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8 years of Sferics Timing And Ranging NETwork - STARNET: A Lightning Climatology over South America

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***Abstract*— This article presents a summary of 8 years of continuous operation of the Sferics Timing and Ranging Network (STARNET) over South America. During the first two years of operation, STARNET was detecting lightning mainly in the Amazon basin and northeast of Brazil with a location accuracy around 10-20 km and a flash detection efficiency of ~ 30-50%. After the upgrades of 2007 and 2009 we have compared STARNET with the Brazilian lightning detection network and WWLLN and it was possible to determine that STARNET was able to measure the lightning activity in most parts of South America with a location accuracy of 5-10 km and stroke detection efficiency of ~ 50-70%. During the last 2-year deployment, STARNET has improved its location accuracy to between 2-5 km. The years of measurements are showing the most prominent regions with lightning activity are in the Amazon basin, mainly at Maicoré and Tocantins, later at Mato Grosso do Sul.**

Keywords—Lightning measurements, VLF system

I. INTRODUCTION

STARNET is a long range lightning network that measures the radio noise emitted by atmospheric discharges, known as sferics, that bounce in the ionosphere-earth surface waveguide (sky waves) and can be detected at several thousands of kilometers at very low frequency (VLF) (Lee, 1986; Morales, 2001). STARNET technology was developed by Resolution Display Inc. through a NASA SBIR grant in the early 1990´s. The antennas measure the vertical electric field in the range of 7-15 kHz and the receiver is able to detect up to 100 sferics per second. To determine the sferics position, STARNET uses the arrival time difference (ATD) technique (Lee, 1986) that requires at least 4 VLF antennas. To compute the ATDs, sferics waveforms measured by a pair of VLF antennas are time cross-correlated in a 1024 millisecond time window. To be a valid ATD, the time lag need to have at least an r^2 greater than 0.99. Besides sferics position, STARNET also has a polarity algorithm that is based on ELF components of the VLF signal (Morales et al., 2007). The locating algorithm uses a minimum of 4 antennas and a maximum of 9 and can combine 30 different network configurations, i.e., if the network has more than 9 antenas, the user can specify combinations of 9 sensors. Then the location algorithm picks the sferics position that had the lowest ATD error.

STARNET was initially deployed in August of 2006 with 2 sensors in Brazil (Fortaleza and São Paulo), 1 in Guadeloupe (Caribbean) and 4 antennas in Africa (Nigeria, Ethiopia, Tanzania and South Africa) as part of P&D Project with COELCE and NSF. In 2007 the Nigerian sensor was moved to Campo Grande, Brazil. In 2008 an antenna was installed in São Martinho da Serra (Rio Grande do Sul, Brazil), while in 2009 two more sensors were installed in Brasilia and Manaus (Distrito Federal and Amazon, Brazil). In 2012 a VLF antenna was deployed at Belém (Pará, Brazil), in 2013 at Ilhéus (Bahia-Brazil), Cape Verde and Trellew (Argentina). Based on ths configuration STARNET is working with 11 VLF antennas that cover South America and part of the Atlantic ocean, Gulf of Mexico and Caribbean.

In this study, we initially present an evaluation of the location accuracy and detection efficiency of STARNET based on a comparison with the Brazilian lightning detection network (RINDAT) (Naccarato et al., 2006), the World Wide Lightning Location Network (WWLLN) (Holzworth et al., 2004), the Lightning Imaging Sensor (LIS) (Boccippio et al., 2002) on board the Tropical Rainfall Measuring Mission (TRMM) satellite and the Vaisala GLD360 network (Demetriades et al., 2010). Furthermore, we show how STARNET observed lightning during these 8 years over South America.

II. LOCATION ACCURACY

To compute the location difference we need to find matches between STARNET and a well defined lightning network. The matches though, pose a problem because each lightning detection system measures different parts of a lightning flash which can cause time differences. For instance STARNET, WWLLN and GLD360 measure sferics, but only STARNET and WWLLN use vertical electrical field. RINDAT measures strokes and LIS the optical lightning path as seen above clouds. Futhermore, each network uses different techniques to determine the lightning positions, i.e., STARNET uses ATD, RINDAT and GLD360 TOA/MDF, and WWLLN TOGA. Therefore it is not possible to guarantee that they will have the same time of occurrence. Due to these characteristics, we set a time constraint for the individual lightning matches. For RINDAT, WWLLN and GLD360 we applied a time window of 1 millisecond while for LIS we used 0.33 seconds. Only sferics and strokes are used for STARNET, RINDAT, WWLLN and GLD360, while for LIS we use flashes. For RINDAT, WWLLN and LIS we used measurements of 2009 while Novembre-2012 through March-2013 was used for GLD360.

