with a characteristic decay time of 1 μs.

IV. Observations of Sprite Halos

High-speed imaging of sprite halos could also be significantly affected by the phosphor persistence of the image intensifier. It was commonly observed in early video records that sprite halos were large-scale diffuse emissions in the shape of a pancake up to ~70 km in diameter near 75-km altitude, and that in the entire volume of halos they varied smoothly with no discernible small-scale spatial structures [2], [5]. In those video records, as well as in some numerical simulations [14], the initiation of sprite streamers seemed to suddenly occur at the lower edge of the homogeneous halo [2]. Figs. 3(b) and 4(a) show one typical example of the above discussed time dynamics of sprites. Such an understanding of sprite dynamics has not been improved until high-speed cameras with short phosphor persistence have been introduced [10], [15], [16]. It is found in these recent observations that prior to streamer initiation, small-scale spatial structures descend rapidly with the overall diffuse emissions of the sprite halo, but slow down and stop to form

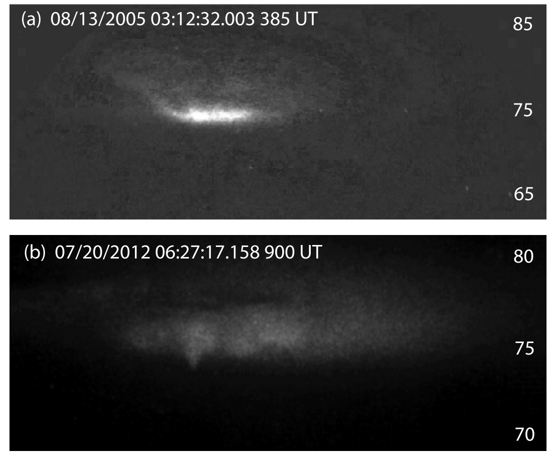

Fig. 5. Same frame of the halo observation as that shown in (a) Fig. 4(a) after implementing deconvolution and (b) Fig. 4(c) after implementing convolution assuming a phosphor persistence with a half-life of 0.2 ms.

the stationary glow in the vicinity of the streamer onset, from where streamers emerge [10]. It has also been demonstrated by comparing observational and modeling results that those descending halo structures are optical manifestations of the pre-existing plasma irregularities in the D-region ionosphere [10]. Fig. 4(c) shows one frame of a typical halo event with the presence of descending halo structures. It is apparent that the halo does not vary smoothly, and that several bright structures are identifiable. From those bright halo structures, sprite streamers are initiated at a later moment of time, as shown in Fig. 4(d).

To demonstrate that the rare observations of small-scale spatial structures in early sprite halo observations are partly due to the long phosphor persistence, we use the deconvolution technique to recover the image shown in Fig. 4(a) and use the convolution technique to artificially apply a long phosphor persistence with a half-life of 0.2 ms to the image shown in Fig. 4(c). The results are presented in Fig. 5. As shown in Fig. 5(a), after implementing deconvolution, the halo emissions concentrate in a smaller region with a higher intensity when compared with those of Fig. 4(a). Bright structures are present in the lower part of the halo. However, we note that due to relatively low spatial resolution, these structures are not discernible as clearly as those of Fig. 4(c). One can see that the region from where sprite streamers are initiated [see Fig. 4(b)] is the brightest region of the halo. In contrast, if a long phosphor persistence is applied to the halo presented in Fig. 4(c), the bright structures in the halo become blurred and not as easily identifiable, as shown in Fig. 5(b).

V. Conclusion

It is demonstrated that long phosphor persistence in high-speed intensified cameras has significant effects on the optical signals of sprites recorded by the cameras. Moreover, a deconvolution technique is used to reduce those effects to reveal the true dynamics of the optical emissions of sprites. Comparison between the deconvolved images and observations recorded using high-speed intensified cameras with short phosphor persistence demonstrates that the effects of long phosphor persistence can be effectively reduced using deconvolution methods. The deconvolution technique is useful in the studies of transient processes that occur so rapidly that their timescales are comparable with or even shorter than the characteristic decay time of the phosphor persistence in the image intensifier of the available camera systems.

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