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The World Wide Lightning Location Network (WWLLN) over Spain

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Abstract. A study to determine the detection efficiency and location accuracy of the Worldwide Lightning Location Network (WWLLN) over Spain is presented by comparing data with those of the Meteorological Spanish Agency (AEMET), taken as a ground truth. The WWLLN operates a planetary distributed network of stations which detect lightning signals at a planetary scale. Very high currents from lightning strokes radiate strong Very Low Frequency (VLF) signals in the band 6-22 kHz, which are detected up to 10,000 km by the WWLLN stations. Two WWLLN stations operate in the Iberian Peninsula since 2012, which are supported by other stations at distances below 4000 km. The stations in the Iberian Peninsula are at a distance of around 800 km. This is a short distance in comparison with the typical distance between WWLLN stations in other areas, which is around 5.000-15.000 km. The WWLLN stations locate the time and position of the lightning stroke detected by triangulation, similarly as Global Positioning Systems do. Distances to each station are obtained by means of the time of arrival of the signal to the corresponding stations. A lightning detection is considered as a valid one when at least five stations detect it with a time and space coincidence with AEMET data of 0.5 s and 20 km, respectively. A study of the WWLLN performance for the whole area of Spain is carried out, obtaining that the detection efficiency of WWLLN is around 38% with a location accuracy between 2 and 3 km. The efficiency for high energy strokes is considerable higher. The results obtained for Spain are better than those obtained in previous studies in other areas of the World, which may be caused by the high density of stations in the Spanish region and its surroundings. A study for two reduced regions with different geographic features is also considered to assess the possible influence of the different typology of storms on the network features. Finally, an application of the WWLLN data for three major storms in 2020, 2021 and 2022 in the Mediterranean area of Spain demonstrates that the WWLLN is well suited for tracking the time evolution of adverse meteorological phenomena.

Keywords: Lightning, Geolocation, WWLLN, Global Lightning Geolocation, Terrestrial Monitoring Sensors, Atmospheric Electricity, Detection Efficiency and Location Accuracy of WWLLN in Spain.

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1 Introduction

The main objective of regional and national lightning location networks is the detection and tracking of Cloud-to-Ground (CG) lightning strokes. CG lightning strokes coexist with Cloud-to-Cloud (CC) and Intra-Cloud (IC) discharges, but the interest usually focuses on detecting the former, since CG discharges are those that mainly pose a danger to people and cause death and other economic damages, such as forest fire or other disasters. For instance, there were 1981 deaths in Spain during the period 1941-1981 which were directly caused by lightning (Núñez Mora et al. 2019). Lightning activity is also important in areas such as those of energy and telecommunications network management. In year 2023, the risk of forest fire was extremely high, due to the long period of drought affecting the Iberian Peninsula, therefore, lightning activity information may be of great interest to prevent fire (Benito-Verdugo et al., 2023; Pérez-Invernón et al., 2023; Rodrigues et al., 2023). On the other hand, lightning discharges are closely related to storm dynamics and provide much relevant meteorological information, relevance which is currently growing, when it seems that global warming is accelerating (Ciracì et al., 2023).

Global networks, such as Earth Networks Total Lightning Network (ENTLN), https://www.earthnetworks.com/, or the Worldwide Lightning Location Network (WWLLN), https://wwlln.net/, provide global Earth information for the purpose of monitoring these atmospheric phenomena and enabling users a faster location and warning of storms and other forms of severe weather hazards, such as tornadoes, downbursts, and hails, for instance. Knowing the accuracy of the data provided by these networks is very important for potential customers which are going to use or analyze those data.

Recent works clearly show the interest in the use of the WWLLN as a fundamental tool to study different geophysical aspects concerning the global lightning activity in the Earth. A comparison of the lightning activity in two areas of the Congo Basin during years 2012 and 2013 based on data from the WWLLN can be found in (Kigotsi et al., 2018). The capacity for analysis at a global scale is used in (Ccopa et al., 2021) to compare the lightning activity during years 2012 and 2013 with the Carnegie universal curve. The relation between storms, gravity waves, and their effect on the ionosphere is addressed in (Chowdhury et al., 2023) using data from the WWLLN and satellite observations from the Global Navigation Satellite System-Total Electron Content (GNSS-TEC). A local use of the WWLLN is presented in (Chowdhury et al., 2021), in which a study of the energetic electron precipitation in the Van Allen belts induced by lightning activity is carried out. New and unexpected studies naturally emerge from the existence of these global networks. In this sense, Jacobson and co-workers address the problem of identifying which part of the attenuation produced in the Extremely Low Frequency (ELF) band, from 5 to 20 Hz, is originated by reflections at the D layer of the ionosphere (Jacobson et al., 2021). It is precisely the information provided by globally-distributed stations such as those of the WWLLN which helps in designing a model to study the wave propagation in the natural electromagnetic cavity defined by the Earth's surface and the lower ionosphere.

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Currently, the performances of the WWLLN are well established for different areas of the Earth, including Brazil (Lay. et al., 2004), Australia (Rodger et al., 2004, 2005), New Zealand (Rodger et al., 2006), United States (Abarca et al., 2010), China (Fan et al., 2018), and part of the Western Hemisphere (Rudlosky and Shea, 2013; Thompson et al., 2014). However, the WWLLN technical performances at other regions are still missing. The main goal of this work is determining the performances of the WWLLN to provide accurate data for the study of lightning or related events in Spain and surrounding areas. To this aim, an initial comparative study will be carried out to determine the detection efficiency (DE) and location accuracy (LA) of the WWLLN over Spain, continental and insular regions, together with surrounding seas. The WWLLN data will be compared with independent ones, taken from the Meteorological Spanish Agency (AEMET), which will be considered as ground truth. This reference data from AEMET cover the period from 1st January 2012 to 30th April 2012, which were open data soon after a new WWLLN station, the 69th one, was installed by the University of Valencia and which is continuously operating since June 2011. Our work will show that the WWLLN provides an excellent detection efficiency (DE) and location accuracy (LA) in the area under study. Once the technical capabilities of the WWLLN in Spain are stablished, the WWLN will be used to monitor three strong lightning and hail activity events which affected the area of Valencia, at the East of Spain, in 2020, 2021, and 2022.

The paper is organized as follows. Section 2 describes the main characteristics of the WWLLN. Section 3 includes some details on the AEMET network used as reference. Section 4 shows and discusses the main results concerning the initial study of the WWLLN performances in Spain, determining its DE and LA parameters in three cases. The whole Spanish region is considered first and, then, two geographically different reduced regions are analyzed to assess the possible effects of geographic features on the storms and their detection. A final, more qualitative example shows the capabilities of the WWLLN network to successfully monitor the evolution of three severe storms which affected Valencia between 2020 and 2022. The main conclusions of the work are summarized in section 5.

2 The WWLLN: main characteristics and present knowledge

The WWLLN under study in this work operates a ground-based planetary-distributed network of stations with VLF antennas, which detect lightning electromagnetic signals around the Earth. Very high currents from lightning radiate strong VLF signals in the band 6-22 kHz, which are detected up to 10,000 km. The WWLLN was deployed by the University of Washington (USA) and the University of Otago (New Zealand), with the cooperation and maintenance of a large number of Universities and Research Institutions around the Earth. The distribution of associated stations around the whole Earth, around 70 stations, makes the WWLLN achieve global location of lightning strokes at a planetary scale with a constantly improved accuracy (Dowden et al., 2002; Lay et al., 2004; Jacobson et al., 2006; Rodger et al., 2005, 2006, 2009; Shevtsov et al. 2016).

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From an electromagnetic point of view, the Earth's atmosphere can be considered as an almost lossless volume located between the ground plane and the ionosphere. The system acts as a parallel plate waveguide with small losses, known as the Earth-Ionosphere Waveguide (EIWG). Lightning activity generates extremely high currents which excite electromagnetic propagating modes in the EIWG. Those modes resonating along the radial direction, i.e., between the ground and the ionosphere, have resonance frequencies controlled by the ionosphere altitude, h~90 km, and are known as sferic modes or, simply, sferics. For the fundamental mode, h is half the wavelength, which gives a resonance frequency of around 1.67 kHz. This fundamental mode together with the first higher order modes are located in the VLF range and may propagate long distances without significant attenuation. For this reason, the WWLLN stations are designed to detect propagating electromagnetic fields in the kHz range, a band where lightning strokes excite a large amount of power and losses are low, enabling their detection at distances around 10,000 km. This explains a successful operation of the WWLLN even when the distances between stations in the WWLLN were around 5,000-15,000 km before 2012. Finally, the detecting hardware of stations can take advantage of audio frequency systems (<20 kHz), such as soundcards, which are cheap and easy to obtain.

