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Time resolved sprite imagery

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Abstract. Fleeting columns of luminosity occurring above large thunderstorms at 50-90 km altitude, presently known as sprites, were imaged with an intensified video charge coupled device (CCD) camera during a July 1995 ground-based campaign near Fort Collins, Colorado. These unfiltered intensified images reveal detailed spatial structure within the sprite envelope. The temporal resolution of standard interlaced video imagery is limited by the 60 fields per second acquisition rate (16 ms). The specific CCD used here, however, is subject to bright events leaking into the readout registers, allowing time-resolution on the order of the linescan rate (63 μs). Typical sprite onset is found to follow the associated cloud lightning by 1.5 to 4 ms. The onsets of the individual sprites within a cluster are generally, but not always, simultaneous to within 1 ms. Sprites tend to have a bright localized core, less than 2 km in horizontal dimension, which rises to peak intensity within 0.3 ms and maintains this level for 5 to 10 ms before fading over an additional 10 ms.

Introduction

Visual sightings [e.g. *Vaughan and Vonnegut,* 1989] of unusual lightning-like discharges extending upward from the cloud tops received unexpected substantiation in 1989 when a low light level video camera under test serendipitously captured a brief flash in the clear air above a distant thunderstorm [*Franz et al.,* 1990]. Subsequent deployment of image-intensified television cameras, ground-based [*Lyons,* 1994a, b; *Winckler,* 1995] and aboard aircraft [*Sentman and Wescott,* 1993; *Sentman et al.,* 1995; *Wescott et al.,* 1995], documented the principal characteristics and the greater than anticipated occurrence rate of these high-altitude luminous structures. In addition, a study of the video from Space Shuttle payload bay cameras has revealed similar high-altitude events plus one clear case of a momentary airglow enhancement apparently associated with an underlying lightning flash [*Boeck et al.,* 1992, 1995].

The upper atmospheric optical phenomena have been referred to in the literature as cloud-to-ionosphere (CI) lightning, cloud-to-stratosphere (CS) discharges, and other discriptive labels evoking transient behavior. *Sentman et al.* [1995] adopted the terms "red sprites" and "blue jets" to describe the two distinct types of structure they observed on their successful summer of 1994 airborne quest for color images of these events. The following summer saw an array of ground based instruments located at the Yucca Ridge Field Station near Fort Collins, Colorado for a campaign dubbed Sprites95. During this campaign *Mende et al.* [1995] acquired spectral observations of sprites, and identified emissions of the N_2 first positive group toward the red end of the visible spectrum consistent with initial spectra obtained by Sentman et al. (private communication).

The video systems used to this point are of the standard 30 frame per second temporal resolution, and by separating the odd-line and even-line interlaced fields a 60 Hz or 16.7-ms resolution can be claimed. Thus *Sentman and Wescott* [1993] have estimated sprite duration to be 17 ms or less. From a large sprite inventory *Lyons* [1994] reports that "duration ranged from 33 to 283 ms." For a typical cluster of sprites *Sentman et al.* [1995] observe that "onset of luminance occurs simultaneously (within video resolution, 16 ms) across the cluster as a whole, coincident with occurrence of cloud lightning below." Their 600 kR apparent central brightness determination is an average through a video field time increment. Finer time resolution may be available soon from photometer measurements, but would be difficult to interpret in the absence of spatial information. In this paper we demonstrate how sub-millisecond time resolution is extracted from the *Mende et al.* [1995] video CCD image data and present our findings regarding sprite duration, simultaneity of onset within clusters, and delay time from associated cloud lightning.

Observations

The Lockheed component of the Sprites95 campaign consisted of two independent parallel CCD video imaging systems deployed at the Yucca Ridge field site (40° 40' N. latitude, 104° 56' W. longitude, elevation 1670 m) through the period July 11-27, 1995. A simple unfiltered imaging channel was aligned with an imaging spectrometer channel on a steerable platform, as described by *Mende et al.* [1995]. The following work addresses only the simple imaging channel.

