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Key Points:
- Geolocation and processing of the low-frequency (LF) data set collected during the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation campaign is fully described and characterized.
- Unique LF observations include discharge peak current, polarity, and possibly type classification based on the emitted radio waveform.
- LF spatiotemporal detection efficiency and storm case studies are discussed and compared to Geostationary Lightning Mapper data.

Supporting Information:
Supporting Information may be found in the online version of this article.

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Lightning Geolocation and Flash Rates From LF Radio Observations During the RELAMPAGO Field Campaign

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Abstract
The lightning data products generated by the low-frequency (LF) radio lightning locating system (LLS) deployed during the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation (RELAMPAGO) field campaign in Argentina provide a valuable data set to research the lightning evolution and characteristics of convective storms that produce high-impact weather. LF LLS data sets offer a practical range for mesoscale studies, allowing for the observation of lightning characteristics of storms such as mesoscale convective systems or large convective lines that travel longer distances which are not necessarily staying in range of regional VHF-based lightning detection systems throughout their lifetime. LF LLSs also provide different information than optical space-borne lightning detectors. Lightning measurements exclusive to LF systems include discharge peak current, lightning polarity, and lightning type classification based on the lightning-emitted radio waveform. Furthermore, these measurements can provide additional information on flash rates (e.g., positive cloud-to-ground flash rate) or narrow bipolar events which may often be associated with dynamically intense convection. In this article, the geolocation and data processing of the LF data set collected during RELAMPAGO is fully described and its performance characterized, with location accuracy better than 10 km. The detection efficiency (DE) of the data set is compared to that of the Geostationary Lightning Mapper, and spatiotemporal DE losses in the LF data set are discussed. Storm case studies on November 10, 2018, highlight the strengths of the data set, which include robust flash clustering and insightful flash rate and peak current measures, while illustrating how its limitations, including DE losses, can be managed.

1. Introduction
In the past decade, there has been an increasing research interest in the storms in sub-tropical South America, specifically north and central Argentina, after they were recognized as the world’s most intense thunderstorms (e.g., Houze et al., 2015; Mulholland et al., 2018; Romatschke & Houze, 2010; Zipser et al., 2006) with associated production of significant severe weather, such as large hail, heavy precipitation, strong winds, and tornados (e.g., Cecil & Blankenship, 2012; Rasmussen & Houze, 2011; Rasmussen et al., 2014). Most studies of these Argentinian storms have relied on satellite-based radar, lightning, radiometer observations that could be used to research various storm climatologies. Data from the multitude of ground-based sensors deployed during the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation (RELAMPAGO) field campaign in 2018 (Nesbitt et al., 2021) a unique opportunity for thunderstorm research using ground-based lightning locating systems (LLSs) combined with ground-based radar and other meteorological data to investigate these storms and their evolution in more detail.

Each of the main types of LLSs and their ranges—(a) short-range VHF mapping systems, (b) longer-range VLF/LF/HF systems, and (c) global VLF systems or satellite-based systems—present a unique set of lightning information (Cummins & Murphy, 2009; Nag et al., 2015). Radio and optical sensors detect different parts of the lightning process. VHF systems observe breakdown and lightning leader processes, providing extensive mapping of lightning channels. VLF/LF/HF systems observe the large displacement of charge in a formed lightning channel, but cannot resolve all information about the space-time evolution of individual flashes or the spatial extent of flashes. Optical systems also observe the current-carrying channel but from the perspective of optical emissions which may differ greatly in energy output to the radio emission (e.g., particularly for strong RF emissions, Jacobson et al., 2013) while providing useful information on the flash
spatial extent. Radiative transfer in the cloud may affect the optical signal propagation toward a space-based LLS depending on the source height and cloud structure (Peterson et al., 2017). Relatively understudied in the Argentinian storms, unique lightning information from very low frequency/low frequency (VLF/LF) systems include discharge peak current, polarity, and lightning type classification based on the received radio waveform. Additionally, a wide-area VLF/LF system is most suitable for following the lifetime of large convective systems such as mesoscale convective systems (MCSs) that travel across larger regions in central Argentina. This suitability is in part due to the wider range of VLF/LF LLS over what is practical with a VHF mapping system, while not suffering from particular loss of detection efficiency (DE) in some storms observed in satellite optical detectors (e.g., from low-altitude lightning or overshooting top occultations; Lang et al., 2020) or from the limited sensitivity of global VLF LLSs. Along with measurements of total lightning flash rates, which can be obtained by all types of LLSs, other known markers of convective strength and severe weather potential can be derived from VLF/LF data, for example, positive cloud-to-ground (CG) flash rates (Schultz et al., 2011, and references therein) and narrow bipolar events rates and height (Jacobson & Heavner, 2005; Jacobson et al., 2007; Suszcynsky & Heavner, 2003).

In this study, the VLF/LF LLS data product from the RELAMPAGO campaign is described and characterized, with respect to the campaign and other LLS data sets, and a few case studies are presented. This study aims to showcase the suitability of the RELAMPAGO VLF/LF data set for thunderstorm research in central Argentina.

