Timing Uncertainty of the Lightning Imaging Sensor

PHILLIP M. BITZER AND HUGH J. CHRISTIAN

University of Alabama in Huntsville, Huntsville, Alabama

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ABSTRACT

The timing uncertainty of the Lightning Imaging Sensor (LIS), on orbit, is not currently accurately known. This is due to an imprecise value of the frame rate in the literature; the conceptual design value of 500 frames per second (fps) is often quoted. As researchers explore more ways to apply LIS data—in particular, the utility of group-level data, which correspond to strokes—a more precise value of the frame rate and timing uncertainty is important for proper understanding and use of the data. In this study, the average on-orbit frame rate was documented. From this, the timing uncertainty for LIS data was determined. Using on-orbit LIS data, the average frame rate of LIS is 558.58 fps and the timing uncertainty for LIS groups and events is 250 μs. It is shown that this uncertainty is associated with the quantization of the time of each frame. Further, the source time of optical pulses from lightning can have a bias that is not currently accounted for in the LIS data. This study shows how this correction can be on the order of the timing uncertainty, and a method in which this correction can be determined is outlined.

1. Introduction

Among the many ways to detect lightning, space-based measurements of the optical emission of lightning have proven to be a reliable indicator of total lightning. The most notable examples of these measurements are the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS). OTD and LIS have been used to study various topics, including lightning climatology (e.g., Cecil et al. 2014), global flash rate (e.g., Christian et al. 2003; Cecil et al. 2014), estimation of the ratio of cloud-to-ground to intracloud flashes (Boccippio et al. 2001), the global relationship between lightning and mixed-phase precipitation (Petersen et al. 2005), and the global electric circuit (Blakeslee et al. 2014; Mach et al. 2011). These studies primarily focus on using LIS-reported flashes, particularly for climatological studies. However, there has been recent interest in deeper-level LIS data, namely, groups, and their correlation to other lightning processes and lightning-detecting instruments (e.g., Østgaard et al. 2013; V. Franklin et al. 2014, unpublished manuscript; R. Winn et al. 2014, unpublished manuscript). These recent studies have focused on stroke-level lightning processes; hence, these studies used LIS groups, which are directly measured and are a more fundamental LIS measurement than flashes, which are a derived quantity.

Given this recent interest in using LIS groups, it is important to know the timing uncertainty of LIS on orbit. This yields the timing uncertainty of data collected in a single frame, for example, groups. The uncertainty should be related to the frame rate, which was originally conceived to be $\gtrsim$500 frames per second (fps; e.g., Christian et al. 2003), with a built value of 560 fps. Unfortunately, many reports in the literature do not reflect this as the built value. Despite this, researchers have used a timing uncertainty of 200 μs as an estimate (e.g., Østgaard et al. 2013) using personal communication from the authors of this manuscript. An accurate measure of the uncertainty is vital when comparing group-level data to strokes measured by other lightning detecting instruments and is particularly important because there are times when it is possible to achieve accurate subframe timing for the beginning of an optical pulse detected by LIS (e.g., Østgaard et al. 2013).

In this study, we find an accurate value for the LIS frame rate on orbit. Using this, we quantify the uncertainty in the time of any particular group. We note the frame rate of LIS, while important, is secondary to the main motivation of this work; the primary quantity of interest to researchers is the uncertainty in the times

Corresponding author address: Phillip M. Bitzer, Department of Atmospheric Science, University of Alabama in Huntsville, 320 Sparkman Dr., Huntsville, AL 35805.
E-mail: pm.bitzer@uah.edu

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recorded in the LIS data files. Finally, we discuss the implications on the derived source time for lightning processes detected near the edge of the field of view of LIS due to differences in propagation distance.

2. Instrumentation

LIS is an optical event detector aboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The optical emission from lightning is detected in time-integrated frames with a 128 pixel × 128 pixel charge-coupled device (CCD); a more complete description of LIS can be found in Christian et al. (1992). There are three basic levels of LIS data: events, groups, and flashes. An LIS event is a single pixel in a given frame in which the detected emission exceeds a variable, but deterministic, threshold. Adjacent or diagonal events (i.e., pixels) occurring in a single frame are classified as groups, which correspond to lightning strokes. Thus, both groups and events are data collected in a single LIS frame. Although not important for this work, groups in different frames that satisfy certain spatial and temporal constraints are combined and classified as flashes (Mach et al. 2007). Groups are considered to be the fundamental measurement made by LIS.