The simple imager had a 50-mm f/1.4 Nikon camera lens focused onto a second generation image intensifier tube with red-extended S-20 photocathode. A tapered fiber optic bundle coupled the intensifier directly to a Fairchild (now Loral) video CCD system. The video signal was overlaid with date and time information and recorded at standard rate on VHS tape cassettes. The look direction is determined from stars appearing within the 15x20 degree field of view. Sprites are sufficiently bright that the intensifier was operated toward the low end of its gain capability, minimizing the noise in the imagery.

The majority of the data were acquired during intervals of a few hours each on six nights of the campaign. More than one hundred sprite events have been identified on an initial review of the tapes. A well placed thunderstorm on July 25, near new moon, provided superlative images of the sprite phenomenon.

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CCD architecture

The Fairchild CCD222 image sensor uses an interline transfer architecture to read out each exposed field, first odd rows and then even rows of standard interlaced video. Upon completion of a 33-ms exposure, the accumulated charge in each photosite of each odd row is shifted horizontally to an adjacent storage element which is shielded from incoming light by an opaque aluminum coating (Figure 1). These storage elements are shifted vertically to a horizontal transport register which continuously reads out image rows at a rate of one row per 63 μs (15.75 kHz), completing a field in 16.7 ms (Figure 2). Then the even numbered rows are similarly stored and clocked out over the following 16.7 ms. By now the odd field photosites have had time to complete their new 33-ms exposure and the cycle repeats. A simple timing diagram is shown in Figure 3.

The limitation of this CCD to be exploited is that very bright features focused onto the image plane not only saturate given photosites but also leak through or under the aluminum shield to contaminate the vertical transport register. This leakage creates vertical streak artifacts on the image as pixels are clocked past. A constant bright object like a light on the horizon produces a vertical line up the entire image. An intermittent bright source, like a high intensity strobe light observed on a distant tower, produces a line segment displaced vertically by an amount depending on the timing. The number of rows crossed by the line segment in an image field multiplied by 63 μs equals the duration of the strobe. Laboratory tests using a pulsed LED confirm this equation. The line segment may cross from the bottom of one field to the top of the next field given appropriate duration and phase of the pulse. Laboratory tests also show that the image intensifier phosphor decay time is 0.5 to 1 ms, depending on the degree of saturation.

Image analysis

Figure 4 displays a sequence of four video fields showing the onset and decay of a sprite event. Each field reads out top row first to bottom row last as it shifts vertically upward into the readout register. The vertical scale indicates relative readout time t_r for each pixel row, in milliseconds. The 1.6-ms gaps between fields are significant, representing the ~25 empty video rows read out before the field synchronization pulse initiates the following transfer. A bright source at the horizon creates a continuous vertical artifact. Three bright members of the sprite cluster contaminate the bottom of the first field near the completion of its read-out. These streaks each begin abruptly. The onset of the first sprite artifact is indicated as point A. The artifacts continue into the second field, holding their intensity for ~8 ms before fading over the following 10 ms.

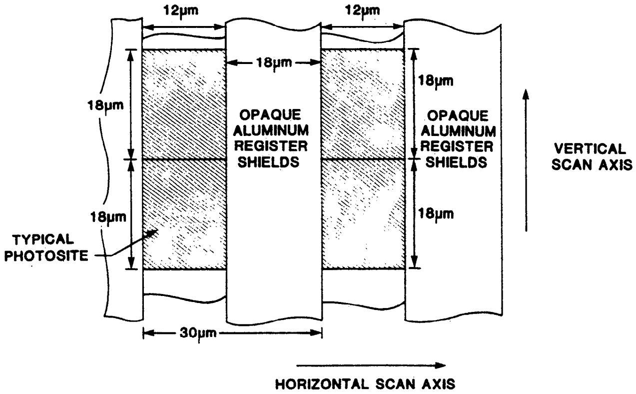

Figure 1. Diagram of the photoelement arrangement on the Fairchild CCD222 image sensor [*Fairchild Weston Systems*, 1989]. At the end of each 33-ms exposure the accumulated charge in the photosite array is shifted to vertical transport registers which are shielded by opaque aluminum.