2. Background

2.1. RELAMPAGO Field Campaign

The RELAMPAGOs field campaign was conducted from late 2018 through early 2019 in west-central Argentina, in the vicinity of the Sierras de Córdoba (SDC) and near the city of Mendoza at the foothills of the Andes mountains. Primarily funded by the National Science Foundation, this campaign was an international collaboration seeking to observe and investigate convective storms that produce high-impact weather (Nesbitt et al., 2021). Accompanying the RELAMPAGO campaign was the Department of Energy ARM-funded CACTI field campaign (Varble et al., 2021) which was planned and operated in coordination with RELAMPAGO to maximize the benefits of each campaign.

The regions around Córdoba and Mendoza exhibit some of the most intense storms in the world as well as the highest lightning flash rate per storm system (Cecil et al., 2015; Zipser et al., 2006), making the region particularly useful in studying thunderstorm evolution and the occurrence of severe weather events associated with these storms, including heavy rainfall, hail, strong winds, and tornadoes. The association of storms in the Cordoba/Mendoza regions with severe weather is based on Advanced Microwave Scanning Radiometer observations from the Earth Observing System (AMSR-E) in these regions (Cecil & Blankenship, 2012) as well as from public reports (Rasmussen et al., 2014).

Severe thunderstorms usually develop near the SDC during the summer months (Mulholland et al., 2018), where common ingredients for severe storms converge. These include tropospheric moisture advected from the Amazon by the South American low-level jet (Vera et al., 2006), a steep lapse rate in midlevel air (Ribeiro & Bosart, 2018), and a strong tropospheric wind shear from upslope flows in the SDC.

The RELAMPAGO campaign incorporated a multitude of instrument types, particularly during the intensive observation period between November 1 and December 15, 2018. Lightning-observing instrumentation included an array of four VLF/LF autonomous magnetic sensors (LFAMS or “LF instrument”) deployed by the University of Colorado Boulder (Deierling et al., 2019), an 11 station Lightning Mapping Array (LMA; Lang et al., 2020) deployed by NASA’s Marshall Space Flight Center, an array of eight electric field mills (Antunes de Sá et al., 2020) deployed by the University of Colorado Boulder, and an array of eight field change meters (CAMMA; Zhu et al., 2020) deployed by the University of Alabama Huntsville. Furthermore, C-band and X-band radars were operating from various institutions during the campaign including the Argentinian Weather Service radar (RMA1) located in Cordoba, the CSU dual polarimetric C-band radar, the CSWR deployable dual-polarimetric and dual-frequency C-band radar, and 3 CSWR mobile X-band Doppler on wheels radars. Hail pads and soundings were also deployed during intensive observation periods, among
other observations; see Nesbitt et al. (2021) for a full list of deployed instrumentation and an overview of the field campaign.

This study focuses on the data set collected by the LFAMS array, deployed to cover a large area including and between Mendoza and Cordoba (Figure 1). Figure 2 shows the LF data availability during the intensive observation period. Data gaps occurred during the campaign mainly due to power outages and their related effects on the instruments, which often occurred. For nominal observation periods, the LFAMS

![Figure 1](image1.png)

**Figure 1.** Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation (RELAMPAGO) deployment map of the low frequency (LF) instrument in Argentina, and a collection of photos taken during the deployment. The photos showcase the instrument’s outdoor antenna structure, consisting of two orthogonal magnetic loop antennas. The blue circles indicate an approximate sensitivity range for the LF instruments (600 km), and the 150 km red range circle defines the main region of interest in RELAMPAGO where the majority of other sensors were deployed.

![Figure 2](image2.png)

**Figure 2.** Low frequency data availability during Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation with the top line plot showing periods with three or more stations available. Shaded regions indicate times of interest when severe weather was reported. Most data gaps during times of interest were caused by local power outages.
data set provides unique complementary data for thunderstorm research in RELAMPAGO, as described for LF data sets in Section 1. These include radio waveforms from lightning events, from which discharge peak current, polarity, and type classification can be estimated. Even outside the range of the other lightning instruments in RELAMPAGO, lightning characteristics of storms such as MCSs or large convective lines that travel longer distances become possible with the LF data set, while still providing some low-level detail about individual discharges not available with space-borne observations.

Other RELAMPAGO data sets are also used to augment this study on the LFAMS performance and RELAMPAGO storm flash rates. These other data sets include those collected by the LMA (Lang, 2020) and CAMMA (Carey et al., 2019a, 2019b; Zhu et al., 2020). Unaffiliated data sets that observed RELAMPAGO storms are also used, such as those collected by NOAA’s Geostationary Operational Environmental Satellite R series (GOES-R) Advance Baseline Imager (ABI; Schmit et al., 2018) and Geostationary Lightning Mapper (GLM; Rudlosky et al., 2019) instruments, and from the Earth Networks Total Lightning Network (ENTLN; Heckman, 2014; Marchand et al., 2019).