In addition to the time constraint, we define different regions in South America in order to pick the best detection of each network and its most reliable location. RINDAT operates 47 sensors located in the center and southeast of Brazil, thus we constrain the matches between 50-40W and 30-20W. For LIS and WWLLN, though, we use the entire South American continent since they have a constant detection efficiency over this region. For GLD360 that covers the globe we selected 4 regions, 3 in South America and one in the Atlantic ocean.

Tables 1 and 2 present a summary of the mean location differences computed against the different lightning networks, while Figure 1 presents frequency distribution. Theoretical simulations for STARNET indicate that this system should have a location accuracy between 2 and 10 km over most of South America and above 20 km in the Atlantic Ocean and Caribbean. RINDAT is expected to have a location accuracy of 0.5-2 km (Naccarato et al., 2003), WWLLN around 10 km (Holzworth et al., 2004), GLD360 around 2 km over the United States (Demetriades et al., 2010) while LIS should be arund 10 km (Boccippio et al., 2002)).

According to the matches shown in Table 1 and 2, and the accuracy of the other networks, the expected values found on the theoretical simulations are within the errors computed, i.e., between 5-10 km in South America and around 20 km at the Atlantic ocean (Table 2 and Figure 1).

TABLE 1. MEAN LOCATION ERROR AND NUMBER OF COINCIDENT MATCHES.

	RINDAT	LIS – All Domain	LIS – Brazil	WWLLN
Mean Distance (km)	8.43	22.08	19.23	12,1
# of Matches	306,875	22,956	6,538	6,260,900

TABLE 2. MEAN LOCATION ERROR AND NUMBER OF MATCHES BASED ON GLD360-STARNET.

	01S-09N and 27-17W	08S-02N and 65-55W	15S-05S and 53-43W	21S-11S and 70-60W
Mean Distance (km)	26,66	11,13	7,58	12,15
# of Matches	87,597	728,870	1,345,711	1,752,731

In Figure 2, we present the spatial distribution of the location difference and it is possible to observe that in most parts of South America STARNET has a location accuracy better than 10 km. These differences follow the theoretical simulations. It is important to pay attention in these maps, because WWLLN and LIS are quite similar, while for RINDAT we do observe an inner and outter difference. Basically, RINDAT uses IMPACT/LPATS sensors that cover between 400-600 km, thus in the inner RINDAT network we should expect an accuracy better than 2 km, but in the outer region we would expect values between 5-10 km.

III. DETECTION EFFICIENCY

The detection efficiency (DE) is evaluated against only RINDAT. According to previous studies (Naccaratto et al., 2006 and Cummins et al., 1998), RINDAT should have a stroke DE between 40-50% and flash DE better than 90% (Cummins et al., 1998). For this study, we are comparing sferics measurements from STARNET and strokes from RINDAT. Furthermore, we propose two approaches for DE:

a) Grid/Temporal: Both STARNET and RINDAT are binned in grids of 1x1 degree with a 15-minute time interval. For each grid that has at least 10 strokes from RINDAT, we compute the ratio between the number of sferics by the number of strokes, and then the mean value for the hour for each grid box.
b) Thunderstorm: Evaluation of the ratio between the lightning occurrences observed by STARNET and RINDAT for each thunderstorm observed on the GOES-IR images (clouds are clusters with Tb < 258 K). The DE is based on ratio of the number of electrical discharges observed by STARNET and RINDAT in each cloud in a time window of ± 15 mi.

Figure 3a shows the stroke detection efficency based on the grid/temporal approach. It is possible to observe that in the main RINDAT area (center/southeast), STARNET presents a DE of 40-60%, and it increases outward. This effect is a response of RINDAT DE drop off that is consistent with sensors employed (IMPACT/LPATS) that measure up to 400-600 km with high DE. In Figure 3b, it is possible to observe that STARNET is able to measure more than 80% of the observed thunderstorms. The regions with 100% indicate that STARNET is measuring more than RINDAT. These results prove that VLF networks can indeed detect thunderstorms and even with good stroke DE.