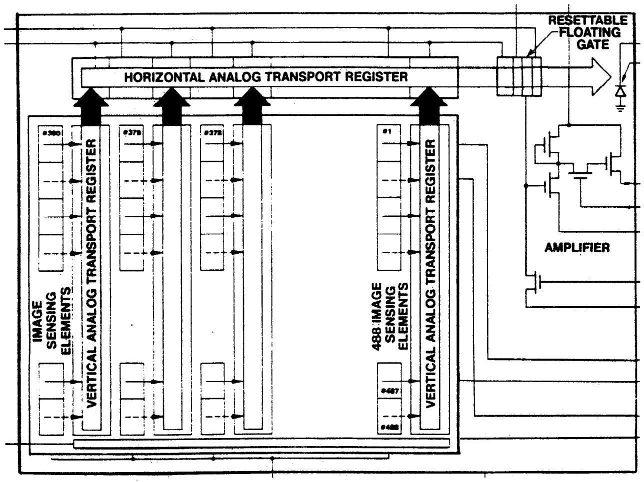

Figure 2. Functional block diagram of the Fairchild CCD222 illustrates how pixel rows are shifted in parallel to a horizontal read-out register [*Fairchild Weston Systems*, 1989]. This continuous process provides the output video signal.

Faintly visible at the top of the second field (point B) is a "ghost" image of the cloud lightning assumed to be associated with these sprites. The true images of the sprite and the cloud lightning appear in the second field at points C and D, respectively. Because the lightning appears closer to the bottom of the image, its artifact takes longer to shift through the vertical transport register to reach the read-out register. The phase is such that the first field is partly shifted out when the lightning occurs, so the ghost appears at the top of the second field. The spatial displacement between the sprite image and the lightning image, distance $\overline{CD}$, gives the sprite artifact an inherent lead of 7.0 ms over the lightning artifact. However, the sprite artifact reads out only 5.5 ms before the lightning artifact (distance $\overline{AB}$). The 1.5-ms difference is the delay time between the lightning and the sprite onset.

The three major sprite artifacts increase from detectability to maximum intensity within ~5 rows or 0.3 ms. The onset of the artifact at right leads the one at left by 1 ms and the one at center by 2 ms. The 0.2° width of the artifacts is much narrower than the saturated sprite images, which indicates the existence of small bright core volumes less than 2 km wide at

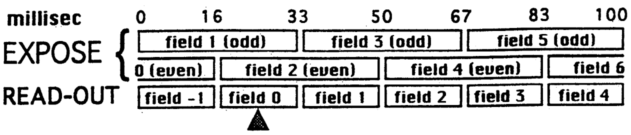

Figure 3. CCD field integration and read-out timing diagram. An event occurring at the black triangle can place identical images in fields 1 and 2 and leave an artifact in field 0 .