2.2. RELAMPAGO LF Data Set

The LF instruments deployed in the RELAMPAGO campaign are based on the 100 kHz sampling rate VLF instrument described by Cohen, Inan, & Paschal (2010), with the proper modifications for operating at 1 MHz sampling rate and collecting VLF/LF (3–300 kHz) data (Cohen et al., 2018). The instrument continuously records radio signals arriving at two air-core magnetic loop antennas, aligned with North-South (Channel 1) and East-West (Channel 2) direction.

From the raw LF data, observed waveforms from lightning radio emissions (atmospherics or “sferics”) can be extracted and comprise the LF Level 1 data product (Deierling et al., 2019). The processing of this data product is illustrated in Figure 3, where the raw LF data is filtered using a “Humstractor” algorithm to remove power-line noise (Cohen, Said, & Inan, 2010), and a threshold detection identifies potential sferic candidates. The threshold detection is a simple check for signals crossing above five times the raw data noise floor. Once a possible sferic has been identified, a data window of 1.2 ms is extracted from both channels with the main peak centered at 200 µs. This process is performed for all four stations. A CG and an intra-cloud (IC) lightning discharge are shown in Figure 4 as an example of the sferics comprising the Level 1 data set.

3. Methodology

3.1. Lightning Geolocation

Multi-site lightning geolocation involves the fusion of information from observations of the same lightning source at different stations to arrive at a geolocation estimate. The most ubiquitous observations used in this scenario are time of arrival (TOA) and magnetic direction finding (MDF) (Cummins & Murphy, 2009). Through their observation equations, one can either directly solve for the source location if observations from enough stations are available, or estimate the location through data assimilation. Although a closed-form solution exists for the simplest cases of multi-site TOA/MDF, it is best to approach the problem with a data assimilation technique, which provides flexibility in addressing model and observation inaccuracies, lack or surplus of observations, solving for extra parameters (clock error, speed of propagation), and arriving at an accurate statistical description of estimate uncertainty. A linearized least squares technique (See Section 3.1.5) is thus chosen for the geolocation.

The geolocation data processing (Level 2 Data Product) is illustrated in Figure 5, where the final product consists of lightning events (discharges) and flashes, with their estimated time, latitude, longitude, and peak current. A quality measure based on the cross-correlation of the sferics for each event is also provided. The next subsections detail each stage of this processing.
3.1.1. Clock Error Correction

The LF instruments deployed in RELAMPAGO suffered from a clock offset from GPS time that would be updated to a new offset with every instrument reset. Two of the instruments also had a constant clock drift of 1 µs s\(^{-1}\) due to an aging oscillator that slowed enough to lose one sampling pulse per million. An example of these clock errors are shown in Figure 6 for November 10. The clock offset can be estimated from a cross-correlation of the Level 1 data with another lightning data set, for example, lightning pulse data from the ENTLN. Both types of errors are corrected in this step.

3.1.2. Sferic Matching

With the time-corrected Level 1 data, the sferics that were observed by each receiver can be matched into lightning events, that is, a source event corresponding to the radio emission observed as sferics by each LF station. In order to perform this matching, sferics within 0.1 s of each other across stations are grouped. For each group, a corresponding amplitude time series is formed for each station, comprised of LF Level 1 sferics placed at their recorded timestamps and zero amplitude between sferics (Figure 7). The advantage of this grouping is that in this short window of time the member sferics are likely to come from the same storm, and the group TOA delay can be removed for all of them in one step, facilitating the sferic matching. If lightning sferics from multiple storms are chosen to be part of the group, the sferics from the weaker storm will be naturally discarded in the following step, without affecting the matching of lightning in the stronger storm.

Figure 4. Sferic panel showcasing observations from the low frequency array of a cloud-to-ground (left) and an intra-cloud (right) lightning events. The location information and pairing of these sferics come from the next processing step of geolocation (Section 3.1).

Figure 5. Flowchart describing the geolocation data processing for generating the Level 2 data product. The gray ad-hoc processes, that is, clock error correction and observation editing, are only necessary in handling specific issues with the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation (RELAMPAGO) data set. Events can be matched with three or more sferic observations, for example, the first event in the matched stack is only composed of three observations. Amplitude-based observations, magnetic direction finding and peak magnitude, are not used in geolocation of the RELAMPAGO data set due to frequent receiver saturation.
main storm. A cross-correlation is performed between the time series from each station and the group TOA is determined and removed as seen in Figure 7 (right). The sferics that line up in time within 2 ms across stations are then assumed to come from the same source, becoming a lightning event output of this stage. Cross-correlation scores are also computed for sferics of an event against a reference sferic, which is chosen to be the first sferic observed in that event. The event quality, a measure of data quality reported for each event based on the expected similarity between sferics, is computed from the minimum cross-correlation score of the sferics of an event.