When a lightning stroke happens, a sferic mode is excited and the antennas and hardware of some of the WWLLN stations around the Earth detect a time limited electromagnetic signal in the VLF band, with a duration of milliseconds. The time of arrival of the signal from the source to the antenna of each detecting station is measured using the timing signal of a satellite Global Positioning System (GPS). This time of arrival is used to calculate the distance from the station to the signal source and, finally, the location of the source is obtained by triangulation, using the distance to several stations, similarly as other GPSs do. The detection of the sferic arrival at each station is a difficult task because of the back-ground noise. Therefore, improved trigger techniques are developed and combined with minimization methods in order to provide the correct timing of the arrival. The time of group arrival method and some improvements can be found in (Dowden et al., 2002) and in (Rodger et al., 2009). The lightning is processed and registered in the WWLLN system and is recorded as a correct detection if and only if the signal is simultaneously detected by a minimum of 5 stations.

The WWLLN had 40 receiving sensors in 2010, providing a DE~11% in 2010 for peak currents greater than 20 kA (Abreu et al., 2010) and a LA of around 5 km. The number of stations increased until an almost stable number of 70 stations since 2010, approximately. In particular, the WWLLN station at Valencia (Spain) was set in operation by the team at the University of Valencia in June 2011, being responsible of the maintenance of this station since then. This fact partially justifies the interest in assessing the still unknown performance of the WWLLN in the Spanish area, but it is not the only reason. Effectively, despite the global nature of the network would suggest that the WWLLN behavior would be similar to that known for other areas of the world, the density of stations is higher in Spain and surrounding areas and it is of interest determining if the performances are affected by this high number of stations.

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The WWLLN receiving sensors use a single 1.5 m whip antenna to measure the vertical polarization of the electric field associated to the sferic signal. The sensing procedure does not differentiate between CG and CC/IC discharges, since the whip antenna is sensitive to the vertical electric field and the two types of discharges show a similar behavior as regards this component of the electric field. The EIWG modes associated to the sferic signals are mainly excited by CG vertical strokes, although they may also be excited by strong IC and CC strokes. Therefore, differences between IC/CC and CG strokes are difficult to be inferred from the sferic signal and both IC/CC and CG are included in the signals measured by the WWLLN (Hutchins et al., 2012).

The WWLLN data are provided to customers and members of the WWLLN in ASCII and mat (Matlab^{TM}) files, giving the following information for each lightning stroke detected:

- Date and time in UTC. Time resolution is given in microseconds.
- Latitude and Longitude in degrees with four decimals.
- Residual fit time error in microseconds (<30 microseconds)
- Number of stations which detect the signal (a minimum of 5 stations).
- Root Mean Square (RMS) power estimation in kW from 7 to 17 kHz in 1.3 ms sample time.
- Power uncertainty (kW) in the power calculation.
- Number of stations which detect the stroke used for the power estimation. A subset of stations within the range less than 10,000 km distant from the stroke are used for the power estimation.

The whip antenna, the preamplifier, and the GPS are located outside the building on which the station is mounted. The preamplifier is wired to a soundcard. The soundcard is a typical commercial one inserted in the board of a desktop computer which has broadband connection inside the building. This computer processes the sferic time-domain signal combined with the GPS timing signal and transmits the data to the processing stations. The antenna is anchored to the steel structure of the building to have a good ground plane and thus provide a good signal-to-noise ratio in the sferic bandwidth (Dowden et al., 2002). The WWLLN receivers are designed to be sensitive to the vertical electric field from lightning strokes, minimizing the influence of magnetic induction. Therefore, the sensors show the important property of being strongly immune to artificial VLF magnetic fields (Lay et al., 2004), signals which are difficult to isolate from industrial machines, household appliances, and other electronic systems. Minimization methods are used to obtain the time of group arrival and lightning locations. The quality of these data is given by the residual fit time error, lower than 30 µs (Dowden et al., 2002; Rodger et al., 2005; Rodger et al., 2009). Finally, the current of the lightning stroke is calculated by means of the detected electric field and is also available in the WWLLN data since 2012.

Prior to address with this work the task of determining the features of the WWLLN in Spain, let us consider the present knowledge of this network and its performance in different areas around the world. As mentioned before, there is a reduced set of bibliography in which the WWLLN DE and LA are analyzed. The more relevant among these studies are summarized in Table 1, which includes details on the time period of the study, the area of assessment, the number of stations available in the WWLLN at that moment and the time-difference and spatial-distance criteria for considering the detected stroke coincident with a lightning stroke of the reference network. The network features in each specific area summarized in Table 1 by means of two parameters: the DE and the LA. It is worth noting that these two quantities must be considered as global values, since they correspond to the detected lightning strokes, independently of their current peak amplitude. More specific information on the dependence of the DE on the current peak amplitude can be found in the works referenced in Table 1. In these works, the WWLLN results are mainly compared with data from other terrestrial networks and, to a lesser extent, with satellite detection systems. These reference terrestrial networks operate continuously at a national or regional scale, while the information coming from satellites is not global and it is only available at limited periods of time, since these systems orbit over a certain area of the Earth at specific times. In addition, they mostly detect Intra Cloud and Cloud to Cloud (IC/CC) flashes with photodiode detectors embedded in the satellite (Suszcynsky et al., 2000; Rudlosky and Shea, 2013; Thompson et al., 2014).

From a general point of view, the details reported in the studies in Table 1 show interesting results which must be taken into account when using data from the WWLLN. As regards the influence of the distance at which the lightning stroke happens, the work by (Rodger et al. 2006), the founders of the WWLLN, reveals a decreasing DE in the daytime for stations beyond 8,000 km and the DE being negligible for stations beyond 14,000 km. However, the DE was good between 10,000 km and 12,000 km during night time, which is a valuable data to decide the geographical distribution of stations. As regards the effect of the lightning stroke energy, low energetic strokes may be dismissed mainly due to the attenuation when distances are large. Therefore, an improvement in DE and LA for high energy strokes is expected, well above the low values included in Table 1 which correspond to all the lightning strokes detected, independently of their peak amplitude.

Focusing on the results shown in Table 1 and references therein, they report a very low DE for the WWLLN measurements, which is in the order of the one percent of the total detected lightning strokes by the reference networks. This is a shortcoming of WWLLN, but it must be taken into account the global scale nature of the network compared with the local or regional scale of the reference agencies. Moreover, the DE has large variations depending on the area of the Earth. Large differences are found in the DE and LA estimations shown in Table 1. The DE was assessed at 0.3% in March 2003 in Brazil (Lay et al., 2004), while the assessment reported in Florida between April and September 2004 was about 4% for currents larger than 50 kA in absolute value (Jacobson et al., 2006). The best data recorded by WWLLN so far was a DE of 31% in the Pacific Ocean in January 2010 (Rudlosky and Shea., 2013). The discrepancies in the results may be due to changes in the number and geographical distribution of WWLLN sensors, since the network has increased the number of sensors over the years. There were eleven stations in the first evaluation in 2003, a number which was augmented to twenty stations in 2004. Differences seem to be also related to increasingly sophisticated processing techniques (Rodger et al., 2004, 2005, 2009). Moreover, the WWLLN has changed the distribution of active receiving sensors in different areas of the Earth. Other explanations for the

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discrepancies may be due to the assumed "ground truth" of the different networks used to compare with WWLLN (Abarca et al., 2010), some of them reporting a DE with errors assumed to be between 80%-90% (Lay et al., 2004; Brundell et al., 2002; Rodger et al., 2006). The technology deployment is focused in the detection of CGs, with exception of Los Alamos Sferic Array (Jacobson et al., 2006), which DE is similar for both CG and CC/IC strokes. As regards the national and regional networks used as reference, they are mainly devoted to the detection of CG strokes and make very coarse estimations of CC/IC strokes. In (Rodger et al. 2004, 2005) and at a regional scale, there were estimated 3.5 times more CC/IC strokes than CG ones (Mackerras et al., 1998; Soriano and de Pablo, 2007) and the WWLLN ratio of the detected CG versus CC/IC events was estimated to be roughly 2:1 (Hutchins et al., 2012b).