IV. CLIMATOLOGY

It is possible to observe almost 8 years of STARNET monitoring lightning over South and Central America, Caribbean and the Atlantic ocean. Since 2006, it is also possible to observe differences not only on the number of sferics detected by year (Table 3), but also in the spatial distribution. In 2006, the network was in the northeast of Brazil, Caribbean and in Africa and it was able to monitor the lightning activity of the second semester in Africa. As STARNET began to change its configuration in 2007, the main focus for monitoring was Brazil and surrounding countries. The Amazon basin and central part of Brazil dominate the lightning activity. As more sensors were installed in the south, i.e., São Martinho and recently Trellew, it is possible to observed the intense lightning activity in northern Argentina, Paraguay, and Bolivia. The hot spots though are in Manicoré, close to Manaus in Amazonia, Sidrolância at Mato Grosso do Sul, and in Tocantins.

TABLE 3. NUMBER OF SFERICS MEASURED BY STARNET SINCE 2006.

Year	Sferics Measured
2006	7,585,405
2007	3,290,597
2008	17,204,274
2009	123,394,328
2010	45,015,908
2011	36,768,128
2012	62,397,672
2013	180,928,944

V. CONCLUSIONS

This study presented that STARNET has location differences of approximately 8-12 km when compared to RINDAT, 19 to 22 km with LIS, 5-12 km against WWLLN and 7-22 km with GLD360. Taking into account that LIS and WWWLLN have an accuracy of 10 km and RINDAT and GLD360 less than 2 km, the location accuracy of STARNET would be between 5 and 12 km in South America and around 20 km over the Atlantic ocean. In terms of stroke detection efficiency, STARNET measures mainly 50% of RINDAT strokes in their best coverage area. For the thunderstorm activity, it is possible to state that STARNET measures more than 80% of them over South America. Futhermore, it is important to state that *All STARNET sferics measurement are publicly released into our website*, http://www.starnet.iag.usp.br (**link ftp**)

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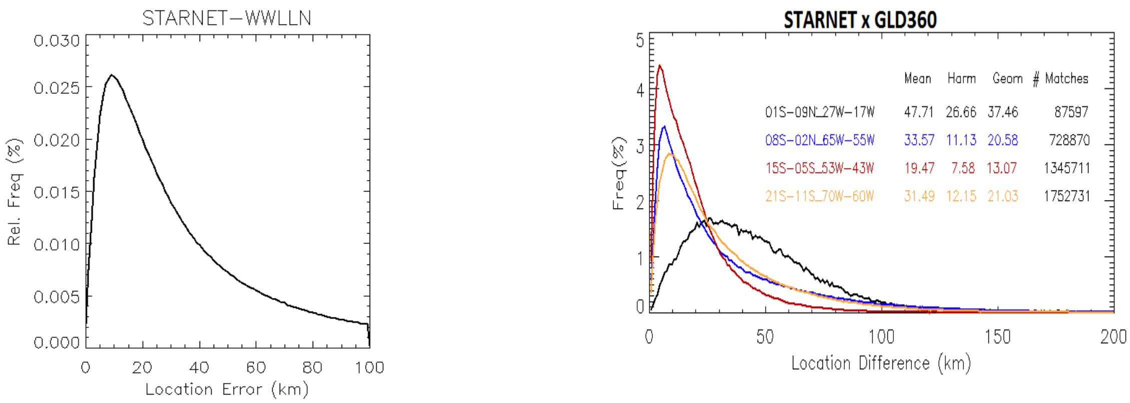

Fig. 1. STARNET location difference between RINDAT, LIS, WWLLN and GLD360.

(a) (b) (c)