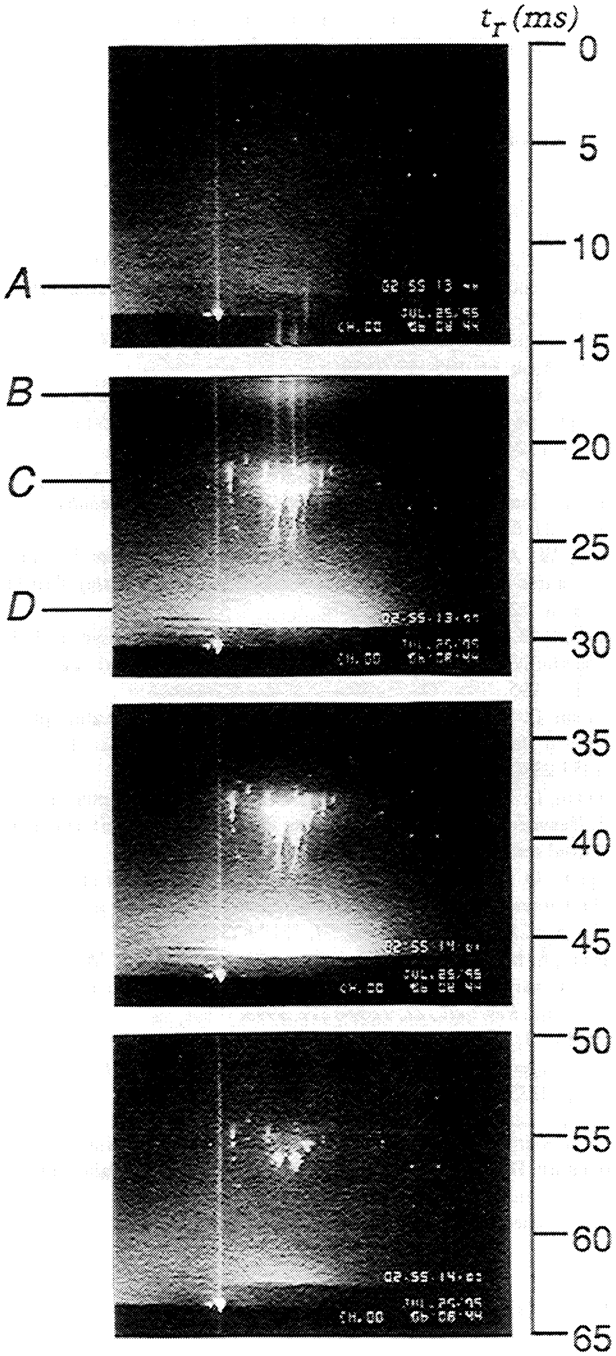

Figure 4. A sequence of four video fields shows the onset and decay of a sprite at 0608 UT on July 25, 1995. The vertical scale shows the relative readout time, t_r, for each pixel row, in ms. A and B indicate the onset of the sprite artifacts and the location of the cloud lightning's "ghost," respectively. C and D indicate the true positions of the sprites and lightning image, respectively. Sprite onset occurs 1.5 ms after the associated lightning discharge (given by $\overline{CD} - \overline{AB}$, see text).

the estimated 520 km range. The remnants in the fourth field likely show the spatial location of these bright cores.

A smaller bright core allows more precise timing, since the length of an artifact on the image is a convolution of the vertical extent of the overdriven portion of the sprite and its duration. Thus the artifact's 5-row onset could represent a 0.3-ms rise time of a point source or a shorter rise time of a distributed source.

The vertical localization of the cloud lightning artifact is consistent with a very brief flash. In height to width ratio, the contour of the artifact is very similar to the contour of the saturated cloud lightning image. An estimated upper limit to the vertical smear of the artifact is ~8 rows, or ~0.5 ms. This brevity can produce saturated cloud lightning images in two fields because of the 16-ms overlap in their 33-ms integration times (refer to Figure 3).

A survey of six clusters on July 25 containing a total of 20 measurable sprite artifacts indicates that the features seen in Figure 4 are typical for sprite events. Figure 5 presents three such examples of sprites and their artifacts extending from previous fields.

Conclusions and discussion

A design limitation of the CCD video camera has been exploited in an unforeseen manner to derive unprecedented submillisecond timing measurements of the sprite phenomena. This section presents generalized timing results and commentary.

