Ground-Based Detection of Sprites and their Parent Lightning Flashes over Africa during the 2006 AMMA Campaign

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Manuscript submitted to the AMMA Special Issue in the Quarterly Journal of the Royal Meteorological Society
December 2008

Abstract

Sprites have been detected in video camera observations in Niger over mesoscale convective systems in Nigeria during the 2006 AMMA campaign. The parent lightning flashes have been detected by multiple ELF receiving stations worldwide. The recorded charge moments of the parent lightning flashes are often in excellent agreement between different receiving sites, and are furthermore consistent with conventional dielectric breakdown in the mesosphere as the origin of the sprites. Analysis of the polarization of the horizontal magnetic field at the distant receivers provides evidence that the departure from linear magnetic polarization at ELF is caused primarily by the day-night asymmetry of the Earth-ionosphere cavity.

1. Introduction

This study is concerned with the ground-based detection of sprites over the African continent, and with the detection of their parent lightning flashes from multiple electromagnetic receivers over the globe. Among the three tropical ‘chimneys’ of prominent lightning activity, Africa is the last to come under scrutiny in the surface instruments because of infrastructural limitations, and so has remained to a large extent the ‘dark continent’. Recent innovation in the African Monsoon Multidisciplinary Analysis (AMMA) (Redelsperger et al., 2007) has thrown important new light on the darkness.

Much is known about thunderstorm activity in Africa on the basis of remote sensing with both satellite and electromagnetic methods, and many previous observations support the idea that sprites would occur with great abundance there (Füllekrug and Price, 2002; Chen et al., 2008). Optical observations of lightning with the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) have established Africa as the tropical ‘hot spot’ for lightning (Christian et al., 2003; Williams and Satori, 2004). In reviewing the meteorological conditions favorable for TLE-producing lightning discharges, Lyons (2006) has noted that sprites and halos are most frequently observed above large mesoscale convective systems (MCSs), and in particular those with expansive stratiform precipitation regions (Lyons et al., 2003). Laing and Fritsch (1993) documented the frequent occurrence of expansive, long-lived mesoscale convective complexes over the African Sahel, and to a lesser extent over the equatorial rain forests and southern Africa. Toracinta and Zipser (2001) have identified Africa in satellite observations as the most exceptional tropical region in the category of MCSs with exceptionally low cloud top temperatures. All of the foregoing storm observations are favorable to the sprite requirement for superlative lightning events, with ‘mesoscale’ characteristics (Boccippio et al., 1995; Williams and Yair, 2006).

Storms with exceptional size are also called into play by the electrostatic requirement for sprites, set forth by the prescience of C.T.R. Wilson (1925) and refined by numerous recent studies (Boccippio et al, 1995; Cummer and Inan, 1997; Huang et al., 1999; Williams, 2001; Hu et al., 2002; Cummer and Lyons, 2005). The electrostatic mechanism for sprite initiation involves an exceptional vertical charge moment change in the parent lightning flash. These charge moments are established in observations primarily by remote sensing in the ELF electromagnetic range, with global reach from single receivers (Huang et al, 1999; Hobara et al, 2006). Similar to the situation for ordinary lightning flashes, Africa is also predominant in events with exceptional charge moment (Hobara et al, 2006; Williams et al, 2007). The present study continues with the use of ELF methods for event characterization.

Given the abundance of MCS activity over Africa, perhaps it not too surprising that perhaps the earliest reference clearly describing a sprite over Africa was published by D.F. Malan, who made naked eye observations of sprites above a distant South African MCS, noting “a long and faint streamer of reddish hue…some 50 km high” (Malan 1937). Lyons and Williams (1993) reported on detailed analyses of low-light television (LLTV) video of lightning-related phenomena taken aboard the Space Shuttle during missions from 1989 to 1991 (Boeck et al., 1998). It was noted that the TLEs (almost all sprites) tended to occur above large MCSs though not necessarily in the portion of the storm with the highest flash rates. Four of 14 events inspected by Lyons and Williams (1993) occurred over the African continent. Among the first African sprite observations reported from the Space Shuttle LLTV examined by Vaughan et al. (1992) were found over Mauritania (~7.5ºN,~ 4.0E) on 28 April 1990. Sprite activity over the Congo basin of the African continent was confirmed in Space Shuttle observations during the MEIDEX (Mediterranean Israeli Dust Experiment) mission in January 2003 (Yair et a.l, 2004).

Prior to the observations reported in this paper, however, no terrestrial camera had yet to record a TLE above an African storm. The energetic parent lightning flashes for these African sprite events were also detected electromagnetically by an unprecedented total number of VLF networks (2) and ELF receivers (6), as summarized in Table 1.