3.1.3. Lightning Observations and Observation Models

The geolocation observations discussed in Section 3.1, for example, TOA, can be extracted for each event at this point. Data editing can be performed here to remove low-quality observations, for example, MDF observations that came from saturated sferics. Saturated sferics were observed whenever a strong lightning radio emission induced a greater B-field at the antennas than the instrument could measure, and it was caused by a combination of large peak current lightning discharges and discharges in close proximity to the LF instrument. The main peak in the sferic can be clipped down to the instrument saturation level or attenuated if in the nonlinear regime of the receiver near saturation. Only TOA observations were used in geolocating the RELAMPAGO data set, given that saturation of multiple LF receivers in the nearby RELAMPAGO storms

Figure 6. Clock error for the Remote sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observation stations based on a cross-correlation with Earth Networks Total Lightning Network data. Vertical lines indicate a station power-on from a shutdown or reset.

Figure 7. Plot of a group of sferics used in the lightning event matching process. Black vertical bars indicate sferics that were matched. The left plot has the sferics real arrival time at each station, and the right plot shows the sferics with the group time of arrival removed.
make amplitude-based observations unreliable, but peak currents can still be estimated using amplitude information from observations that did not saturate.

The sferic waveform arriving at an observer will have a characteristic time delay with respect to the originating lightning event, according to its propagation speed and distance between the source and the observer. Thus it provides the observer with a pseudorange measurement if the originating event time is known. With enough observations in a multi-site instrument array with synchronized clocks, the originating event time can be found in conjunction with the source location.

Systematic errors affecting the LF receiver can affect the pseudorange measurements, including the clock error for each receiver and the signal transmission delay from the antenna to the analog to digital converter, which is assumed to be negligible for our instruments. The observation equation for TOA, \( t_{oa} \), derived from the law of cosines for spheres, is then given by:

\[
 t_{oa} = \frac{r_e}{v_{pr}} \arccos \left( \sin \phi_{sensor} \cdot \sin \phi_{tg} + \cos \phi_{sensor} \cdot \cos \phi_{tg} \cdot \cos (\lambda_{tg} - \lambda_{sensor}) \right) + t_{tg} + \epsilon_{clk},
\]

where \( \phi \) and \( \lambda \) are latitude and longitude, \( r_e \) is the radius of the spherical Earth, \( v_{pr} \) is the signal propagation speed, \( t_{tg} \) is the time of the originating strike at some epoch common to all observers, and \( \epsilon_{clk} \) is the clock error for the observing station. This observation equation assumes a spherical Earth, groundwave propagation of the LF sferic, and a known speed of propagation.

The uncertainty in the lightning location solution derived from the \( t_{oa} \) equation depends on the problem geometry, that is, location of lightning sensors, also referred to as topology. Furthermore, the problem geometry dictates an observable region within which lightning events can be located unambiguously, and outside of which lightning events will have multiple location solutions. Some of these ambiguous solutions can fall within the observable region. A minimum array of three sensors is required for the existence of an observable region, and increasing the number of sensors and appropriate placement will increase the array’s observable region and minimize the impact of ambiguous lightning location solutions appearing inside the observable region.

For estimating peak current, an attenuation model (Figure 8) based on finite-difference time-domain (FDTD) modeling of lightning propagation (Marshall, 2012) is used with the assumption that a known peak radiated field a distance away from the source, for example, 100 km, is proportional to the source’s peak current by a constant parameter (Orville, 1991). The attenuation model is based on a power law fit to extrapolate the FDTD attenuation at closer and farther observation distances.
3.1.4. A Priori Generation

Given the nonlinear nature of the observation equation, any solution that depends on the linearization of the model may violate the local linearization assumption. In order to avoid this issue with the linear least squares estimation in the next step, a low-fidelity a priori is generated beforehand using the full nonlinear model for each event so that the linearization of the observation model is representative of the domain near the true state solution.

A priori is generated for each lightning event through a grid search for the global minimum of the time difference of arrival cost function:

\[
f(t_{oa}^A, \lambda_{oa}^A) - t_{oa}^B, \lambda_{oa}^B) - t_{oa}^C, \lambda_{oa}^C) + (t_{oa}^A, \lambda_{oa}^A) - t_{oa}^C, \lambda_{oa}^C) + t_{oa}^A + t_{oa}^C)^2,
\]

where \(t_{oa}\) stands for an observation of TOA (sferic initial peak), \(t_{oa}\) is computed from Equation 1, and the uppercase A, B, and C letters stand for a collection of three observing stations. If more than three sensors observe the lightning event, then the smallest cost function among the possible station pairs is used for the a priori. While this implementation is expensive, with the cost function computed for every grid point, the nonlinear global minimum is guaranteed to be found. A square grid length of 0.1° latitude/longitude is chosen with acceptable computation cost in the a priori generation while maintaining the local linearization assumption for the least squares estimator in the next subsection.

As discussed in Section 3.1.3, the array topology affects the lightning location uncertainty derived from the TOA observation model, and ambiguous solutions to lightning events outside the observable region may be falsely located inside the observable region. In order to characterize the TOA lightning location observability for the RELAMPAGO LF array, a simulation of a priori lightning estimates was generated.