Result 1. The typical sprite onset is found to follow the associated cloud lightning by 1.5 to 4 ms. This result stems from a limited number of observations. For many sprites no artifact of the lightning was seen. Sometimes a consistent

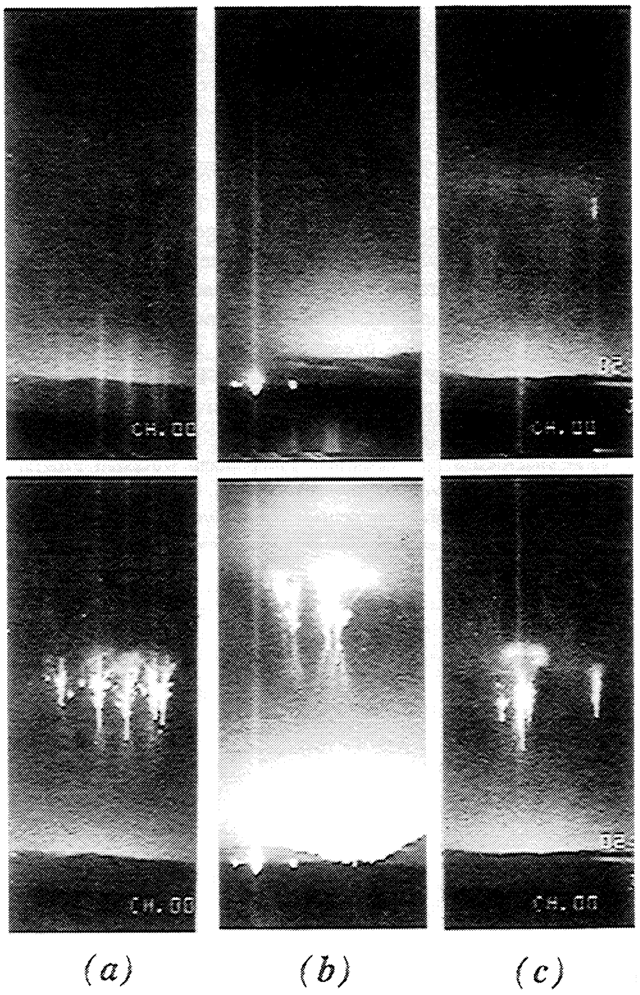

Figure 5. A collage of three additional sprite images and their artifacts extending from previous fields.

result would have the lightning ghost lost in the gap between image fields. More often the cloud lighting was too far over the horizon or too deeply embedded to generate the intensity required for an artifact. Caution must also be exercised not to confuse imaged airglow with a ghost image of cloud lightning. When airglow appears it is always near the altitude of the sprite, and it always appears in two consecutive image fields. Panel (c) of Figure 5 shows airglow in both fields.

Result 2. The onsets of the individual sprites within a cluster generally, but not always, occur simultaneously to within 1 ms. Figure 5(c) shows a counterexample, with the small sprite to the right starting 5 ms earlier than the primary sprite.

Result 3. Sprites tend to have a bright localized core, less than 2 km in horizontal dimension. This core rises to peak intensity within 0.3 ms and maintains this level for 5 to 10 ms before fading over an additional 10 ms. Though the sprites usually saturate the CCD across a much broader area, only the cores are sufficiently bright to create the vertical streak. The observed sprite artifacts all appear of the same width within a factor of two, and the width does not appear correlated with intensity. The artifact from the beacon on the horizon (an unresolved point-source) has a similar width, thus the characteristic sprite core could be much narrower than 2 km. Laboratory measurements show a relationship between wider source angular dimensions and artifact widths broader than this minimum. Nearby cloud lightning artifacts also demonstrate this relationship in the field.

While the rise time of the sprite core is quick, no conclusion is made regarding the light curve that a narrow field photometer would measure for example. A higher intensifier gain would presumably broaden the streak and provide timing information on the rate of horizontal spreading. A smaller aperture setting on the camera lens would prevent the broad saturation and probably also the leakage, but could show additional structure within the proper sprite image.

Different configurations of this CCD camera will be tested in future sprite campaigns. Only 40 minutes of observation are represented in the present timing results. A larger inventory of sprite images stemming from a variety of thunderstorms will provide a more persuasive data base.

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