Timing for the LIS comes from a 1-s pulse provided by the satellite. This pulse provides a reference to real time. An internal clock on LIS provides more precise timing between the 1-s pulses. At intervals governed by the frame rate, the LIS CCD is read out; this is referred to as a frame. When read out of the frame occurs, the time is recorded using this internal clock. Hence, each frame is time tagged, and all events in a single frame share the same time tag.

Originally, LIS was designed to process 500 frames per second; however, an oscillator capable of producing precisely 500 frames per second was unavailable. It requested a change to an oscillator that would produce on the order of 560 frames per second. Since the CCD read-out electronics could support the higher speed and the increased frame rate would result in better performance, the change to a faster oscillator was approved. The internal LIS counter had already been designed at this point and unfortunately had insufficient resolution to optimally accommodate the increased frame rate.

TRMM underwent an orbit boost in August 2001; this date separates two time periods known as "preboost" and "postboost." The postboost altitude is 402 km, while the preboost altitude is 350 km. The time in the LIS data has a correction applied to account for transit time, using the average transit time for pixels near nadir assuming a source altitude of 12 km. However, this correction is for the preboost altitude. In addition, the time reported is not the end of frame, but is 1 ms prior to the end of frame; that is, the time is adjusted so that the (approximate) middle of the frame is reported (D. Mach 2014, personal communication). Hence, the time reported in the LIS data is approximately the source time in the middle of the frame in which the optical emission occurred, assuming a preboost altitude. For LIS data postboost, this correction is obviously not correct. This discrepancy is addressed herein and we provide a framework in which the user can apply an appropriate correction.

3. Methodology

To quantify the frequency of LIS frames, we use group-level data. Once the groups are extracted, the groups are sorted in time. We then find groups that occur in time-adjacent frames, which we refer to as "time contiguous groups." Equivalently, we could use "time contiguous events," but using groups reduces the processing required without loss of any information; that is, we maintain the necessary data to identify optical detections in adjacent frames. Since the frame rate is not precisely known, we first identify possible adjacent frames by plotting all the time differences between the time-sorted groups. Since the time between frames is nominally known to be $\lesssim 2$ ms, we use a maximum separation of 4 ms between groups on the first pass through the data to define adjacent frames with detected optical emission.

For each series of time contiguous groups, we determine the time between each group, which is equivalent to the time between each frame. We also find the overall time from the first to the last frame of a series of time contiguous groups. In this manner, we can find the average frame rate. Once an average frame rate is found, we then compare the times recorded in the LIS data to a time given by the average frame rate. The difference yields the uncertainty of the reported time of a group; it also clearly applies to the uncertainty in the time of events. Further, the results can be used for flash-level data as well, as the time for a flash in LIS data is the time of the first group.

4. Results

a. Frame rate

We have analyzed the last six full years of LIS data (2007–12) to find the characteristics of a series of time contiguous groups. The first notable result is the time between any two frames, as recorded in the LIS data, typically alternates between ~1.5 and ~2.0 ms for any particular series of time contiguous groups. Given this

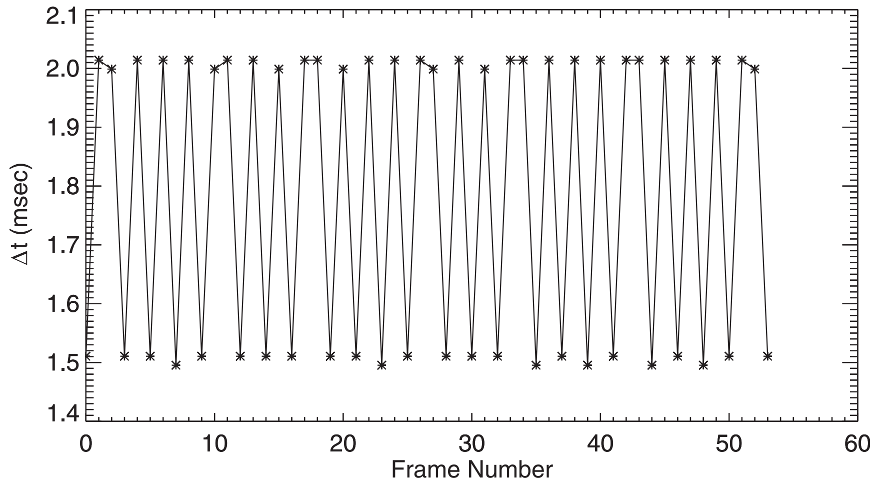

FIG. 1. Difference in the times between groups for one series of time contiguous groups.

information, we rerun the code to identify adjacent groups that have a maximum time difference of 3.3 ms. Figure 1 shows an example of one series of time contiguous groups from 25 February 2011.