Table 1. WWLLN performance compared with other networks between 2004-2022.

Authors	Time Period	Area	Available Stations	Criteria	DE (%)	LA (km)
Lay et al., 2004	6, 7, 14, 20, 21 March 2003	Brazil 40°-55°W, 15°-25°S	11	3 ms, 50 km	0.3	20.25 ± 13.5
Rodger et al., 2004	23, 24 Jan. 2003	Australia 142°-154°E, 25°-37°S	11	3 ms, 50 km	1.0	30.0
Rodger et al., 2005	13 Jan. 2004	Australia 142°-154°E, 25°-37°S	18	3 ms, 50 km	13.0	3.4
Rodger et al., 2006	1 Oct. 2003 to 31 Dec. 2004	New Zealand 165°–180°E, 34°-49° S °	26	0.5 ms	5.4	-
Jacobson et al., 2006	27 Apr. to 30 Sept. 2004	Florida Circle with radius of 400 km	19	1 ms, 100 km	<1.0	15.0 - 20.0
Abreu et al., 2010	1 May to 31 Aug. 2008	Canada, 41.78°–45.78°N, 77.48°–81.48°W	29	0.5 s	2.8	7.24 ± 6.24,
Abarca et al., 2010	5 Apr. 2006 to 31 Mar 2009	United States 25°– 45°N, 75°– 125°W	38	0.5 s, 20 km	6.2	NS(4.03), EW(4.98)
Rudlosky and Shea, 2013	1 Jan. 2009 to 1 Jan. 2012	Western Hemisphere 38°N–38°S, 165°E-17°W	38-66	330 ms, 25 km	≤9.2	11.0
Thompson et al., 2014	1 Jan. 2010 to 30 Jun 2011	Western Hemisphere 38°N–38°S, 165°E-17°W	38-66	0.4s, 0.15°	≤20	-
Fan et al., 2018	1 Jan. 2013 to 1 Jan. 2015;	China 24°–40°N,93°–105°E	70	0.5 s, 50 km	10.0	9.97 ±0.54,
Kigotsi et al., 2018	2005-2013	Congo Basin 4° S-1° N, 25° E-30° E 4° S-1° N, 18° E-23° E	11-67	0.5 s, 50 km	≤7.5	-

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As regards the effect of the lightning stroke energy, the DE of the WWLLN rises with increasing stroke peak current for both positive and negative CG lightning strokes, as it is first discussed in (Rodger et al. 2006) and later in (Fan et al. 2018). In fact, results shown in Table 1 report low values of the DE ranging from values around 1% to 20%, as mentioned above, partially due to the fact that this figure is a global value for all peak amplitudes. In addition to the summary data presented in Table 1, details in these studies referenced therein show that the WWLLN DE is above 50% for CG strokes with currents greater than 40 kA, with a large variability depending on the region, providing a spatial accuracy of around 15 km. Another interesting fact also mentioned in these works is that the DE is always higher over the Oceans, although some variability is observed with the seasons (Rudlosky and Shea., 2013). The same is observed in (Thomson et al., 2014), where higher values were obtained for the Pacific and Atlantic Oceans. This DE for high peak currents is good enough to resolve convective-storm cells within a larger storm complex, a large, circular, long-lived cluster of showers and thunderstorms that can cover a large region and lasts more than 12 hours. A storm complex often emerges during the late-night and early-morning hours, it is identified by satellites and it is characterized by heavy rainfall, wind, hail, lightning and, possibly, tornadoes (Jacobson et al. 2006).

The choice of the time- and spatial-coincidence criteria is crucial and affects the results in the DE and LA (see Fig. 1 of Thomson et al., 2014). It strongly depends on the characteristics of the available reference data. In this context, (Fan et al., 2018) presents a comparison of WWLLN data with two reference measurement sets: data from national terrestrial sensors and data from satellite observations. In doing the comparison with the terrestrial network, the coincidence between lightning strokes is constrained to events happening within a time difference of 0.5 s and a distance of 50 km, however, the comparison with satellite data is not filtered for a distance of 50 km and provides better accuracy in determining the distance of the lightning stroke. As mentioned above, the WWLLN stations are expected to detect VLF signals generated at distances of around 10,000 km. However, their effectivity worsens for low amplitude strokes, therefore, the geographical distribution of the stations may affect the network features. This is a simplistic explanation, because there is influence of the propagating conditions, land or water, and the noise environment in the station. However, a trend is observed in the DE in the work by Kigotsi et al (2018), by comparing using the Lightning Imaging Sensor (LIS), where the DE increases from around 2% to 6% between 2005 (23 WWLLN sensors) and 2013 (67 WWLLN sensors) in the continental areas of Congo Basin.

Concerning the study presented in this work, 69 WWLLN stations were operative around the world at the time period considered, year 2012. As regards the area under study, Spain, the six most relevant stations for our analysis are shown in Fig. 1. Three stations, represented with green dots, were already operative in 2012, located in Valencia (Spain), Lisbon (Portugal), and Sheffield (England). Three new stations were deployed later, between years 2020 and 2022, shown with white dots in the figure. These new stations were deployed at Gijón (Spain), Tihany (Hungary), and at the Eastern Mediterranean, at around 4,000 km, deployed by the Tel Aviv University. Other stations from the National Spanish, Portuguese and French National Agencies which will be used as reference are also shown with red, yellow and blue dots, respectively. It is worth noting that this distribution of WWLLN stations is denser than that of other areas, where stations are deployed at distances of

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around 10,000 km. This high density may affect the features of the WWLLN in this region, not only because of an improved measurement capability, but also because of the increase in the available stations, which raises the chance of a stroke being simultaneously detected by at least five stations, and thus being registered as a valid stroke.

3 The reference station: the AEMET

The WWLLN performance in Spain will be determined by comparing its data with those measured by AEMET, so let us briefly describe the main features of this meteorological national agency. AEMET's sensors are spaced at distances of less than 400 km, distances well suited for the dimensions of the whole area of Spain, both the continental and the insular regions. These sensors detect the low frequency (LF) emissions of lightning. LF is the International Telecommunication Union (ITU) designation for radio frequencies (RF) band, the range between 30 kHz and 300 kHz. The LF signals from lightning strokes are intense and propagate with little attenuation as surface waves over the Earth's crust. Localization of lightning strokes is carried out by AEMET using IMPACT LF sensors (IMPACT ES /ESP and LS7000/7001 of VAISALA). These sensors are produced by Vaisala (https://www.vaisala.com/en/products/systems/lightning/single-point-sensors), which is a company specialized in equipment for lightning detection. This equipment is employed in around 45 national networks worldwide. The procedure starts determining the direction from which the electromagnetic signal arrives using a Magnetic Direction Finder (MDF) (Orville & Huffines, 1999; Cummins et al., 1998, Pérez-Puebla, 2004a, Pérez-Puebla, 2004b; López-Diaz et al. 2012; Cummins et al., 2009). Using the information received by at least two sensors, the intersection of the lines determines the location of the lightning. In addition, the propagation time of the signal to the sensor is determined, which depends on the distance of the sensor to the surface impact point of the discharge. Using the information from two sensors, the time of arrival delay between them determines a hyperbola with the possible locations of the discharge and the intersection of the different hyperbolas will define the possible discharge location. At least, four sensors are needed so that the location is not too ambiguous. Finally, to optimize the location, the intersection of circles is used instead of hyperbolas. Both techniques, MDF and time of arrival, are combined to obtain a better accuracy in the stroke location.