Table 1: Sprites over Africa: Charge Moment Change (C-km) for Parent Lightning

	Time (UT)	USA (N.C.)	ISRAEL	JAPAN	HUNGARY	ANTARCTICA	USA (R.I.)	WWLLN	ZEUS
August 30, 2006									
Sprite (amorphous)	22:50:27.726-74	N.D.	+2200	+2320	+1700 16.5N 6.1E	+1250	YES	N.D.	N.D.
Sprite (amorphous)	22:50:28.192-209	N.D.	+800	+107	+960 (+660) 14.2N 8.5E	+450	NO	N.D.	N.D.
Sprite carrot (very bright)	23:16:32.698-715	N.D.	+1100	+900	+1280 7.3N 4.1E	+450	NO	N.D.	N.D.
Complex dancer	23:20: 46. 936 to 23:20:47.119	N.D.	+1800	+1430	+1320	+140 +315	YES	23:20:47.101932 13.6N 4.7E	N.D.
September 21, 2006									
Sprite (very bright)	00:17:22.762-796	+810 (760)	+1680	N.D.	+1750	+905	YES	00:17:22.771931 12.6N 5.1E	N.D.
Sprite (bright)	00:24:28.594-645	+1510 (700)	+2000	N.D.	+2200	+790	YES	00:24:28.600607 12.8N 5.7E	N.D.
Halo (or dim sprite)	00:28: 48.017-105	+640 (270)	+820	N.D.	N.D.	+403	NO	N.D.	N.D.
Sprite	00:36:54.822-889	N.D.	+770 (minor)	N.D.	N.D.	+180	NO	N.D.	N.D.
Sprite (Dancers)	01:09:31.053-169	N.D.	+860	N.D.	N.D.	+343	YES	01:09:31.036016 13.2N 6.1E	01:09:31.151463 11.5N 5.20E
Halo	01:57:19.749-766	-700 (700)	+850	N.D.	-680	-437	NO	N.D.	N.D.
Bright cloud flash	02:01:49.971-987	- 960 (630)	+1100	N.D.	-1000	-618	NO	N.D.	N.D.
Sprite (very bright)	02:27:48.235-268	+1340 (900)	+2500	N.D.	+1490	+1326	YES	02:27:48.248509 13.5N 5.1E	02:27:48.248703 13.7N 5.25 E
Sprite	02:34:27.763-832	N.D.	+1600	N.D.	+1140	+ 35	NO	N.D.	N.D.
Sprite	02:44:01.657-721	N.D.	+1400	N.D.	+980	+500	NO	N.D.	N.D.

USA (N.C.) = North Carolina (Duke University)
ISRAEL = Mitzpe Ramon ELF Observatory
JAPAN = Moshiri ELF Observatory in Hokkaido
HUNGARY = Nagycenk (ELF) Observatory
ANTARCTICA = Syowa Station (Tohoku University ELF Observatory)
USA (R.I.) = Rhode Island (MIT ELF Observatory)
WWLLN = World Wide Lightning Location Network
ZEUS = VLF Network in Europe for lightning detection

2. Methodology

The establishment of observations for sprite detection over Africa was piggy-backed on a project to operate the MIT C-band Doppler radar for AMMA in Niamey, Niger. The selection of Niamey international airport for radar operation also afforded opportunities for video camera operation.

a. Video Camera Observations

A portable low-light television (LLTV) camera system was assembled and transported to Niamey. Video was acquired using a Watec LCL-902K unit, a non-intensified half inch CCD with 0.00015 Lux sensitivity and 570 lines resolution. Optics employed were an f/0.8 Computar 6 mm lens (~55 degree horizontal field of view). The tripod-mounted unit could be easily deployed with power supplied by a 12 V automotive battery and inverter. Video time stamping to the millisecond was applied to each field of video using a KIWI-OSD-RTD unit from PFD Systems, and a Garmin Model 18-LVC GPS receiver. Video was written to an S-VHS video cassette recorder.

Initial attempts to operate the camera in the main control tower were thwarted by local runway illumination and building lights. The camera and recording equipment was subsequently moved to a smaller tower on the east end of the east-west-oriented main runway, remote from both the main control tower and the lights of the city of Niamey located west of the airport, and where dark conditions prevailed facing east. Fortuitously, the most prevalent direction of MCS/squall line approach to Niamey was also from the dark eastern sector.

b. Satellite Observations

MeteoSat satellite imagery available in real time at both the MIT radar site and at the ASECNA (Agence pour la Sécurité de la Navigation Aérienne en Afrique et á Madagascar) forecast office in the main airport building in Niamey was used to document the occurrence of mesoscale convective systems over West Africa and to make decisions in late afternoon about the value of late evening observations with the video camera. These satellite data were also archived by Meteo France for AMMA with 30 minute resolution, from which movies of the MCS evolution were produced, as a forecasting tool. In general, the MCS 'targets of opportunity' for the video camera observations developed in central and eastern Niger, and in northern Nigeria. In the majority of cases, however, the observations of sprites were spoiled by the advection of upper level cirrus cloud into the Niamey area, thereby blocking our view of the mesosphere over MCSs further east. The nights of August 30 and September 21 were special exceptions, and the MeteoSat imagery described below documents that well.

c. Remote ELF observations

The strong electromagnetic radiation from the lightning discharges responsible for sprites in the mesosphere is radiated globally in the ELF region. For the African sprites documented in this study with the video camera, these signals were detected by six separate ELF receivers, in Antarctica, Hungary, Israel, Japan and two within the United States. The vertical charge moment change of the causative lightning could be evaluated on the basis of these separate observations, and can be compared. Furthermore, the reception of signals by multiple stations has enabled a comparison between theory and observation on the polarization behavior of the ELF magnetic field. A brief description of the ELF receiver sites and their data-processing methods follows below:

Duke University (USA)

The Duke University sensors used here are located at a field site near the university (35.98°N, –79.10°E). The data presented here were recorded with two EMI BF-4 magnetic field coils (<0.1 to 500 Hz bandwidth, sampled continuously at 2.5 kHz) to provide the full horizontal vector magnetic field. GPS provides absolute timing accuracy. In our quantitative analysis we combine finite difference propagation simulations (Cummer and Inan, 1997) and a deconvolution approach (Cummer and Inan, 2000) to extract a full current moment waveform of the first 80 ms of the discharge from the directly propagating portion of the recorded signal (i.e., the around-the-world components are neglected). Given the long propagation distance (~8000 km) of the direct signal, which filters out much of the lightning signal above 200 Hz, our time resolution in this analysis is approximately 5 ms. Thus, for summary purposes, the 8 ms charge moment change is computed from our current moment waveforms, and is dominated by the return stroke and any short duration continuing current. The 80 ms charge moment change includes any significant long duration continuing current as well.

The analysis here has been cross-checked by computing an expected Schumann resonance waveform from our extracted current moment waveform using the model of Huang et al. (1999). In all cases the 80 ms duration current moment waveform was consistent (given the background noise) with the around-the-world signals, indicating that the 80 ms charge moment change is our best estimate of that of the entire flash.

ELF observation system in Mitzpe-Ramon, Israel

The ELF instruments in Israel are located at Tel Aviv University's Wise astronomical observatory near the town of Mitzpe-Ramon (MR) in the Negev Desert (30.6°N, 34.8°E). This remote area which has much reduced anthropogenic electromagnetic noise levels is located far from industrial activity which produces different kinds of ELF interferences (50 Hz power supply lines) contaminating the signal. The station has two horizontal magnetic induction coils for receiving the magnetic field in the north-south direction (H_{ns}) and the east-west direction (H_{ew}) and one vertical electrical ball antenna for receiving E_r. The three electromagnetic field components are sampled at 250 Hz using a

16-bit A/D converter. A notch filter at 50 Hz is used to remove the most offensive power line harmonic. The raw time series data are saved in 5-min files, controlled and monitored via PC-Anywhere, with all analysis performed during post-processing. The system uses accurate GPS timing for temporally correlating with other electromagnetic and optical instruments involved with the AMMA project.

ELF Receiver in Moshiri (Japan)

The ELF electromagnetic field has been continuously monitored in Moshiri (MSR) station, Hokkaido Japan (44.2 N 142.2 E) since 1996 (Hobara et al., 2000, 2001), and the whole ELF system was upgraded in 2005 (Ando et al., 2005). Moshiri Observatory is considered to be one of the electromagnetically quietest places in Japan. Two horizontal magnetic fields are measured by orthogonally oriented induction search coils, aligned with geographical north and east, respectively. The vertical electric field is observed with a capacitor type antenna. These antenna systems are fully calibrated and sampled at the frequency of 4000 Hz with a pass-band of 1 kHz, so that the waveforms of ELF signals (Schumann resonances, ELF transients, etc) are continuously recorded for any further analysis. A GPS receiver provides an absolute time stamp for each sampling point.

Schumann Resonance (SR) station in Nagycenk (Hungary)

The SR station at Nagycenk Observatory (NCK; 47.62ºN, 16.72ºE) was established in 1993 starting with the quasi-real time determination of the spectral parameters (peak frequency, amplitude) of the vertical electric field component, E_Z in the frequency range of 5-30 Hz in 1993 (Sátori et al., 1996). The SR recording system was completed with the measurement of the two horizontal magnetic field components (H_{NS} and H_{EW}) and supplied with UTC timing with GPS accuracy in 1998 making possible the recording of SR transients as well. The vertical electric field component is measured with a capacitive ball antenna and two horizontal magnetic components are recorded with two induction coils aligned with the geographical north-south and east-west directions. Increased storage capacity made possible the quasi-continuous recording of time series after July 2004 (Sátori, 2007). The background and transient SR measurements are operating in parallel with different sampling rates: 100 Hz in the first case and ~513.8 Hz for recording SR transients. 12 bit A/D converters are used in both cases.

Time series for SR transients are collected without preprocessing and stored in ~20 second blocks with ~9ms gaps between them. GPS based UTC time stamps are recorded together with the time series of the field components. The onset of a detected SR transient is considered when the gradient of the signal in the E_z field component exceeds a threshold. The uncertainty of the given onset time is +/-2 ms. TLE-associated SR transients are found by matching the transient onset times with the optical observation times. The direction of the event is deduced from the orientation of the Poynting vector at maximal signal amplitude. The source-observer distance (SOD) along the great circle path is deduced by comparing the measured complex impedance spectrum of the transient to a set of model impedance spectra calculated for various SODs. Finally the CMC of the source is estimated by deducing the current moment spectrum of the source from the measured field component spectra and by fitting an analytical spectrum of an exponentially decaying current to it. The CMC estimate is calculated from the parameters of the fitted analytical spectrum. The procedure is described in detail in Huang et al. (1999).