The time between any two frames is not exactly 1.5–2.0 ms, as is evident in Fig. 1. Frames that are separated by ~1.5 ms have a precise difference of 1.511 or 1.495 ms, while the frames separated by ~2.0 ms have a difference of 2.014 or 1.999 ms. While this has been noted as far back as 1997 (R. Blakeslee 2014, personal communication), it has not been documented, nor have the implications on timing been considered.

We note the actual time differences differ from the approximate time difference by only ~15μs, which suggests the precision of the time tag in the LIS data is not representative of the "true" time precision; regardless, the time in the LIS data is more precise than the uncertainty. In the following discussion, we refer to the separation of frames by 1.5–2.0 ms while acknowledging the precise values in the LIS data are the ones mentioned here. Because the two values of the time between frames is (almost) always one of either 1.5 or 2.0 ms, it suggests the timing uncertainty is associated with a quantization error.

Nominally, these time differences between frames would suggest an average frame rate of ~575 fps. While the time differences usually alternate between 1.5 and 2.0 ms, there are times this does not hold true. As an example with a run of three time contiguous groups, the time difference between the first and second frames will nominally be 2.0 ms and the time difference between the second and third frames will be 1.5 ms. However, there are times when the time difference between the first and second frames is 2.0 ms, and the time difference between the second and third frames will also be 2.0 ms. This usually occurs every 2–10 frames. Hence, a simple estimation of the average frame rate is not correct. Frames 1 and 2 in Fig. 1 show this effect, which repeats several more times in the figure. Although not explicitly shown herein, we note, rarely, that frames can be separated by ~1 ms. When this occurs, the next time difference between frames is ~2.5 ms.

To get the average frame rate, we first find a series of time contiguous groups and find the total time. This is divided by the number of frames, which is one less than the number of groups in the series, to get the average frame rate during the run. Alternatively, we can take the time difference between n groups to find the average frame rate. To illustrate this method, consider $n = 3$ groups contiguous in time, occurring in frame 0, frame 1, and frame 2. The first group has a time tag of 0 ms, which is the time of the frame in which that group occurred. The second group has a time tag of 2 ms, while the third group has a time tag of 3.5 ms. Hence, we get a time for frame 1 to be 2.0 ms and frame 2 to be 1.5 ms. Thus, the average frame rate determined by these three time contiguous frames is 571 fps.

In accordance with the previous discussion, we find the average frame rate (FR) of a series of n time contiguous groups using

$$\overline{\mathrm{FR}} = \frac{1}{n-1}\sum_{i=1}^{n-1}(t_i - t_{i-1}), \qquad (1)$$

where t_i is the time of the ith group (using a zero-based counting scheme). This is repeated for all series of time contiguous groups in the dataset considered herein. The results are averaged for each year and are reported in Tables 1 and 2. The weighted mean of the frame rate over all years using $n \geq 10$ and $n \geq 20$ is 558.67 and

TABLE 1. Summary of frame rate statistics for a series of $n \geq 10$ time contiguous groups. Median, mean, and standard deviation are in fps.

Year	No. contiguous groups	Median	Mean	Std dev
2007	42 040	559.605	558.694	6.310
2008	45 896	559.605	558.627	6.190
2009	43 712	559.605	558.685	6.265
2010	39 297	559.605	558.665	6.183
2011	43 768	559.605	558.706	6.201
2012	45 991	559.605	558.661	6.169

558.58 fps, respectively. Notably, the mean frame rate for any particular year varies only slightly from the weighted mean, suggesting the average frame rate of LIS is quite stable.