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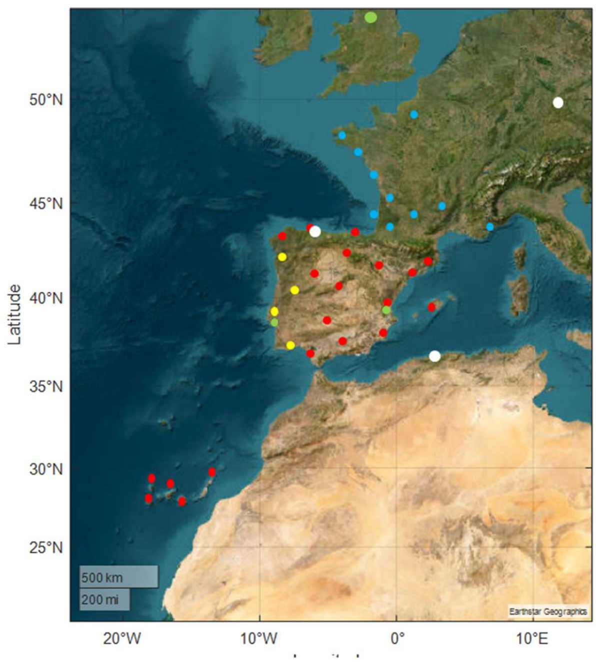

Figure 1: WWLLN and national lightning detection networks in Spain and surrounding areas. The green color circles correspond to the WWLLN sensors in 2012 and white circles represent the new WWLLN sensors deployed between 2020 and 2022 relative to 2012. Red circles show the positions of the AEMET sensors in 2012: 14 sensors in continental Spain, 5 in Canary Islands, 1 in Mallorca. Four sensors of IPMA in Portugal are shown in yellow color, while blue color shows the 10 sensors of Météo France.

The AEMET's lightning detection network is made up of twenty electric discharge detectors distributed throughout the peninsular territory (14), the Balearic (1) and Canary archipelagos (5) (Orville and Huffines, 1999; Cummins et al., 1998; Pérez-Puebla, 2004; López-Diaz et al. 2012). These detectors capture, analyze and discriminate the electromagnetic radiation generated in atmospheric electrical discharges occurring within their range, between 50 km and 1,000 km. Through collaboration agreements, information is also received from four sensors belonging to the network of the Portuguese meteorological service (IPMA) and from ten sensors of the French meteorological service (Météo-France) (Rodrigues et al., 2010; Santos et al., 2013; Núñez et al, 2019). The map with these sensors is shown in Fig. 1, which also shows the position of WWLLN sensors in 2012 and 2024. These data are integrated into the system and allow optimal coverage of the entire Iberian Peninsula and the surrounding seas. Through several current technological innovation projects carried out by AEMET, some of the detectors are being replaced by others with higher technology features (Núñez et al., 2019).

The CG lightning detection probability of this type of network ranges between 85% and 95%, while his localization accuracy ranges from 100-200 m to 1 km. Likewise, the median of the peak intensity (maximum value of recorded electrical intensity) has an accuracy error of about 15-20% and the accuracy in determining the polarity (sign of the electrical discharge) is 100%. As regards high-intensity lightning strokes, intensity greater than 5 kA, a detection efficiency of more than 90% is achieved with a LA value much lower than 0.5 km (Rodrigues et al., 2010; Santos et al., 2013).

The networks detect and keep track of lightning stroke events, providing the time and geo-location, together with information on the originating current. The raw data files in ASCII format containing this information for each lightning stroke were available in the web page of AEMET until the end of year 2012. The data used in this work as ground truth for comparison with our WWLLN data have been obtained from the AEMET web page at that time for the area of Spain. These open data provided the time of the events with 1 s time resolution, together with information about the current for the first stroke. The lightning strokes from the AEMET network during the period January 1, 2120 - April 30, 2012 are shown in Fig. 3 as green dots on the terrestrial map in the area of latitude [32°N, 45°N] longitude [20°W, 5°E], in which the spatial filtering for Spain is clearly visible.

The interest of national and regional agencies used as reference is directed to the detection of CG lightning, disregarding the detection of IC/CC strokes. The IC/CC lightning strokes were initially registered by the stations, however, most of them were discarded at post-processing by taking into account its calculated current. Some IC/CC lightning strokes could not be filtered out because of their strong current, as it happens in the USA National Lightning Detection Network (NLDN) and the Canadian National Lightning Detection network (CLDN) (Abarca et al., 2010; Fleenor et al., 2009). Thus, an unknown reduced percentage of IC/CC is included in the files. There are roughly 5 to 10 times as many flashes that remain in the cloud as there are lightning strokes which travel to the ground (Núñez et al., 2019). There is not a clear current threshold to differentiate CG from IC/CC, which explains the small percentage of IC in the data. Some proposals have been made (Rakov & Uman, 2003) to distinguish between IC/CC or CG by analyzing the rate of change of the electromagnetic field, which can be obtained from the time-domain measurement of the signal. The misclassification IC/CC-CG was first addressed in 1994/1995 by the USA NLDN (Cummings et al. 1998; Wacker and Orville 1999; Jerauld et al. 2005; Orville et al. 2002; Cummings et al. 2006; Biagi et al. 2007). Typically, low current IC/CCs are erroneously classified as CGs, and some proposals were made to discard positive CG strokes with peak currents less than 10 kA, or reclassify them as IC (Grant et al. 2012).

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4 The WWLLN performance in the area of Spain

A study concerning the features of the WWLLN in different areas of Spain is presented and discussed in this section, followed by an example of application of the WWLLN stations. First, the network performance is studied for the whole Spanish area during 2012, son after the Valencia station was deployed by two authors of this work. Storms are strongly affected by geographic features. Two qualitatively different regions are considered then to study this influence on the storms or on their detection. In this sense, a second similar study is also included concerning a reduced and geographically uniform region, the Plateau Spanish region. The third study considers the opposite situation: a reduced region at the mediterranean coast of Spain which includes a transition between a coastal and a maritime region in which severe storms usually happen at the beginning of autumn. Finally, a study to assess the capabilities of the WWLLN to monitor three severe storms at Valencia, at the East coast of Spain, in 2020, 2021, and 2022, is presented. Fig. 2 describes the different areas of these studies. Red and orange for the first study, the green region is the Plateau region of the second study and the cyan rectangle depicts the area at the East of Spain of the third study and the monitoring application.

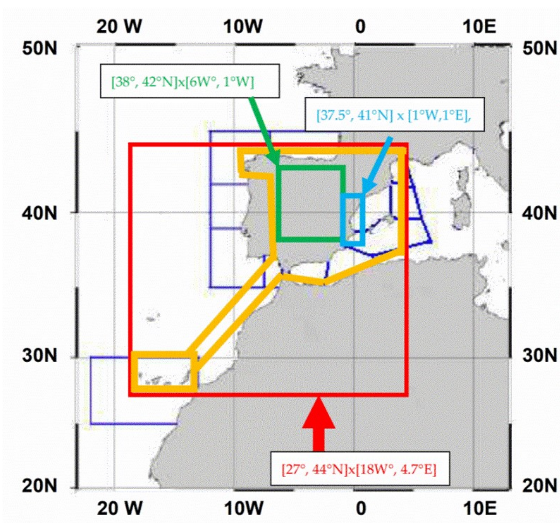

Figure 2: Blue lines define the typical areas covered by the AEMET network. Yellow lines enclose AEMET data during the period January-April 2012. Red, orange, green, and cyan lines define the areas of WWLLN data used in the three studies presented in this work [27°, 44°N]x[18W°, 4.7°E], [38°, 42°N]x[6W°, 1°W] and [37.5°, 41°N] x [1°W, 1°E], respectively.

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4.1 Detection Efficiency and Location Accuracy of the WWLLN in Spain

The WWLLN performance in the area of Spain is first analyzed using data from this network (http://www.wwlln.com) during the period from 1st January 2012 to 30th April 2012. The data were generated using the most recent technique described in (Rodger et al., 2009). Two reasons support the choice of this time span. First, data from AEMET were openly available to the authors at that period, and second, this period was close in time to the moment at which the station in Valencia (Spain) was deployed by the team of this work in the year 2011. The objective is to determine the detection efficiency of the WWLLN in the whole region of Spain, including continental and insular regions, using the AEMET data as true data (Abarca, 2010).