The a priori simulation consisted of lightning events generated all over the array domain outlined in Figure 9. Their corresponding TOA observations are then given as an input to the a priori algorithm. The resulting a priori locations and the maximum location error for that location is shown in Figure 9 for two station topologies and in Figure S1 for all topologies. Based on this a priori error a domain mask is generated
for each network configuration to include only the regions where the a priori simulation maximum location error is less than 100 km, defining the observable region for the array. The masks are then used in limiting the number of ambiguous solutions geolocated by discarding events that fall outside the mask boundaries. Note that lightning outside the simulation domain in Figure 9 would further decrease the unambiguous coverage region, but that effect is offset by the sensitivity and finite range of the LF instruments.

### 3.1.5. Least Squares Filter and Flash Clustering

Finally, the observations and a priori are fed into a linear least squares statistical (LSQ) filter for an estimate of lightning occurrence time and location along with their uncertainties given by the TOA model, assuming an unbiased gaussian distribution of TOA uncertainty of 10 µs and negligible model and linearization errors. The TOA uncertainty is the best guess based on the station clock correction and cross-correlation performed in Section 3.1.1 for the RELAMPAGO LF data set, and it limits the location uncertainty to a minimum of 3 km. The LSQ filter is set up in a batch format, which performs the estimation of all lightning events at once. While mathematically equivalent to performing the least squares on each lightning event, given that they are independent of each other, the batch format allows for solving extra constant parameters that affect the lightning events, for example, clock error, propagation speed, gain errors. Sparse matrix operations are employed to remove computation overhead in batch LSQ without extra solve-for parameters, and a rolling window batch LSQ of at most a few hundred events is used to limit computation time when extra solve-for parameters are estimated. Extra parameter estimation was not investigated in this study.

After geolocation and application of the observability mask, lightning events are clustered into lightning flashes. Inspired by similar LLSs, a simple agglomerative (bottom-up) hierarchical clustering is employed based on a spatiotemporal distance criteria of 10 km to the flash centroid and 0.3 s to the last event of a flash. The location uncertainty of an event loosens the distance criteria directly, and, unlike other LLSs, the distance criteria is tightened according to the quality of an event. This quality-based penalty is necessary in the RELAMPAGO data set since no quality control is performed on the Level 1 data, and a large number of detected events can be from ill-defined emissions (sferic overlap) or nonlightning radio signals (man-made RF interference), otherwise yielding misleading geolocations. The penalty introduces a maximum location error of 100 km for zero quality events and quickly decreases to 2 km at 0.2 quality score before tapering to 0 km at 0.6. The largest number of unsuitable events was empirically found to occur below 0.2–0.4 in the RELAMPAGO data set, and the penalty distribution was chosen so that false event detections are minimized while keeping a high flash DE. The flash inherits time, latitude and longitude of the events by means of a weighted centroid, using event qualities for weights, while the reported flash quality and peak current are from the events with strongest quality and peak current respectively. Flash area is computed from the convex hull of events within a flash, and flash duration is the length of time between the first and last events in a flash.

### 3.2. Detection Efficiency (DE)

The loss in perfect DE of the LF array can be mainly attributed to three factors: (a) the detection of a proper event in the Level 1 data directly related to instrument sensitivity, (b) the discard of events and loss of precision associated with the observability mask and problem geometry, and (c) the discard of events based on cross-correlation score and loss of events that could not be properly matched. Assuming a measurable instrument sensitivity and expected peak current distribution of lightning events, factor (a) can be theoretically investigated. Factor (b) can also be estimated using the same models and assumptions used in the geolocation steps above. The last factor presents several challenges that make it difficult to predict, as it requires a full understanding of false positive and negatives in Level 1 detection and pairing steps along with their expected cross-correlation score. This understanding is made even more difficult when a superposition of signals has to be considered, which is a common feature of high flash-rate storms and noisy sensor environments. The DE analysis for the RELAMPAGO LF data set comes primarily from a simulation of lightning events, which combines the losses by factors (a) and (b). Losses from factor (c) and overall DE are discussed in Section 4, with direct comparisons of the empirical LF and GLM data.
Our DE simulation employs random sampling of $10^6$ lightning events (first event in flash) uniformly distributed over the interest region (Latitude: $-38^\circ$ to $-27^\circ$; Longitude: $-70^\circ$ to $-60^\circ$). The $10^6$ flashes are then generated by sampling the subsequent events (discharges). The number of subsequent discharges, that is, multiplicity, is sampled from a geometric distribution with probability 0.2 so that the mean multiplicity is 5, around the expected multiplicity of negative CGs (e.g., Kitagawa et al., 1962; Rakov & Uman, 1990; Zhu et al., 2015). The location of subsequent discharges is sampled from a normal distribution with 0 mean and 10 km standard deviation about the first event. The time of subsequent discharges is sampled from an exponential distribution with mean of 0.15 s after the first event. The peak current for all events are sampled from a log-normal distribution with $\mu = 2.14$ and $\sigma = 0.78$, which was found from the log-normal fit of lightning peak current in the National Lightning Detection Network (NLDN) data between 2012 and 2018 in the United States. Figure 10 shows the histograms of flash area, duration, multiplicity, and peak current that result from the simulation sampling input.