Figure 2 shows the distribution of the frame rate for the year 2009, and it is similar for all years in the dataset considered herein. Time contiguous groups with a small number ($n < 10$) of groups may not yield an accurate measurement of the average frame rate. To show this, consider a series of 10 time contiguous groups (nine frames) that result in time differences of 2.0, 2.0, 1.5, 2.0, 1.5, 2.0, 1.5, 2.0, 2.0 (e.g., frames 10–19 in Fig. 1), resulting in an average frame rate of 545.45 fps. Hence, we use a series of time contiguous groups with at least 20 groups to quantify the average frame rate. It should be noted that the weighted mean frame rate using runs with at least 10 groups only differs by ~0.1 fps from the runs with at least 20 groups, so this effect is small when averaging over many data samples.

Peculiarly, the median frame rate for $n \geq 10$ and $n \geq 20$ changes by ~1.3 fps (0.2%), while the mean differs by less than 0.1 fps. Although the median is usually considered to be more resistant to outliers than the mean, the distributions herein show a slight change in median, while the mean is essentially the same. Although not shown, the distribution for $n \geq 10$ is less consistent with being drawn from a Gaussian distribution than the $n \geq 20$ distribution. Clearly, the standard deviation of the distributions (Tables 1 and 2) suggest there are more outliers in the $n \geq 10$ time contiguous groups. Therefore, we use the $n \geq 20$ results to conclude the average frame rate for LIS is 558.58 fps with a 68% error of 3.30 fps.

b. Timing uncertainty

There is no timing standard that can be used to determine the uncertainty for the times in the LIS data. Therefore, we estimate the timing uncertainty of any particular frame, and hence group, using 558.58 fps (the weighted mean for $n \geq 20$) as the average frame rate to generate a list of "correct" times. We then compare

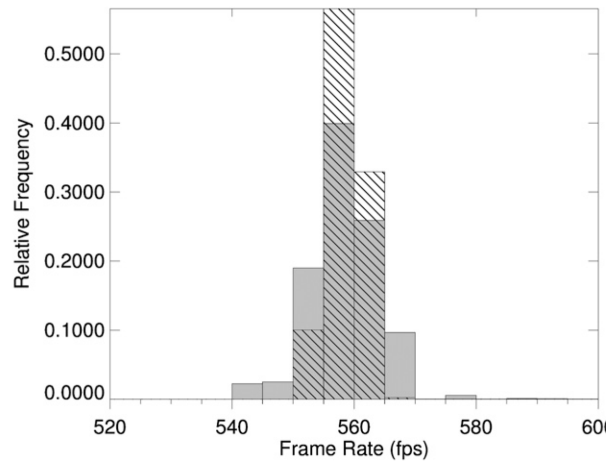

FIG. 2. Distribution of the average frame rate using a series of time contiguous groups with at least 10 groups (gray) and 20 groups (black hatching) for the year 2009. Not shown are 86 data points (0.20%) for series with at least 10 groups that lie outside the plot domain.

these to the times recorded in the LIS data for the time contiguous groups to get the difference between the recorded time in the LIS data and the time given by the average frame rate. Quantifying the uncertainty in this manner has a drawback: it is not known a priori what the first time of a series of time contiguous groups should be. Hence, we subtract off the mean of the difference when doing the comparison to account for the unknown first time. In this manner, we can derive what the time of each group should be from the average frame rate and compare that to the time recorded in the LIS data to estimate the uncertainty.

The distribution of the time differences for every series of time contiguous groups in the year 2012 with $n \geq 20$ is shown in Fig. 3. Results for the other years in this study are strikingly similar. This distribution is largely uniform, with 80% of the time differences between the timing of the average frame and the time recorded in the data within $\pm 200\,\mu$s, and 95% within $\pm 250\,\mu$s. The standard deviation of this distribution is 148.7 μs. Hence, researchers can safely use $\pm 250\,\mu$s as the uncertainty in the time of a particular group. We

TABLE 2. As in Table 1, but for $n \geq 20$.