The time span of the lightning data chosen is usually a period with low seasonal activity in Iberian Peninsula. The main storm activity in Iberia prior to 2012 was typically distributed in the period May-September, in which around 84% of the storm phenomena with lightning events were detected (Soriano et al., 2005). Although the period under study had a low activity in terms of lightning strokes, the AEMET data contain a significant number of 20,651 lightning strokes in the whole Spanish region. The 2012 AEMET data file has 20,651 lines, each line has 9 columns with the following data: month, day, hour, minute, second, discharges, peak current, latitude, and longitude.

To analyze the WWLLN detection efficiency relative to the AEMET network, we look for time and location coincidences within a given deviation to identify the strokes events shared by both networks. Several criteria have been used by different authors to define shared lightning strokes and, thus, to establish a coincidence. The particular criterion chosen greatly depends on the characteristics of the available data of the independent networks. These reference networks are assumed to provide true data, since their certainty is reported to be above 90%. Obviously, the coincidences in time and location are used with a given tolerance or deviation from the ground truth. Lay et al. (2004) and Rodger et al. (2005) used both a time deviation of 3 ms and a space deviation of 50 km to establish the coincidence. Jacobson et al. (2006) used a time gap within 1 ms and a maximum distance of 100 km. When the data available have a high temporal resolution, the time criterion alone seems good enough to establish shared events, i.e., there is no need of using a combined spatial coincidence. This explains why the work by Rodger et al. (2006) for New Zealand and Abreu et al. (2010) for the area of Toronto only impose a time difference of 0.5 s to decide coincident events.

As regards the study in the area of Spain presented with this work, the lightning activity data available from the AEMET have a time resolution of 1 s. This coarse time resolution forces the use of both temporal and spatial coincidence criteria to ensure confidence in this analysis. As the AEMET data were given with a resolution of 1 s, we establish a maximum time difference of 0.5 s between AEMET and WWLLN strokes to define the temporal coincidence. This large time tolerance is far from the

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range 0.5 ms - 3 ms used by other researchers (Rodger et al. 2005, Jacobson et al. 2006, and Rodger et al. 2006), however it is the same as in (Abreu et al., 2010; Abarca et al., 2010), and the more recent work by Fan et al. (2018). This time coincidence is combined with a spatial coincidence of 20 km. Therefore, a WWLLN lightning stroke is shared by the AEMET reference if both events happen with a difference in time lower than 0.5 s and the distance between them is below 20 km.

In this first assessment study, the region of the world under consideration is the whole area of Spain and small near areas of the Atlantic Ocean and the Mediterranean Sea, inside the latitude interval 27.39°N-43.83°N and longitude interval 18.01°W-4.66°E (red rectangle in Fig. 2). The limits of this rectangular area are defined by the maximum and minimum latitudes and longitudes of the AEMET available data, which are spatially filtered to reduce to the non-rectangular orange region in Fig. 2, exclusively describing the Spanish area. As regards the WWLNN network, it collects global Earth data, therefore, the very large files contain all the registered events, therefore, these data must be geographically filtered to obtain data for this same area.

Figure 3a depicts the lightning strokes detected by AEMET in the Spanish orange region of Fig. 2 during the period January 1, 2012 - April 30, 2012, located as green dots in the map. The green dots in Fig. 3a comprise a total of 20,651 lightning strokes, which serve as reference for the WWLLN data during the above-mentioned time period. We look for the WWLLN lightning strokes that are coincident with AEMET data following the above-mentioned criteria of time coincidence and spatial coincidence. In the WWLLN, lightning data events around the whole Earth are stored in files on a day-to-day basis. Each file corresponds to one day and has a size of about 30 Mb. Therefore, we first obtain the WWLLN files for the period January 1, 2012 to April 30, 2012, which occupy a total 8.1 Gb. Later on, we filter the data of these files to extract the data inside the area defined by [27.39°N, 43.83°N] x [18.01°W, 4.66°E] (red area in Fig. 2). This data file is a smaller one, with a size of 2.7Mb and includes 54,079 lightning strokes. This last file was used for further processing in order to compare it with the AEMET data. Although it does not correspond to the same geographical area yet, it has a manageable size. Finally, this file was spatially filtered with the AEMET spatial filter (orange region of Fig. 2), providing a small file having the WWLLN data reduced to the Spanish region, with a total of 12,855 lightning strokes.

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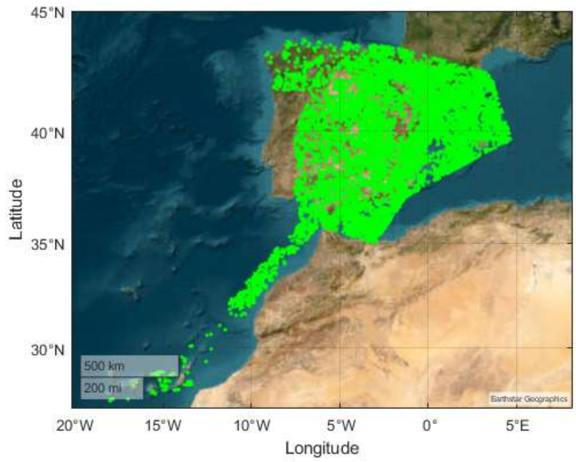
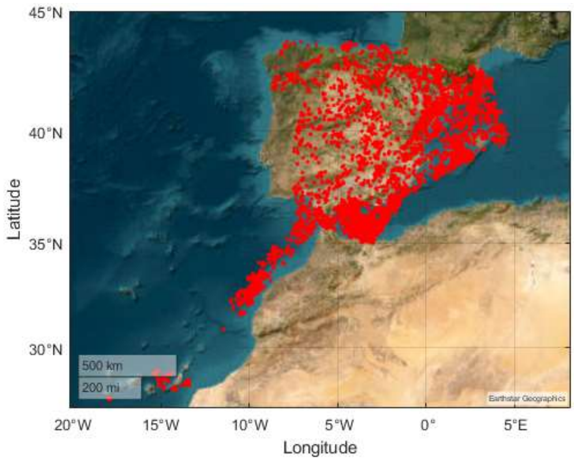


(a)



(b)

400 **Figure 3: (a) Lightning strokes detected by the AEMET network during the period January 1, 2012 - April 30, 2012. (b) Strokes detected simultaneously by the WWLLN and the AEMET networks during the period January 1, 2012 - April 30, 2012.**

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To look for events shared by the WWLLN and AEMET, a correspondence is searched for in the file of the AEMET data for each lightning stroke in the file of WWLLN data. In the first stage, we look for temporal coincidence of each WWLLN stroke with AEMET strokes, using a maximum time deviation of 0.5 s. In the second step, the maximum distance of 20 km between the WWLLN and AEMET stroke is checked. In doing so, we obtain 7,843 WWLLN lightning strokes which match with one of the 20,651 lightning strokes detected by AEMET. These coincidences are plotted in Fig. 3b and are used for further analysis and to determine the DE and the LA. These 7,843 coincidences represent 61% of the total of 12,855 lightning strokes registered by the WWLLN filtered in the AEMET territory, and yield a WWLLN DE of 38%, relative to the AEMET network. The rest of lightning detections of the WWLLN can be considered true detections without any comparison frame, most likely because they are CC/IC lightnings, which can be detected by the WWLLN but not by AEMET. This DE for the WWLLN in Spain is a considerable good result when compared with those included in Table 1. This significantly high value may be partially explained by the fact that the density of WWLLN stations in the region of Spain and surrounding areas is considerably greater than in the areas described in Table 1. Effectively, we have a distance around 800 km for two stations in Spain, while the stations in other areas are typically separated by distances around 10,000 km. In addition, the increase in near stations raises the chance to fulfil the requirement of simultaneous detection by five stations to accept a stroke as a valid one.

The distribution of the detected lightning strokes, according to above criteria, are presented in Fig. 4. It resembles a clear Rayleigh distribution, a distribution typical for nonnegative-valued random variables. This distribution is often observed when the over-all magnitude values are related to two independent components. This is our case, where the location error depends on two parameters, latitude and longitude. The detection error has a maximum probability at 3.5 km for the interval 0-20 km.