ELF station operated in West Greenwich, Rhode Island (USA)

MIT has operated ELF receiving equipment on the Alton Jones Campus of the University of Rhode Island in West Greenwich since 1993. Recording procedure and instrument details for background (Heckman et al., 1998) and transient (Huang et al, 1999) Schumann resonance observations have appeared in earlier publications. Three component field measurements are normally in place, but during the AMMA campaign in summer 2006, the vertical electric channel was disabled by local lightning and so the usual wave impedance calculations for event characterization were not possible.

ELF Receivers operated by Tohoku University (Japan)

Tohoku University currently operates Schumann resonance receiving sites in Onagawa, Japan, Esrange, Sweden and Syowa station, Antarctica. For this study, the events of interest were captured only at Syowa station (39.506E, 69.018S) in Antarctica. For procedure at Syowa, first the candidate events for the Q-burst of the parent lightning are selected by considering the propagation time lag between Niamey and Syowa station. In the case multiple bursts are detected, the initial peak is selected as the candidate for the parent stroke. Then the magnetic Lissajous figure for the event is examined to verify consistency with a propagation direction from Niamey. Finally the charge moment change is estimated according to the method shown in Section 2.6.3 of Huang et al. (1999).

d. VLF Network Observations

World Wide Lightning Location Network (WWLLN)

The WWLLN uses long range radio reception in the part of the VLF band (1 to 24 kHz) which includes the peak power from lightning (7 to 15 kHz). These waves travel long distances (6 to 10 Mm) allowing the entire globe to be monitored with just 28 WWLLN receiving stations (see Lay et al., 2007). The lightning detection efficiency (DE) of WWLLN has been studied by several authors (c.f. Lay et al., 2007; Rodger et al., 2006; Jacobson et al., 2006; Dowden et al., 2008; Lyons et al., 2009) in which it has been estimated that WWLLN detects lightning with a time error of < 30 microseconds and a spatial location error of about <= 15 km, even in areas for which no WWLLN stations are nearby. These studies have shown that WWLLN detects lightning strokes with peak currents >50 kA, and is therefore useful for these TLE studies, where large peak currents are usually correlated with the probability of occurrence of TLEs (Lyons et al, 1996). The parent lightning flashes for four of the fourteen sprite events are included in Table 1.The WWLLN global detection efficiency is only a few percent of total lightning, but typically over 20% DE for studies like the current one (4 of 14) and another study of

TLEs in South America (Taylor et al., 2008).

In addition to the four strokes directly located here, WWLLN detected very close strokes (within 20 milliseconds) in the thunderstorm areas producing the TLEs for two additional events.

ZEUS Lightning Detection Network

ZEUS is a long-range lightning detection network with receivers located at six sites over Europe (Birmingham in UK, Roskilde in Denmark, Iasi in Romania, Larnaka in Cyprus, Athens in Greece and Lisbon in Portugal). The system was manufactured by Resolution Displays Inc. ZEUS receivers record the radio noise (sferics) emitted by cloud-to-ground lightning discharges in the very-low-frequency (between 7-15 kHz). The VLF signal is preamplified at each receiver site and the signal is synchronized to GPS time. At each receiver site an identification algorithm is executed that detects a probable sferics candidate, excludes weak signal and noise and is capable of capturing up to70 sferics per second. Then the lightning location is retrieved (at the central station of the network) using the arrival time difference triangulation technique. The arrival time difference values represent positions between two outstations with the same time difference, and their intersection defines a sferic fix. The ZEUS location algorithm requires a minimum of four receivers to record the same event. Further details on ZEUS network can be found in Kotroni and Lagouvardos (2008). A study of the location accuracy of the ZEUS system is underway that compares its measurements with those from the LINET lightning detection network (Betz et al. 2004) over Europe. Preliminary results have shown that the location accuracy of ZEUS over the study area is of the order of 6 km (Lagouvardos et al., 2008).

3. Results

Sprites were documented in video camera imagery on two nights, August 30 and September 21, 2006. A summary of all 14 events, together with the independent electromagnetic documentation of the parent lightning flashes by remote ELF and VLF receivers, is shown in Table 1. Consistent with earlier studies (Williams et al., 2007), all of the events identified as sprites in the video camera observations (left hand columns) are associated with positive ground flashes and hence with vertical charge moments with positive polarity. One halo event however on September 21 is identified as having negative polarity for the majority of receiving stations. The seventh event on September 21 is labeled a ‘bright cloud flash’, and may not be a TLE at all, but just a bright lightning flash. Its polarity is also judged to be negative by most receivers. Specific documentation of conditions on the two separate nights is discussed in turn below.

a. MCS on August 30, 2006

A large isolated MCS was noted in MeteoSat Imagery 300 km east of Niamey. The video camera was set up by 2240 UT, with a camera azimuth angle of 85 degrees, and a faint sprite was noted in the monitor in real time. (This was the only such event during the entire program.) Four sprites in total were detected on the video tape in the interval 2250-2320 UT during playback after the field program, and their GPS times are included in Table 1.

Visual observations during this period of sprite observations showed a complete absence of stars below about 20-30 degree elevation from the horizon, attributable to the mineral dust typical of the West African Sahel. Diffuse flashes of light from distant lightning were noted in the east, with rates of 1-2 per minute.