Year	No. contiguous groups	Median	Mean	Std dev
2007	4141	558.270	558.598	3.315
2008	4635	558.270	558.610	3.326
2009	4421	558.070	558.548	3.277
2010	3866	558.270	558.581	3.282
2011	4559	558.270	558.596	3.209
2012	4587	558.270	558.555	3.362

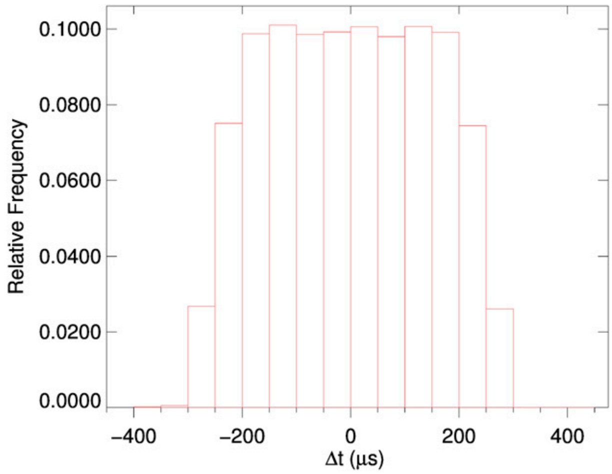

FIG. 3. Difference between the time associated with a frame rate of 558.58 fps and the time recorded in the LIS data for all series with at least 20 time contiguous groups in the year 2012.

note the uncertainty of a particular group is not correlated with the time difference between two frames; that is, a time difference of 1.5 ms does not imply the time is necessarily underestimated.

The uniform distribution, coupled with the time between frames (almost) always taking on one of two values, implies the uncertainty is simply associated with a quantization error, as might be expected. Since the distribution of the differences between the time in the LIS data and the correct times is zero mean, the value of the least significant bit (LSB) is given by $\sigma\sqrt{12}$, where σ is the root-mean-square of the distribution; given the standard deviation of 151.3 μs of the distribution in Fig. 3, this implies the LSB is equivalent to 524 μs. Coupled with the usual difference in the time between frames of 1.5–2.0 ms, we can safely say these results are consistent with the statement that the timing uncertainty is due to quantization.

c. *Correction for off-nadir events*

While LIS time is corrected for near-nadir events and a preboost satellite altitude, there is no correction for events that occur off nadir. This does not affect the ultimate taxonomy of LIS data, as groups (i.e., adjacent events) would have the similar time delays, but this can affect comparisons of LIS to other instruments. In addition, the true source time of the optical signal will be biased because of the change in satellite altitude. To quantify the needed correction to determine the true source time, we must consider the various corrections that should be used relative to the arrival time:

$$t_a = t_s + \frac{r_{\mathrm{post}}}{c} + \frac{r_{\mathrm{off}}}{c}. \tag{2}$$

TABLE 3. Summary of various quantities used in correcting the LIS time for off-nadir events.

Variable	Value
r_{post}	$402 - 12 = 390$ km
r_{off}	Varies with pixel location
t_{LIS}	Given in LIS data
$\tilde{r}_{\mathrm{pre}}/c$	1.27 ms

Here, t_{a} is the time that the optical signal arrived at the instrument, t_{s} is the source time (time of the optical emission at the source), r_{post} is the distance an optical signal propagates from the source height to the postboost satellite altitude, r_{off} is the additional distance off-nadir originating signals propagate relative to nadir; that is, the total distance the optical signal propagates is $r_{\mathrm{post}} + r_{\mathrm{off}}$, and c is the speed of light.

Currently, the time in the LIS data, t_{LIS}, is related to the arrival time by

$$t_a = t_{\mathrm{LIS}} + \frac{\tilde{r}_{\mathrm{pre}}}{c}, \tag{3}$$

where $\tilde{r}_{\mathrm{pre}}/c$ is the correction applied to account for the average transit time for near-nadir pixels and a preboost altitude (D. Mach 2014, personal communication).

To find the source time t_s, relative to the time given in the LIS data, we solve (2) and (3) for t_s:

$$t_s = \frac{\tilde{r}_{\mathrm{pre}}}{c} - \frac{r_{\mathrm{post}}}{c} - \frac{r_{\mathrm{off}}}{c} + t_{\mathrm{LIS}}. \tag{4}$$

This will yield the source time relative to the middle of the frame. The values used in this equation are summarized in Table 3. For near-nadir events, $r_{\mathrm{off}} \approx 0$ and the correction is trivial. For off-nadir events, we use empirical methods based on LIS data to find the necessary correction. Example code to carry out these methods can be found in the LIS/OTD user's guide (Boccippio et al. 1998).

While the science data files for LIS contain events, groups, and flashes, information about navigation, instrument and platform statuses, and threshold information is also included. These fields are updated every second and are collectively referred to as 1-s data. In particular, the navigation information can be used to geolocate LIS pixels; in turn, this can be used to determine the time difference between nadir and off-nadir events. For reference, LIS pixels are counted using a zero-based index, that is, the CCD pixel locations range from 0 to 127.