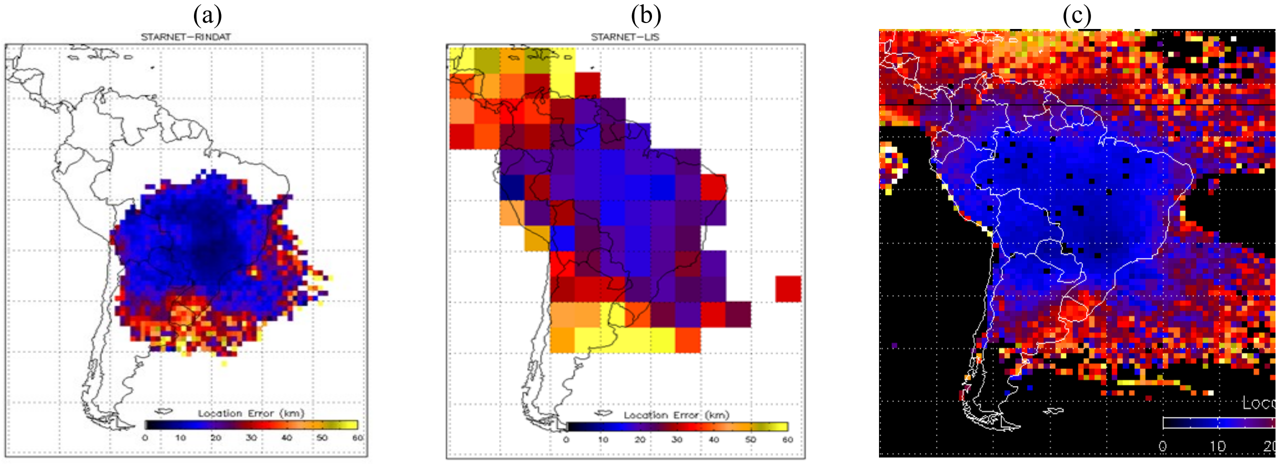

Fig. 2. STARNET Location difference between (a) RINDAT; (b) LIS; and (c) WWLLN. RINDAT and WWLLN are binned at 1 degree while LIS is at 5 degrees.

(a) (b) (c)

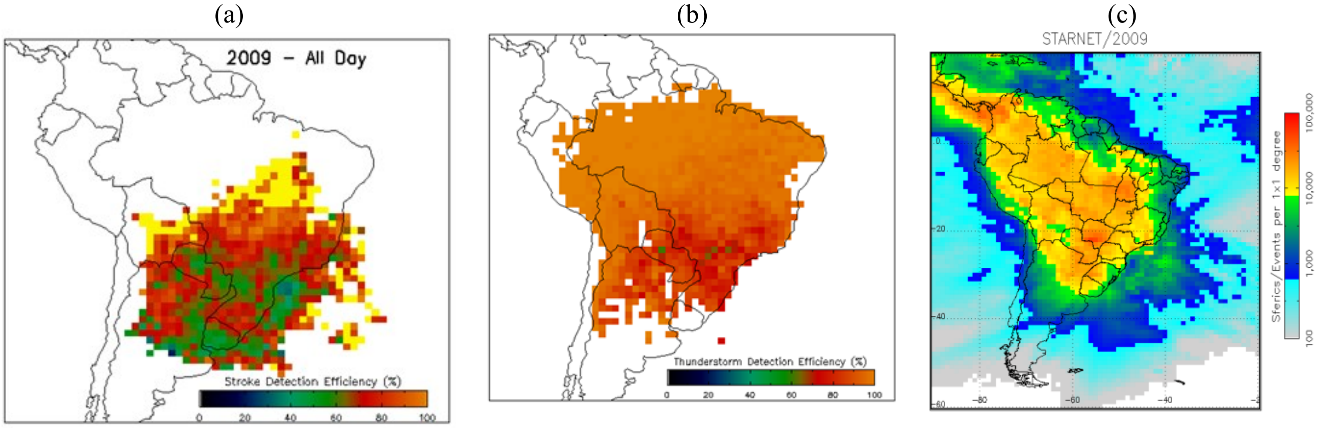

Figure 3. (a) left – STARNET Stroke detection efficiency; (b) right – STARNET thunderstorm detection efficiency; (c) 2009 STARNET sferics distribution.

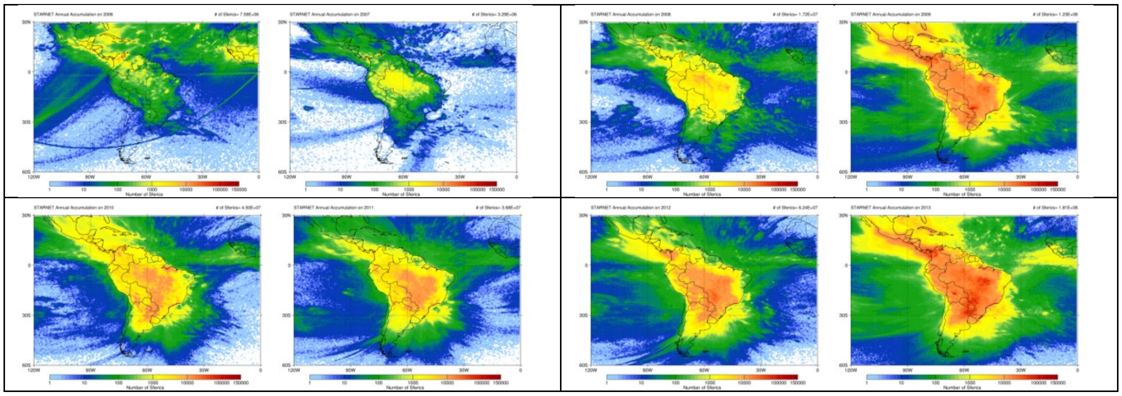

Figure 4.Annual sferics distribution as observed by STARNET since 2006.