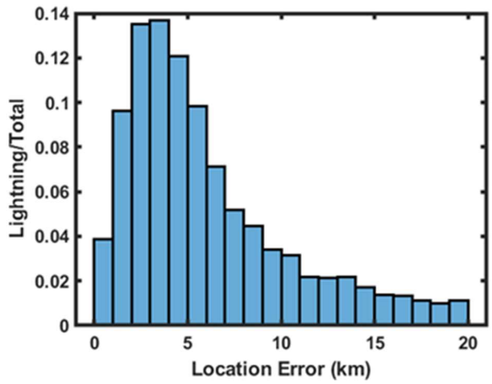

Figure 4: Location error for the lightning strokes and probability distribution for the WWLLN correctly detected according to the criteria 0.5 s-20 km.

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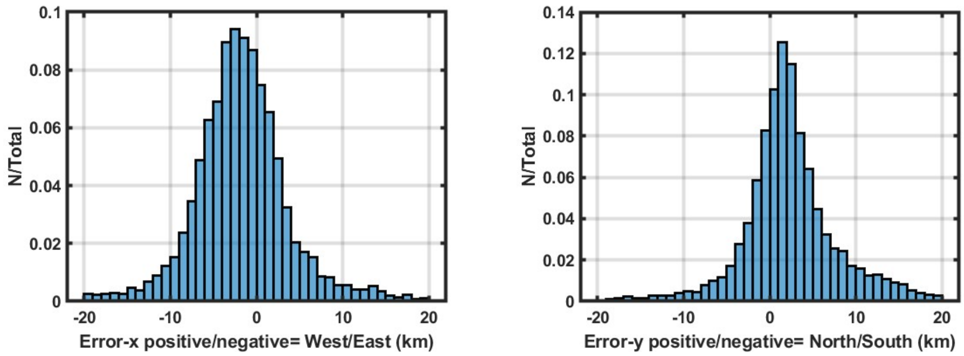
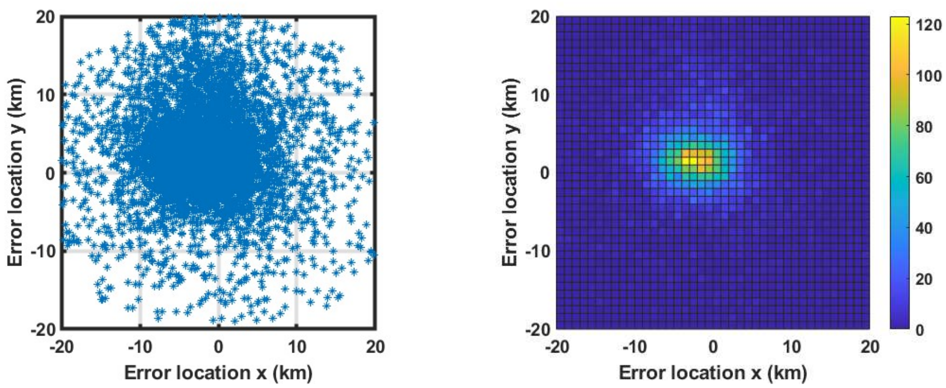
The distribution of locating errors along longitude (Δx) and latitude (Δy) are shown in Fig. 5.a-b and as a scatter plot in Fig. 6, in which a slightly systematic error in the location is observed in northward and westward directions. The standard error is larger in the East-West direction, since the Gaussian broadens in the East-West error.



(a) (b)

Figure 5: Location error along longitude and latitude: (a) Error in km along longitude. (b) Error in km along latitude.



(a) (b)

Figure 6: Location error for the lightning strokes along *x*-longitude and *y*-latitude, at region [27°- 44°N] x [18W°- 4.7°E]. (a) Error in km. (b) Color code showing the number of lightning strokes at each *x*-*y* error.

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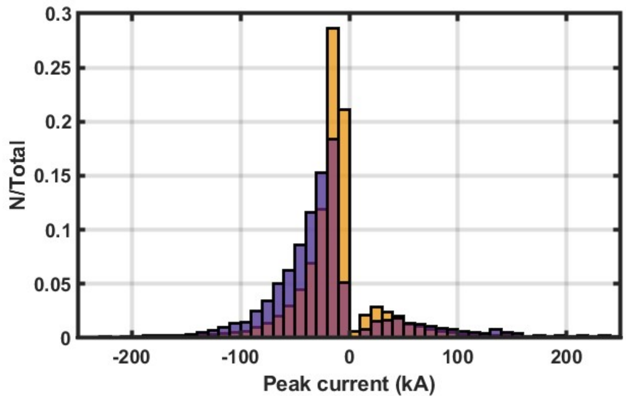

Figure 7: Distribution of AEMET return strokes by the WWLLN, in blue color, and total AEMET return strokes, in orange color.

Quantitative data concerning the LA for the WWLLN at Spain can be inferred from the Gaussian shaped probability distributions depicted in Fig. 6. More specifically, the average error along the East-West direction is Δx=-1.7 km (minus is a deviation towards west), 95% confidence interval [-1.9, -1.6] km, while the average error along the South-North direction is Δy=2.3 km, 95% confidence interval [2.2, 2.4]. The deviation is larger along East-West (σ_x =5.7 km) than along South-North directions (σ_y =5.3 km).

The distribution of AEMET strokes in bins of 10 kA, together with the distribution of strokes detected by the WWLLN, is shown in Fig. 7. The distribution of peak currents is shifted towards negative strokes, which is in good agreement with references of Table 1. There are 3,471 CG positive lightning strokes (positive peak current), versus 17,180 negative lightning strokes in the AEMET data, a 16.8% of the detected CG strokes. The same ratio is preserved for the subset of 7,843 strokes detected by the WWLLN. The figure shows the usual distribution of negative and positive CG strokes: nearly 90% of the global lightning activity corresponds to negative peak currents. The average negative peak current in negative CG is -25.40 kA and in positive CG is 8.59 kA in AEMET data, while for the matched WWLLN, the average results are -39.53 kA for negative CG strokes and 13.43 kA for positive ones. These results show a clear shift of the WWLLN operation towards detection of high-energy lightning strokes.

To establish the dependence of the network features on the energy of the lightning strokes, the distribution of the DE is calculated in bins of 2 kA. The result is mapped in Fig. 8, where each point (red circles) represents the DE for an interval of 2 kA. These discrete results are smoothed with a five-point mobile average (line in blue color) and standard errors in bars are also included. The information provided by both data in Fig. 8 shows that the DE increases with the peak current, however,

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for both positive and negative high energies, above 100 kA, the DE looks slightly noisy, which is likely due to the small amount of available data (see Fig. 7 for peak currents greater than 100 kA in absolute value). Despite these slight fluctuations observed for high energy lightnings, Fig. 8 shows that the DE of the WWLLN is also remarkably good for lightnings with high peak currents, the more dangerous ones. Results of Fig. 8 are very similar to previous works referred to in Table 1 (Abarca et al., 2010; Rodger et al., 2006; Fan et al., 2018).

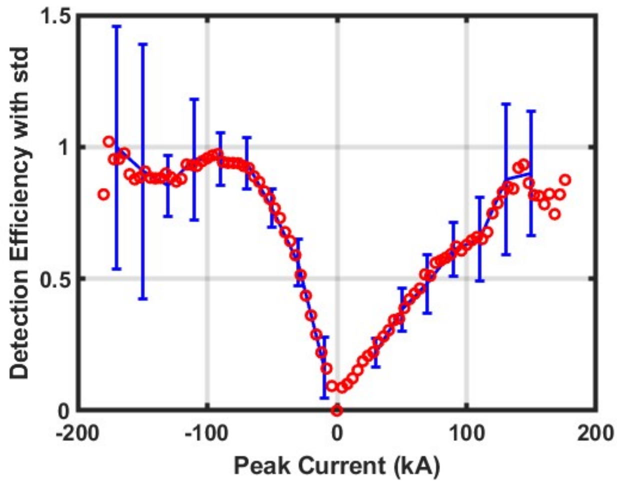

Figure 8: Detection efficiency of the WWLLN versus lightning stroke energy. Data correspond to a bin size of 2 kA. Data smoothed are shown with the blue line.

4.2.- Detection efficiency and location accuracy in two reduced areas: The Spanish Plateau and the East coast of Spain.