We first determine the pointing vector, which determines the direction from the satellite to the earth's surface, for the center of the LIS CCD. The center of the

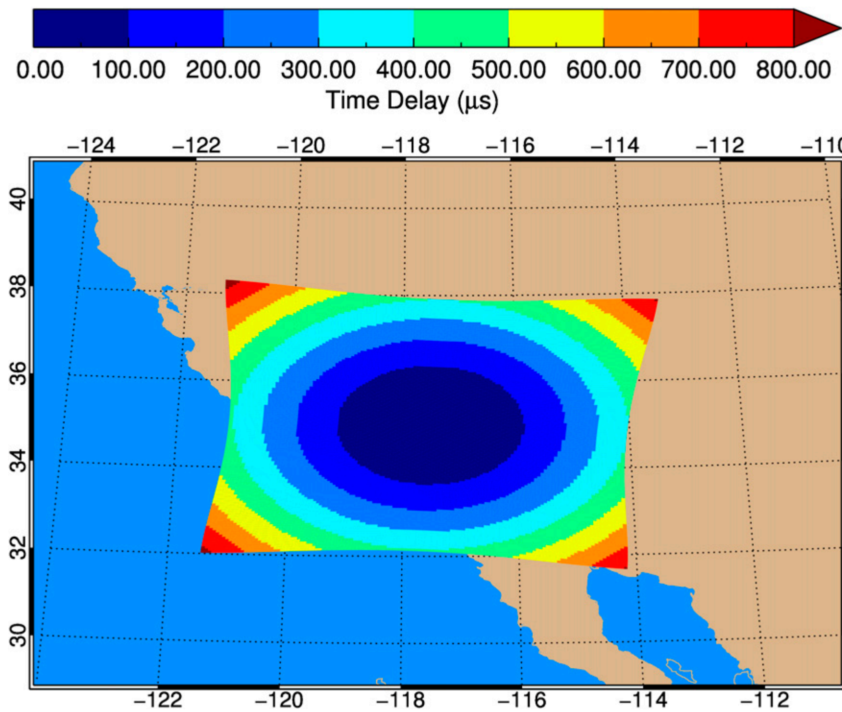

FIG. 4. Time difference for a signal to propagate for an arbitrary location with the LIS field of view and one at nadir, r_{off}/c. This is the LIS field of view at 1134:59 UTC 7 Jan 2010; the footprint of LIS is near the West Coast of the United States.

CCD is the (x, y) pixel (63.5, 63.5). Next, this pixel location is geolocated, assuming a 12-km source altitude. This yields the center of the LIS field of view. This geolocated position is then found in Earth-centered Earth-fixed (ECEF) coordinates using the World Geodetic System 1984 (WGS-84) ellipsoid. Then, the location of the satellite, located 402 km above earth's surface, is found in ECEF coordinates. The distance between these two locations, r_{post}, is used to find the time for an optical signal to propagate from the nominal source altitude near the earth's surface to the satellite, assuming the optical pulse propagates at the speed of light. Any errors resulting from the assumption of a 12-km source altitude and the orbit altitude of 402 km are negligible for this analysis.

To find the time difference for all pixels in a particular frame, we then repeat the previous process for all pixels of the CCD: the pointing vector for each pixel in the CCD is found, the pixels are geolocated, the ECEF coordinates of the geolocated positions are found, and the time for an optical signal to propagate to the satellite is determined. The difference between these times and the time for a signal from nadir to propagate to the satellite yields r_{off}/c and is used to correct the time in the LIS data to give the true source time for an optical pulse for each pixel.

As an example, consider an event that occurred at 1134:59 UTC 7 January 2010. Figure 4 shows the difference in the time for a signal to propagate from nadir and for all pixels in the field of view. During this 1-s period, the (0, 0) pixel is located near a longitude of $-121.5°$ and a latitude $32.0°$. The value for r_{off}/c for an event that occurs in pixel (93, 103) (approximately 50 pixels from the center) is 240 μs. This delay is on the order of the timing uncertainty derived in the previous section. Clearly, the time delay that should be accounted for increases, for events that occur near the edge of the LIS field of view. This is a nonnegligible effect that researchers must consider when using LIS data at the level of events and groups.