A MeteoSat image at 23:30 UT is shown in Figure 1. The large quasi-circular MCS east of Niamey is clearly evident, with cloud top temperature <65 C indicated by the orange coloration. Based on MCS-Tracking analysis (Morel et al., 2002; Tomasini et al., 2006), this MCS is growing at this time, with a minimum cloud top temperature of -82C. The green star indicates the position of the parent cloud-to-ground lightning determined by the WWLLN for the sprite event at 23:20:47.101932 UT. The location is consistent with the idea originating in earlier studies (Boccippio et al, 1995; Williams, 1998; Lyons et al, 2003) that the parent discharge lies in the trailing stratiform region of a squall line propagating westward toward the camera observation site in Niamey.

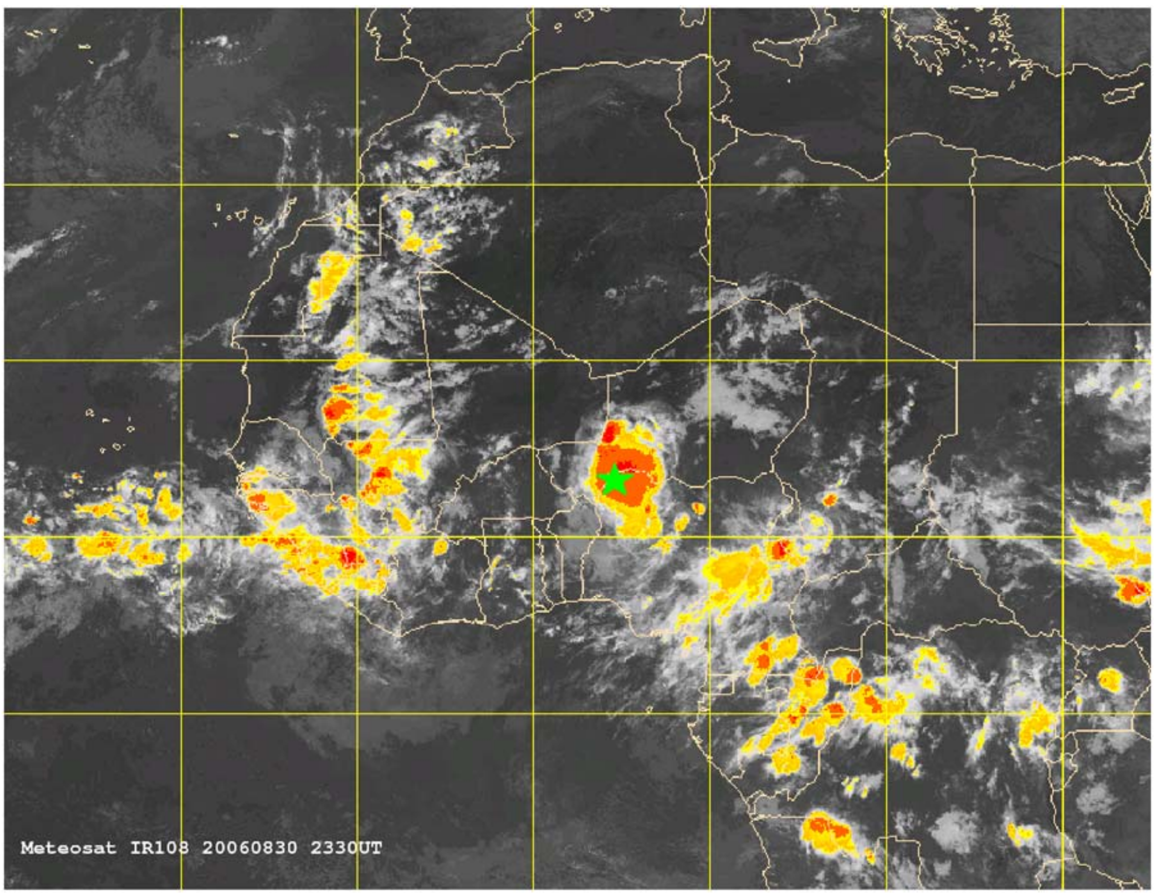

Figure 1 MeteoSat imagery for 23:30 UT on August 30, 2006 showing large MCS east of Niamey, and the location (green star) of the parent cloud-to-ground lightning flash for the sprite at 23:20:47.101932 UT determined by the WWLLN.

b. Clustered MCSs on September 21, 2006

Viewing conditions generally improved through the wet season in Niamey (July-September), consistent with the gradual decline in both total condensation nuclei and cloud condensation nuclei documented at the nearby ARM (Atmospheric Radiation Measurement) site (Miller and Slingo, 2007) at Niamey airport (data not shown). By this date, the viewing conditions were as good as they had ever been, and stars were visible in the monitor, with a note that no stars were visible below 10-20 deg elevation angle from the horizon. The video camera was set up for logging by 2345 UT on September 20. At 0035 UT the camera was pointing east (90 deg azimuth), and very dim, diffuse flashes of light from distant lightning were noted. Figure 2 shows a MeteoSat image for 02:30 UT showing a bowed squall line MCS 400 km east of Niamey with a north-south orientation. According to the MCS-Tracking analysis (Morel et al., 2002; Tomasini et al., 2006), this MCS is growing, with a minimum cloud top temperature of -81C.