With the lightning events sampled, the simulation computes the amplitude of the radio signals arriving at each station using the same peak current model explained in Section 3.1.3. Events that arrive at three or more stations with a signal stronger than that station’s sensitivity are considered to be detected, and a flash is considered detected if any constituting event is detected. The sensitivity used for the simulation is the worst sensitivity observed in the active periods of Section 4.1, with 0.37, 1.5, 2.0, and 0.37 nT for LF1, LF2, LF3, and LF4, respectively. Time of arrival observations are then simulated for each detected event-station, with the 10 µs expected uncertainty added as noise. The detected events are then geolocated based on the observations. Finally, DE is computed by counting the number of detected and geolocated events inside 0.1° × 0.1° latitude and longitude bins divided by the number of true events in that bin. Only events with less than 50 km uncertainty are counted. The average number of true events in a bin is around 470 events and 80 flashes, confirming the statistical significance of the simulation.

The resulting DE for events and flashes of this simulation is shown in Figure 11 for the nominal topology with four stations available, and Figures S2 and S3 show the results for all topologies. Most of the DE loss comes from a combination of station range and corresponding observation mask. The most significant station loss of DE comes from LF2 and LF3, which have worse sensitivity, and the observation masks for those topologies dominate the DE map, that is, LF1-LF2-LF4 mask on the northwest and LF1-LF3-LF4 mask on
Elsewhere, the large observation mask with all stations prevails, but only for events with high enough peak current, for example, the eastern lobe of the array DE. Within the mask contribution to DE, the range dependent detection outwards from LF2 and LF3 is also prominent. Note that in the real world, the sensitivity can vary significantly from this average value, as the noise floor at the stations changes due to interference from natural sources, for example, nearby lightning, and man-made sources, for example, HVAC systems.

4. Geolocated Events and Flash Rates

The RELAMPAGO LF geolocated results, the Level 2 data set (Deierling et al., 2021), are characterized in this section, and compared to lightning data from GLM. A one-to-one relationship is not expected since the LF array and GLM employ very different sensor technologies, that is, VLF/LF radio pulses versus infrared CCD imaging detection from orbit, where the pixel width projection corresponds to between 8 and 16 km on the ground. Each technology also detects different parts of the lightning process as described in Section 1, with the LF system not able to capture spatial extent of flashes. The GLM flash clustering algorithm collects GLM groups, which are comprised of single-pixel GLM events, within 330 ms and 16.5 km of each other (Mach, 2020). The LF algorithm uses a similar, but variable, criteria for clustering, which includes LF event uncertainty and quality. Both algorithms suffer from erroneous clustering of independent lightning flashes to some extent, because of the instruments’ spatiotemporal resolutions and clustering criteria. This effect becomes a concern with high flash rate densities, causing underestimates of flash rates and overestimates of flash duration and multiplicity. GLM data is preferentially affected due to a smaller spatial resolution and pixel aliasing in the flash clustering. Additionally, GLM flash area is computed from the collection of pixels within the flash, in contrast to the LF flash area, which is computed from the convex hull of constituent event locations and cannot capture the spatial extent of flashes due to the small number of LF lightning emissions when compared to VHF or optical sources.

Strengths and limitations of the LF array in RELAMPAGO are discussed in the two sections below, with the first section (Section 4.1) using data from multiple days of storm activity and the second section (Section 4.2)
focusing on a sample period of storm activity on November 10, 2018. DE variability of the LF array is caused by station resets or station sensitivity variability (See Section 3.2), particularly affected by the noise floor increase from storms close to a station.

4.1. Collection of Time Periods of Storm Activity and All LF Stations Online

A collection of time periods with significant storm lightning activity that coincides with all four LF stations online is chosen for this study:

1. November 10, 2018 19:00–22:30 UTC
2. November 11, 2018 20:00–22:00 UTC
3. November 17, 2018 00:00–06:00 UTC
4. November 26, 2018 05:00–11:00 UTC
5. December 4, 2018 21:00–24:00 UTC.

Figure 12 characterizes the flash area, duration, multiplicity, and peak current distribution of flashes for this period, and Figure 13 presents the average flash rate density observed with the LF array and GLM.

A flash quality measure, from the largest cross-correlation score of event sferic waveforms within a flash (See Section 3.1.5), is helpful in determining false-positive or mismatched lightning flashes. A minimum flash quality choice of 0.4 was chosen since the largest number of unsuitable events was empirically found to occur below 0.2–0.4 in the RELAMPAGO data set. This choice of a minimum flash quality has an effect on the observed flash multiplicity. Since flash quality is chosen to be the maximum event quality within the flash, lower multiplicity flashes, in particular single-discharge flashes, are affected more strongly by a flash quality threshold. Thus, while the minimum flash quality filter is useful in reducing the number of false positive event detections, most of the impact on true positive detections lies on single-discharge flashes, reducing the DE of single-discharge flashes. Aside from the flash quality, there is another contribution to the lower single-discharge bin caused by higher density flash rates on November 11, 2018, which produced the largest percentage of flash data during these observation periods. The flash clustering algorithm is more likely to cluster physically unrelated discharges during high flash density rates, decreasing the number of single-discharges reported. The remaining multiplicity bins, especially beyond multiplicity of 2, agree with the expected geometric distribution.
The flash area and duration plots are indicative of an acceptable flash clustering algorithm. Longer flash duration is mostly reported on the GLM data set from the high flash density period on November 11, 2018, and as such it is expected to indicate lower flash rates than the LF data for that period. The peak current distribution has a slower decay than expected. The energetic tail is due to the flash clustering selectivity for higher peak currents, that is, the reported flash peak current is the maximum reported peak current in the associated events.