We can repeat this analysis for a large number of the 1-s periods; consider all the LIS data from 2010. The delay for each pixel for each 1-s period is found, and the average time delay is shown in Fig. 5. However, this figure should be interpreted with caution. This does not yield a correction value that is valid for all orbit positions of LIS; that is, this figure does not show the time delay for any particular 1-s period. The satellite rotates relative to earth's surface, changing the field of view of LIS; hence, this changes the correction for the time that should be applied. Instead, researchers wishing to apply the off-nadir correction should follow the method

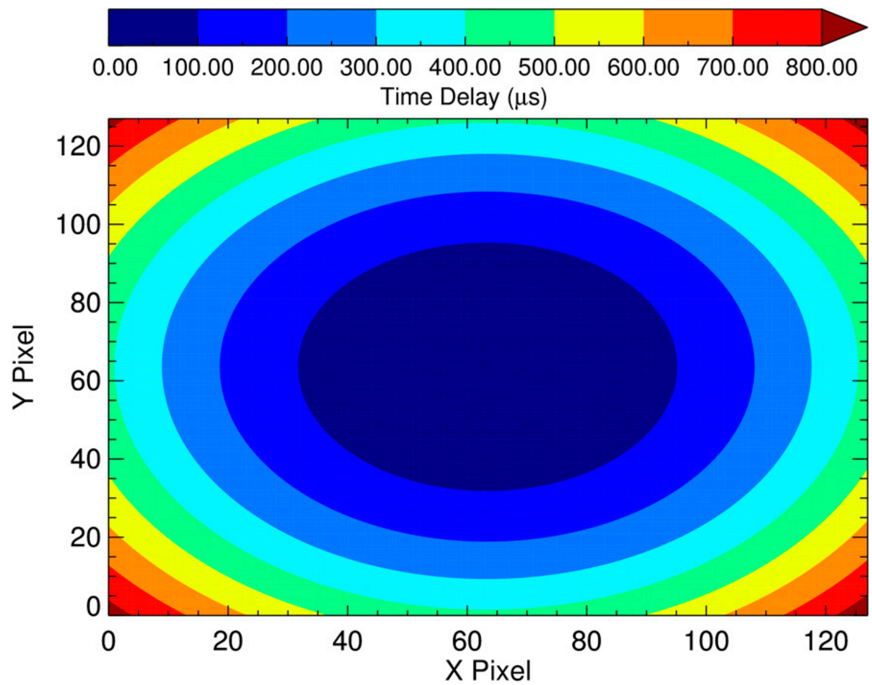

FIG. 5. Average time delay that should be accounted for, for events in each LIS pixel in 2010. Note this is an average effect; to get the delay for a particular event, researchers should use the methods outlined in the text.

outlined herein: first, geolocate the nadir location of the satellite near the earth's surface and find this position and the position of the satellite in ECEF coordinates. Then geolocate the pixels of interest and determine these locations in ECEF coordinates. Because LIS event data contain the *x*, *y* pixel, the time correction for the source time for an event (or group) of interest can be found.

5. Conclusions

We have quantified the timing uncertainty of LIS data using on-orbit data. Using time contiguous groups, we find the average frame rate of LIS to be 558.58 fps. From this, we then find the uncertainty associated with LIS data. We show LIS data can be used with an uncertainty of 250 μs at the 95% confidence level. In addition, we find there is effectively a zero bias in the LIS timing. In the future, we will compare these results with an LIS flight spare, which is currently scheduled to launch in 2016 to fly aboard the International Space Station.

We have also shown how users can account for the different transit times for optical pulses produced by lightning that are not in the center of the LIS field of view. Code to accomplish this is already available, and the data to make the necessary correction are included in LIS data files. These effects can be nontrivial, even for optical pulses from lightning not near the edge of the field of view. On average, an event that is 50 pixels from the center of the CCD has a source time that is 240 μs before the time reported in the LIS data, and this correction increases to $>$700 μs for events near the corners of the field of view.

This work also has implications for the Geostationary Lightning Mapper (GLM). This instrument is based on similar technology as LIS and is scheduled to launch in 2016 on GOES-R. The methods and results found herein will be immediately applicable to GLM and are vital as researchers start to use lower-level LIS data to better understand what information is reported by space-based optical measurements.

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