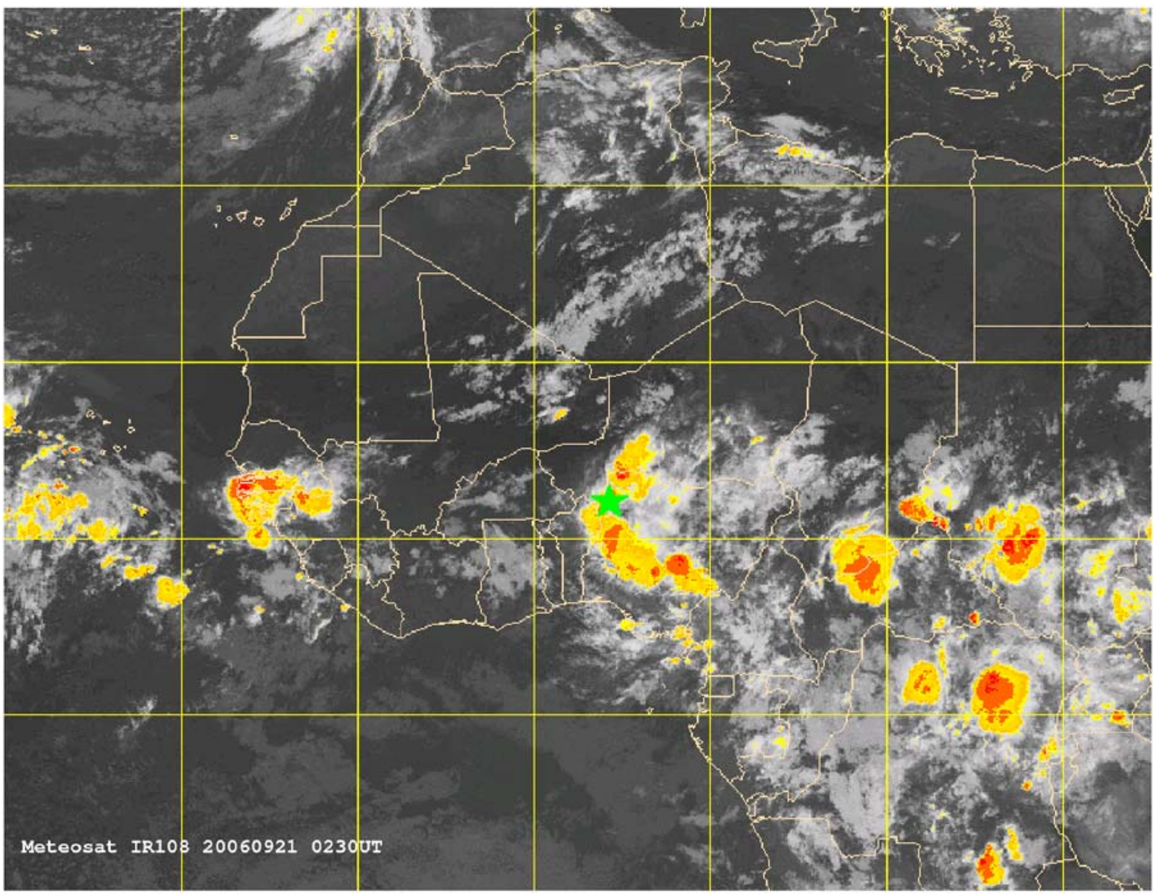

Figure 2 MeteoSat imagery for September 21, 2006 at 02:30 UT nearest the time of the sprite observed from Niamey at 02:27:48.235 UT. The green star shows the location of the parent ground flash located by the VLF networks WWLLN and ZEUS, which are within about 20 km of each other (and small compared to the size of the star).

Ten sprites were noted in the camera imagery during replay following the field program, in the 2.5 hour-interval 0015 – 0245 UT (Sept 21), as indicated in Table 1. The green star in Figure 2 shows the location of the parent lightning of the sprite event at 02:27:48.235 UT, as determined by both the WWLLN and the ZEUS VLF networks. (The time of this event agreed within 200 microseconds between the two networks, and the location by 20 km.). Figure 3 shows a video camera image of the very bright sprite produced by this energetic lightning flash.