The average flash rate density map, that is, the number of flashes per hour per km$^2$ averaged during the period of storm activity and shown in Figure 13, reveals a spatial dependence where the LF DE decreases close to the mask boundaries, as expected. However, the storm on November 17, 2018, delineated by the storm path from just south LF4 to LF3, seems to have suffered from greater DE loss than can be explained by sensitivity and problem geometry alone. The November 17 period reported the lowest average flash quality than any of the other periods, suggesting that the lower quality and threshold filter have caused the DE loss. Additionally, geolocation uncertainties greater than 10 km in some cases lead to a shift in storm location. For example, the November 11 storm system southeast of LF2 was geolocated slightly northward when compared to GLM, leading to an overestimate of LF DE in the north and underestimate on the south of the storm.

For an estimate on geolocation accuracy, LF flashes were matched to GLM flashes using a tolerance criteria of ±0.5 s, 25 km in latitude and 25 km in longitude. Since high flash rate periods would significantly impact the proper matching of the flashes, that is, high likelihood of independent flashes occurring in the same area, the activity period on November 26 was chosen, for which the expected number of flashes is less than 0.1 per second within a 25 × 25 km area. The resulting distance error distribution of the LF flashes estimate with respect to the GLM matches is seen on Figure 14, with a median error of 5.6 km.

The overall performance of the RELAMPAGO LF flash data with all stations online is comparable to GLM and similar LLSs, with a sub 10 km accuracy, center DE greater than or equal to GLM’s, and flash properties indicating a successful clustering algorithm. Some limitations are observed in DE loss away from the array center and biased impact on single-discharge flashes by the quality filter. In the next section, the November 10 overall period and two of its storms are investigated.
The November 10, 2018, 19:00–22:30 UTC observation period is marked by several storms, mostly initiating east of the Sierras de Córdoba (Northeast of Mendoza’s LF4) and most of them moving eastward, perpendicular to the Sierras de Córdoba. The period is particularly dominated by two high-flash-rate storms north-east of LF3. One of the storms has supercell characteristics (Trapp et al., 2020). The flash area, duration, multiplicity, and peak current characterization of flashes for this period are shown in Figure 15. Figure 13 presents the average flash rate density during the 19:00–22:30 UTC observation period (LF and GLM) and a plot of LF DE with respect to GLM. An animation of the LF and GLM flash data is also part of the supporting information media files.

On the maps of average flash rate density, the main four active regions in the center are well observed by the LF array. As the eastern-most storms approach the mask boundary, a quick loss of DE is observed as expected from the previous theoretical and empirical analyses. The low DE region close to LF4 between two storm centers, around $-32.5^\circ$ latitude and $-66^\circ$ longitude, is caused by a combination of lower radio energy storm and worse sensitivity of instruments during strong radio emissions, particularly LF2 and LF4. The smaller storms in the northern and southern lobes of the LF array observation mask are barely observed in the LF data.

The first drop in DE observed in Figure 16 coincides with the beginning of the storm within 50 km of LF2, which worsens the sensitivity of that station and, consequently, the overall array DE for other storms. The following downward DE trend after 21 UTC is primarily caused by storms reaching the eastern limits of the
The sudden drop in DE at 21:30 UTC is caused by a temporary blackout of LF1. These observations are corroborated by the animation in the Movie S1 (Supporting Information).

5. Storm Case Studies

Continuing with the analysis on the November 10, 2018 period and as an example of storm case studies that can be performed with the RELAMPAGO LF flash data, the two high flash rate storms from November 10 are investigated in the sections below.

5.1. November 10, 2018, 19:30–22:30 UTC Storm Near LF2

A severe storm with supercellular characteristics (Trapp et al., 2020) moved eastward during IOP4 through the RELAMPAGO domain between 19:30 and 22:30 UTC on November 10, 2018 and stayed within 100 km of LF2, with flashes occurring within a few kilometers of the station around 20:30 UTC and the LMA indicating a lightning hole. A dynamic storm envelope was computed for this storm, and only flashes within this mask are used in the analysis below.