In order to address the possible effects of geographically features on the DE and the LA, we now restrict the analysis to a pair of particular regions with different geographical characteristics. First, a smaller rectangular area inside the continental area of Spain, a plateau region with a homogeneous geographical shape. Second, a small part at the Valencia coast, at the East of Spain, which describes a transition region between the coastal East of Spain and the Mediterranean Sea. The differences in the geography in both regions produce important differences in the climate at these two reduced regions. The aim of this subsection is to determine if these differences are reflected in the DE and the location error of the WWLLN.

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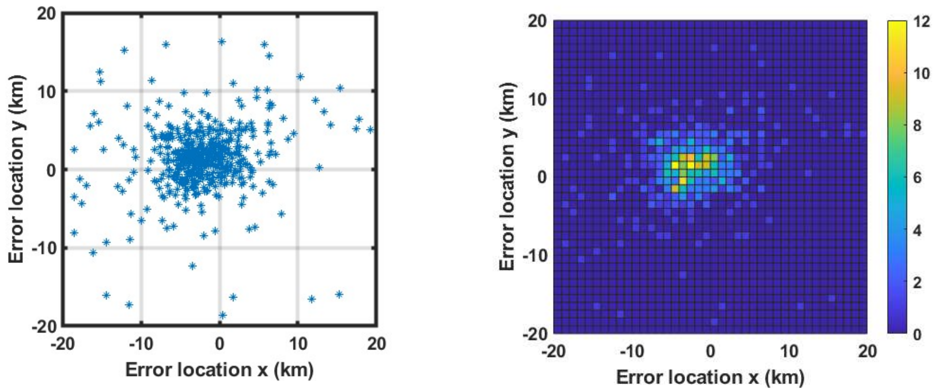
The first region considered is defined by latitude [38°, 42°N] x longitude [6°W, 1°W], which is inside the plateau area of the Iberian Peninsula (green rectangle in Fig. 3). Geographically, it is a homogenous region which avoids the main mountainous regions. In this case the AEMET file contains 3,389 lightning strokes, while the WWLLN file has 1,229 strokes. There are 493 coincidences, which are 14.5% of the lightning strokes recorded by AEMET and 40% of the lightning strokes detected by the WWLLN.

Figure 9 shows the errors along latitude and longitude for this reduced area. The results in this figure yield an average location error along the East-West direction of Δx= -2.3 km, confidence interval of 95%, [-2.8, -1.8], and deviation σ_x=5.6 km. The average location error along the South-North direction is Δy=1.4 km, confidence interval of 95%, [1.0, 1.7], with deviation σ_y=4.2 km. These results for Δx and Δy are not significantly different from the results obtained using the larger area. However, the results for the scattered plot of Δx, Δy seem better than previous ones, with lower standard deviation, as can be seen by the differences between Figs. 6 and 9. Effectively, Fig. 9 shows data more concentrated around their mean value than those represented in Fig. 6, which corresponds to lower standard deviations and, therefore, better location error. For this area, the average negative peak current in negative CG strokes is -17.92 kA and 10.26 kA in positive CG ones for the AEMET data. As regards the matched WWLLN strokes, the corresponding average results are -28.23 kA for negative CG strokes and 31.01 kA for positive CG strokes. In this area, the differences in absolute value between positive and negative CG lightning strokes is lower than in the former larger area. This is probably related to the different characteristics of the storms and more likely due to the influence of geographic features than to the characteristics of the sensors.



(a) (b)

Figure 9: Location error for the lightning strokes along *x*-longitude and *y*-latitude for the plateau region, [27°, 44°N] x [18W°, 4.7°E]. (a) Error in km; (b) Color code showing the number of lightning strokes at each *x*-*y* error.

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Finally, a third region including coastal and maritime parts is considered. The region under study correspond to a small area of the Spanish Mediterranean coast, longitude and latitude given by [37.5°, 41°N] x [3°W, 2°E], which is plotted with cyan color in Fig. 2. The comparative study of the lightning activity detected by the WWLLN with the AEMET data provides similar results as those shown in Fig. 9 (not represented) with a DE of 25%. As regards the location error, the results yield an average location error along the East-West direction of Δx= -1.8 km, confidence interval of 95%, [-2.1, -1.5], σ_x = 5.4. The average location error along the South-North direction is Δy=2.1km, confidence interval of 95%, [1,9, 2.4], σ_y = 4.8. These results for Δx and Δy are not significantly different from the results obtained using the larger area, however the results for the scattered plot of Δx, Δy seem better than previous ones.

Table 2 summarizes the efficiency and location error for the three regions studied in subsections 4.1 and 4.2 according to AEMET reference data from 2012. Similar values are observed for the location accuracy. As regards the efficiency, the comparison of the two reduced areas suggests that the better results obtained for the coastal region may be originated by the typically more intense atmospheric phenomena occurring in this region when compared with those at the plateau region. The comparison with the DE of the global region of Spain, with a greater value of 38%, probably due to influence of the Atlantic area, draws attention on the variability of this efficiency. However, it is worth noting that, according to results shown in Fig. 8, high energy strokes, the most dangerous ones, are expected to be properly detected in all the regions.

Table 2: Location accuracy and Detection Efficiency for the WWLLN in three studies of subsections 4.1 and 4.2. Comparison is made with AEMET reference data from 2012.

Region	Est-West Δx	95% CI	South-North Δy	95% CI	DE %
Spain (orange in Fig.2)	-1.7	[-1.9, -1.6]	2.3	[2.2, 2.4]	38
Spanish plateau (green in Fig. 2)	-2.3	[-2.8, -1.8]	1.4	[1.0, 1.7]	14.5
Mediterranean Spanish coast (cyan in Fig. 2)	-1.8	[-2.1, -1.5]	2.1	[1.9, 2.4]	25

4.3.- Three severe meteorological events at the Spanish Mediterranean coast.

Once the technical features of the WWLLN are determined, the network data can be useful in different applications. The following is an example of the use of the WWLLN to monitor the evolution of three major lightning and hail storms that affected the Valencia region the following days: April 18, 2020, August 30, 2021, and August 17, 2022. The region under study is the small area of the Spanish Mediterranean coast considered in the last study of the previous subsection, plotted in cyan color in Fig.2.

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Figures 10 to 12 show the results for the three storm events. Figures 10a, 11a, and 12a are taken directly from AEMET, while Figs. 10b, 11b, and 12b have been generated with WWLLN data. In these figures, the locations of the lightning discharges are indicated with dots. The color code is used to temporally locate the lightning discharges in one-hour bands. For each day and for each one-hour interval starting from 00:00h to 23:00h, the lightning location is plotted with a different color, which allows visualizing each storm time evolution.

The storm of April 18, 2020 is shown in Fig. 10. The lightning strokes detected by the AEMET are shown in Fig. 10a, while Fig. 10b shows the strokes detected by the WWLLN. According to the AEMET data there were more than 11,000 lightning strokes in Valencia land and sea, and 510 CG lightning strokes in Valencia land. The storm of August 30, 2021 is shown in Fig. 11. Again, Fig. 11a shows the lightning strokes detected by AEMET, while Fig. 11b shows the events detected by the WWLLN. Finally, similar plots for the storm of August 17, 2022 are shown in Fig. 12a for AEMET and Fig. 12b for the WWLLN data, respectively. There were 28,666 lightning strokes in Spain; in Valencia region there were 810 CG and 2,514 IC, total 3,324 (CG+IC).

An acceptable match is observed. Good concordance is seen for the point distribution giving location and the color for the corresponding time. The WWLLN network detects fewer lightning strokes than AEMET because it does not detect low power discharges, as described by Fig. 8, showing a DE decrease below 50 kA. On the other hand, WWLLN detects IC lightning that AEMET has discarded, which justifies that discharges detected by WWLLN do not appear in the AEMET map. The concordance shown in hits study indicates that the WWLLN data are a useful tool for thunderstorm tracking which can be used in combination with other techniques (Du et al. 2022). More specifically, Figs. 10 to 12 demonstrate the capability of WWLLN to provide good agreement with LF data from AEMET to resolve convective-storm cells within a larger storm complex generated in a Cut-off Low Pressure System feed with the humidity of the Mediterranean Sea, which is typically a more frequent phenomenon in the Western Mediterranean Basin than in inner continental areas such as it happens in the Spanish Plateau considered before in this work.