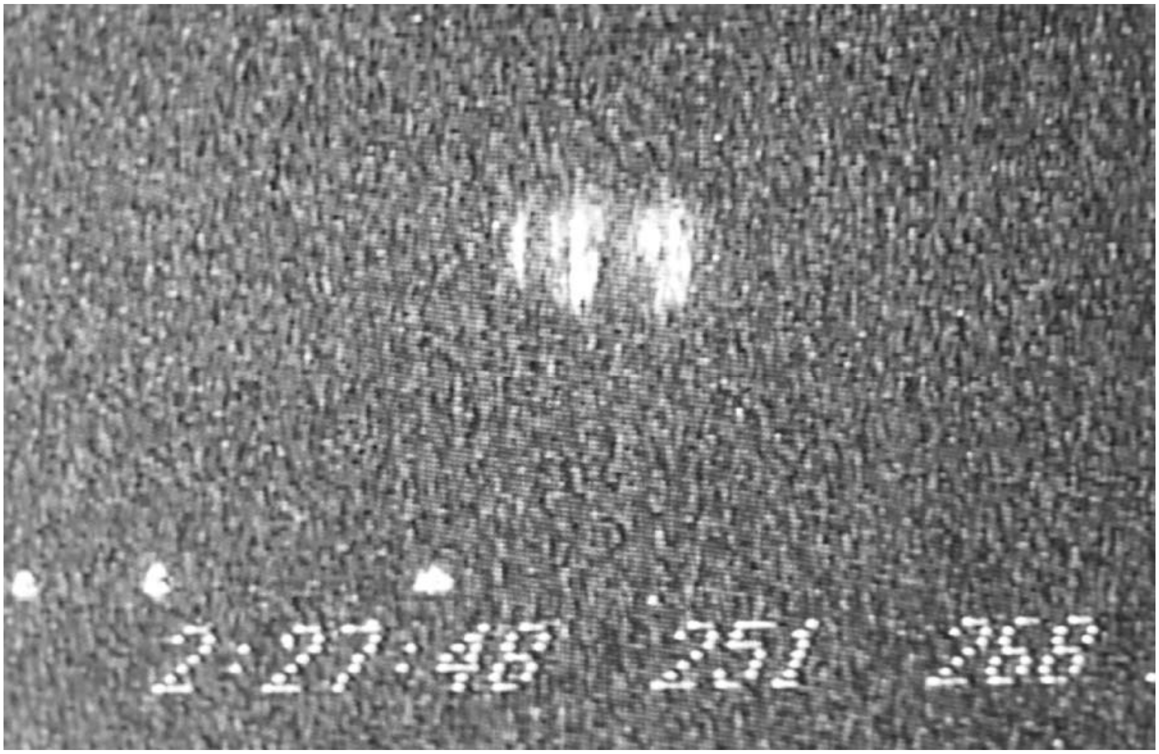

Figure 3 Sprite image recorded in Niamey, Niger for the event at 02:27:48.235-268 UT (Table 1) on September 21, 2006.

c. Comparisons of Charge Moment Change in ELF Measurements

As documented in Table 1, ELF observatories at multiple locations worldwide detected the global radiation from the sprite-producing lightning for these events. Calibrated sensors at the receiving sites have been used to calculate the vertical charge moment change of the parent lightning flashes. Comparisons of these determinations for all fourteen sprite events and all receiver detections are shown in Figure 4. The values from different locations are often, though not invariably, in good agreement, supporting the capability of characterizing a source property from different distances of observation.

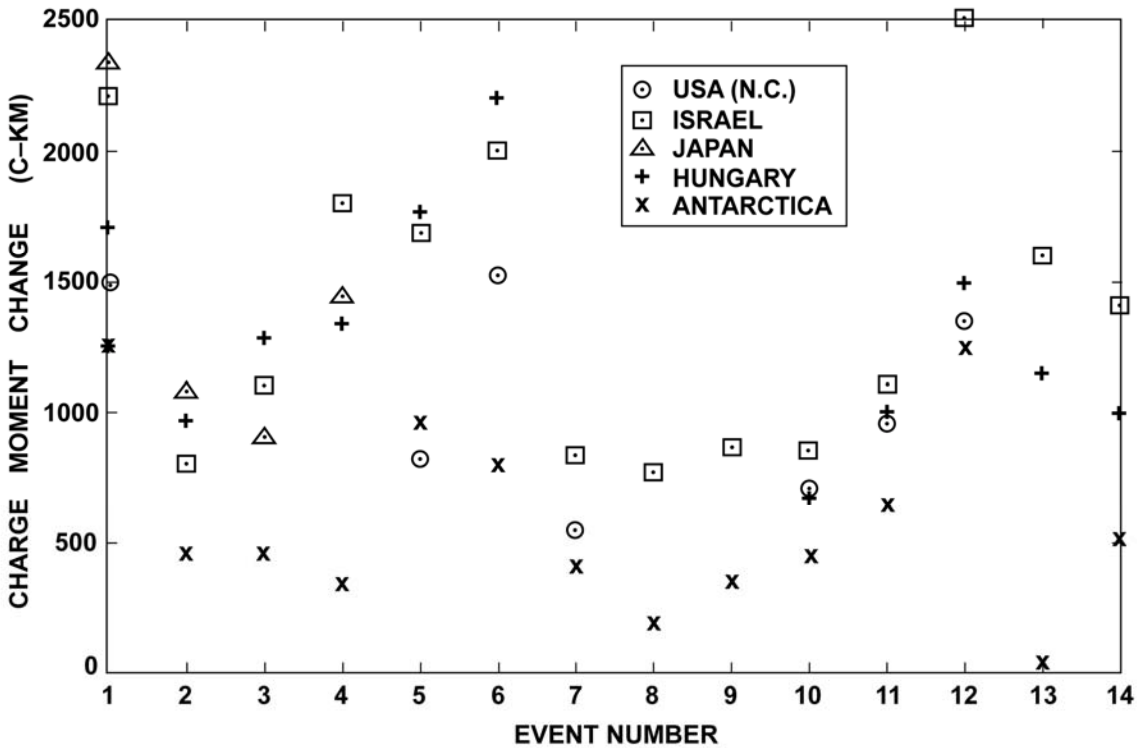

Figure 4 Comparisons of charge moments from different ELF receiving sites for all 14 events in Table 1.