Figure 17 showcases the storm’s evolution in the context of flash rates, and average flash area, duration, and multiplicity. The storm spatiotemporal evolution is also shown on a map, which includes the overall storm mask shape. Though there is general agreement between the LF and GLM data sets, GLM reports around twice the flash rates observed by the LF array in the middle of the storm’s lifetime. The drop in LF DE around 20:30 UTC is likely caused by the coinciding storms initiating near LF4 and the associated drop in sensitivity. Given the constant average flash area, duration, and multiplicity, the drop in DE does not seem to be caused by a clustering or quality problem with the data processing. Two sudden drops in DE are caused by resets of the LF stations. The LF array is not expected to capture the spatial extent of flashes well as described in the beginning of Section 5, especially for lower multiplicity flashes, hence the large disparity between the LF array and GLM average flash area.
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5.2. November 10, 2018, 21:20–24:00 UTC Severe Storms

Another case investigated on November 10 was comprised of severe convective storm cells exceeding radar reflectivities of 60 dBZ that initiated in Lago Pampa de las Salinas area around 21:20 UTC. The complex of storms moved over Villa Yacanto and the DOE CSAPR2 radar around 00 UTC on November 11, 2018. Similar to the previous case study, a dynamic storm mask was computed for selecting the relevant data. The LF array lost a station during this storm, operating with only three stations for half the period.

The evolution of lightning activity of the storm complex shown in Figure 18 suggests similar agreements between the LF and GLM data sets as in Section 5.1 and analogous conclusions with respect to flash area, duration, and, by extension, the LF flash clustering. The overall LF DE is higher than in the previous case study as expected from the storm location being in the middle of the LF array. Even with the loss of a station, the LF flash rates match those of GLM, and it is expected that even higher rates would have been observed with all stations online, as seen just before LF3 goes offline. Increases in GLM flash duration accompany a drop in GLM flash rates at 22:30 UTC and 23:40 UTC, which might explain the lower GLM DE with respect to the LF array at times of high flash density, as described in the beginning of Section 5. On the other hand, the large stratiform region developed could also explain the increase in GLM flash duration, but the GLM flash area is not increasing and thus not supporting indications of larger/longer flashes.

Figure 16. Maps of average flash rate density for the LF data set (left), Geostationary Lightning Mapper (GLM) data set (middle), and a map of the average flash density ratio between the two data sets (right) between 19:00 and 22:30 UTC on November 10, 2018. The observation mask used in the LF data is shown on all plots. Time series of the 15 min average flash rates observed by the LF array, the GLM instrument, and the detection efficiency of the LF array in comparison to GLM is also shown on the bottom plot.
increases, possibly explaining the lower GLM DE and increase in GLM flash duration. In contrast, the LF multiplicity increases in conjunction to flash rate spikes, indicating a higher number of both longer-duration and independent flashes are being observed and properly clustered separately.

Figure 17. Map of the November 10 storm near LF2 (left), and (right) plots of flash rates, and average area, duration, and multiplicity observed by the low frequency array and Geostationary Lightning Mapper between 19:30 and 22:30 UTC on November 10, 2018.

Figure 18. Map of the November 10th storm initiated near Lago Pampa de las Salinas (left), and (right) plots of flash rates, and average area, duration, and multiplicity observed by the low frequency array and Geostationary Lightning Mapper between 21:20 and 24:00 UTC on November 10, 2018.
6. Summary

The LF array and data collected during the RELAMPAGO campaign were described and characterized in this study. The methodology for geolocating lightning events was detailed, along with the expected limitations for the RELAMPAGO LF data set, mainly due to instrument sensitivity, clock error, and LF station array geometry. Expected DE losses were simulated, discussed, and later observed in the empirical data presented. For characterizing the LF flashes in RELAMPAGO, an overall period of active storms and all LF stations online was investigated, and compared against GLM data for validation purposes. Flash properties reported, for example, area, duration, multiplicity, and peak current, suggest a successful flash clustering algorithm. For quality control of events and flashes, a quality measure is derived from the cross-correlation of waveform observations comprising an event and flash. A 0.4 flash quality threshold was found to be useful in reducing the number of false positive flash detections, at the expense of a reduced DE of single-discharge flashes, on which lies most of the impact on true positive detections. Flash geolocation accuracy was estimated to be better than 10 km. Spatial-dependent DE losses were seen in the data as expected, while DE losses due to station availability and sensitivity changes can have a strong and dynamic effect. Characterizing these losses is thus shown to be an important step in any future research using this data set. Two case studies of storms on November 10, 2018, were investigated, demonstrating among other things the necessary assessments in using flash rate measurements in light of DE losses. Flash rate, clustering and lightning energy temporal evolution were presented and evaluated for these two storms. This description and characterization of the RELAMPAGO LF data set provide the foundation for its use in future research of RELAMPAGO storms, individually or in combination with other RELAMPAGO data sets. In particular, classification of the radio waveforms observed from the geolocated events can be used to study different lightning types, such as energetic IC lightning, in different RELAMPAGO storms. The LF flash data can also provide context to lightning evolution in storms when outside the coverage of other RELAMPAGO networks.

Data Availability Statement

RELAMPAGO LF, LMA, ABI, and GLM data sets used for this research are available in these in-text data citation references: Deierling et al. (2019, 2021), GOES-R Calibration Working Group & GOES-R Program Office (2017), GOES-R Series Program (2019) and Lang (2020). ENTLN data supporting this research are available upon request from Earth Networks (Earth Networks, 2020).

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