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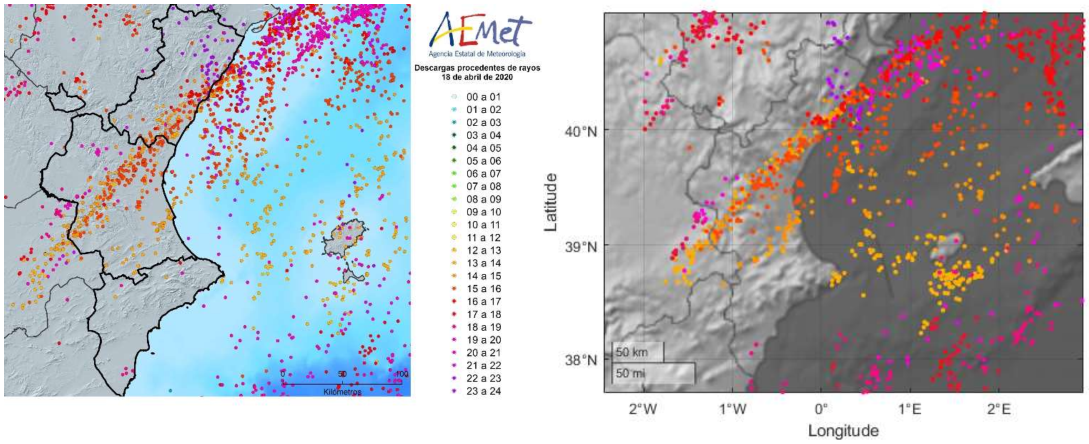
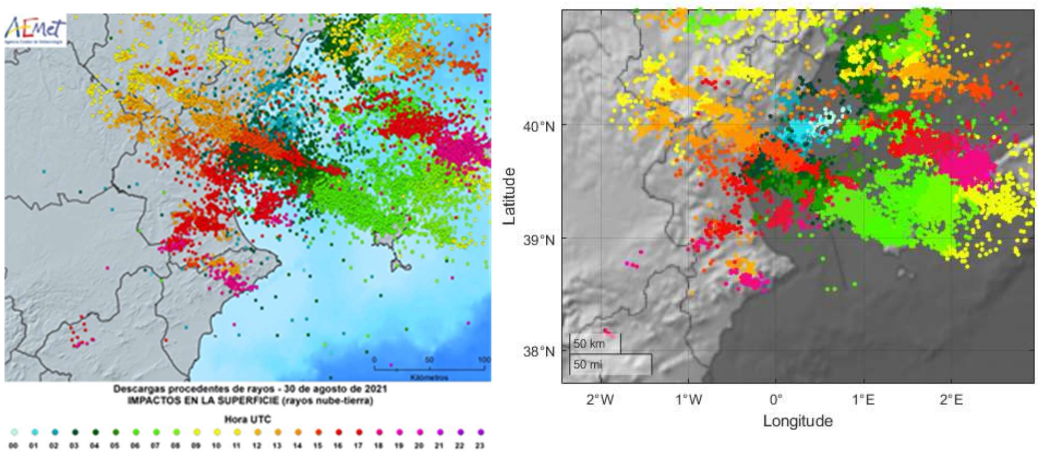


(a) (b)

Figure 10: The lightning storm of April 18, 2020 on the Spanish Mediterranean coast. Location of the lightning strokes with circular dots, different colors for different time periods: (a) AEMET. (b) WWLLN.



(a) (b)

Figure 11: The lightning storm of August 30, 2021 on the Spanish Mediterranean coast. Location of the lightning strokes with circular dots, different colors for different time periods: (a) AEMET; (b) WWLLN.

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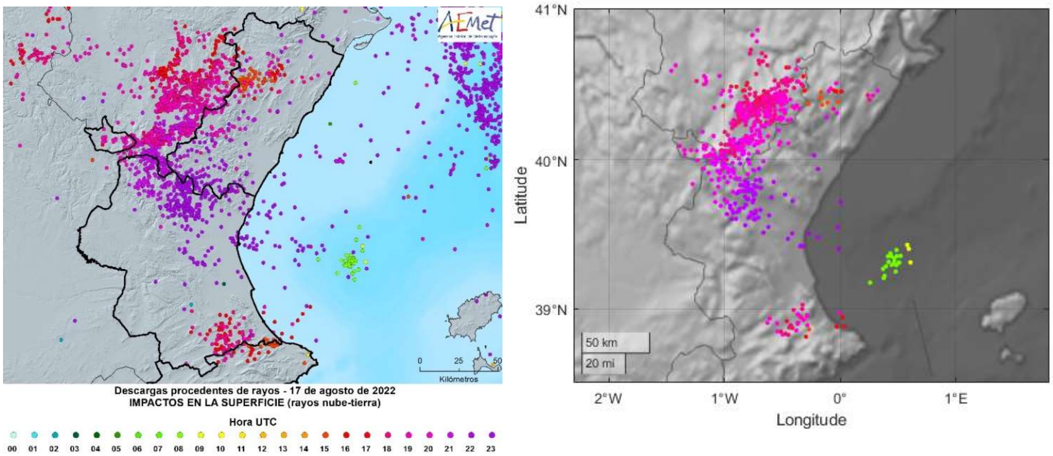

(a) (b)

Figure 12. The lightning storm of August 17, 2022 on the Spanish Mediterranean coast. Location of the lightning strokes with circular dots, different colors for different time periods: (a) AEMET; (b) WWLLN.

4. Conclusions

The work presented here contributes to the set of existing studies that analyze the operation of the WWLLN around the World, which did not include characteristics of this network in European countries yet. The performance of the WWLLN is evaluated in the area of Spain by comparison with data from the Spanish AEMET network as ground truth during the time period from

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1th January 2012 to 30th April 2012, soon after the deployment of one new WWLLN station in Spain. At that moment, sensors in the Spanish area were very close in terms VLF receivers, at a short distance of around 800 km, while typical receivers were around >5000-15000 km in other regions. The current number and distribution of the WWLLN stations, around 70 stations, is similar to that considered in the study with data from 2012, therefore, results presented here are valid nowadays.

For the time interval considered, a global study for the whole region of Spain has been firstly addressed. A total of 20,651 lightning strokes were detected by AEMET in this case. As regards the coincident detections by the WWLLN, this network detects a total of 12,855 strokes in the whole area of Spain, 7,843 CG being corresponding to one of the 20,651 strokes detected by AEMET in the same area. This yields a theoretical CG detection of 38% of the lightning strokes detected by the AEMET. The rest of lightning strokes detected by the WWLLN seems to mainly correspond to CC and IC strokes, which are not considered by AEMET. This DE value of 38% is a significantly improved result for the WWLLN as compared to its behavior for other areas (summarized in Table 1). This is likely due to the high density of stations in the Spanish area and surroundings which, in one hand, allows a better measurement of low intensity strokes and, on the other hand, raises the chance of a stroke being simultaneously detected by five or more stations. The study of the influence of the lightning peak current on the efficiency and location errors shows results consistent with previous reported works. It is worth noting that the DE considerably improves with high energy strokes, the more relevant to be monitored, with DE values above 50% when peak currents are higher than 50 kA, approximately.

The previous global study has been followed by two subsequent analyses concerning two reduced areas with different geographical characteristics: a continental homogeneous area, the Spanish Plateau, and a transition region including the abrupt change between coastal and maritime zones, the Mediterranean coast at Valencia. The goal of this second work was to find out if the well-known differences in the storms occurring at these two typically different areas produce differences on the DE and LA. Similar results have been obtained for the accuracy. As regards the efficiency, higher values have been obtained for the results at the coast, which is likely explained by the more intense phenomena occurring at coast-sea transitions and it is in good agreement with previous works reporting better detection over sea areas.

A final application of the WWLLN has been included that shows the global network capabilities to monitor the time evolution of climatic events. The application to three severe storms which affected the Mediterranean Spanish coast at Valencia during years 2020, 2021 and 2022 shows good agreement with results available from the AEMET national agency used as reference in this work.

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Competing interests

The contact author has declared that none of the authors has any competing interests.

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