For some pairs of receiving stations, the agreement in estimates for charge moment change is even better. Figure 5a shows comparisons of charge moment change for simultaneously observed events from Israel and Hungary. Points of perfect agreement would fall on the 45 degree line. The agreement is not perfect but is still of high quality for measurements of this kind, though Israel appears to be reading a little high. Figure 5b shows a like comparison in common events observed from the USA (Duke University) and from the Moshiri Observatory in Japan. Again, the agreement is excellent. In both Figures 4 and 5 it is important to note that the majority of CMC values are in excess of the threshold (500-1000 C-km) generally believed necessary for the dielectric breakdown of the mesosphere at altitudes of ~75 km where sprites have been observed to initiate, according to the ideas initiated by C.T.R. Wilson and confirmed in other studies (Wilson, 1925; Huang et al., 1999; Hu et al., 2002; Cummer and Lyons, 2005; Hu et al., 2007).

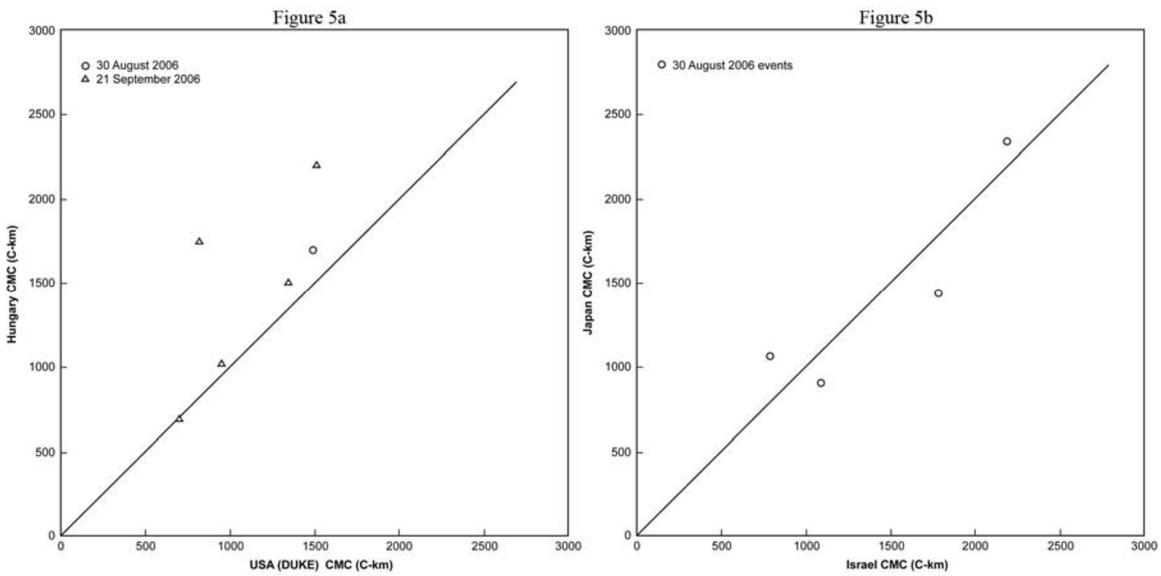

Figure 5 Pairwise comparison of vertical charge moments for common sprite lightning events recorded in (a) Hungary and the USA (Duke) on both days, and in (b) Israel and in Japan for sprite events on August 30. The diagonal line represents the line of perfect agreement.

d. Detailed analysis of the ELF Magnetic Field for an Exceptional Sprite-Producing Lightning Flash on September 21.

One of the strongest events appearing in Table 1 is the flash detected on September 21 nearly coincidently (02:27:48.248 UT) by the WWLLN and ZEUS networks and producing the 'very bright' sprite in the camera at Niamey shown earlier in Figure 3. This event was detected by five ELF receivers, strong evidence in itself that this lightning flash served to illuminate the entire Earth-ionosphere cavity with ELF radiation. Such a circumstance was achieved many years ago by Ogawa et al. (1967), but in the present case all receivers are equipped with a pair of orthogonal magnetic sensors. These observations enable both global triangulation, but also a detailed analysis of the magnetic polarization behavior and its control by the asymmetry by the Earth-ionosphere cavity (see the Appendix).

The global picture for this single powerful event is shown in Figure 6. This Figure shows all five great circle paths between receivers and lightning source, based on best estimates of magnetic direction finding for each receiving station. The intersection of great circle paths at the VLF-determined location of the lightning source is clearly imperfect, and this result is well known at ELF and is caused (in part) by the recognized departures from linear polarization in the horizontal magnetic field at ELF. Figure 7 shows the observed Lissajous patterns in the horizontal magnetic field at all five receiving stations. The departure from strict linear polarization is readily apparent in all cases. The Appendix presents a detailed analysis of these results with a model that includes the day-night asymmetry of the natural Earth-iononsphere waveguide and which is capable of producing simulated Lissjous patterns for the five receiving sites (Figure 8), for direct comparison with the observations in Figure 7. The strong similarity between observations and theory is evidence that the observed departure from linear polarization is caused by the day-night asymmetry.

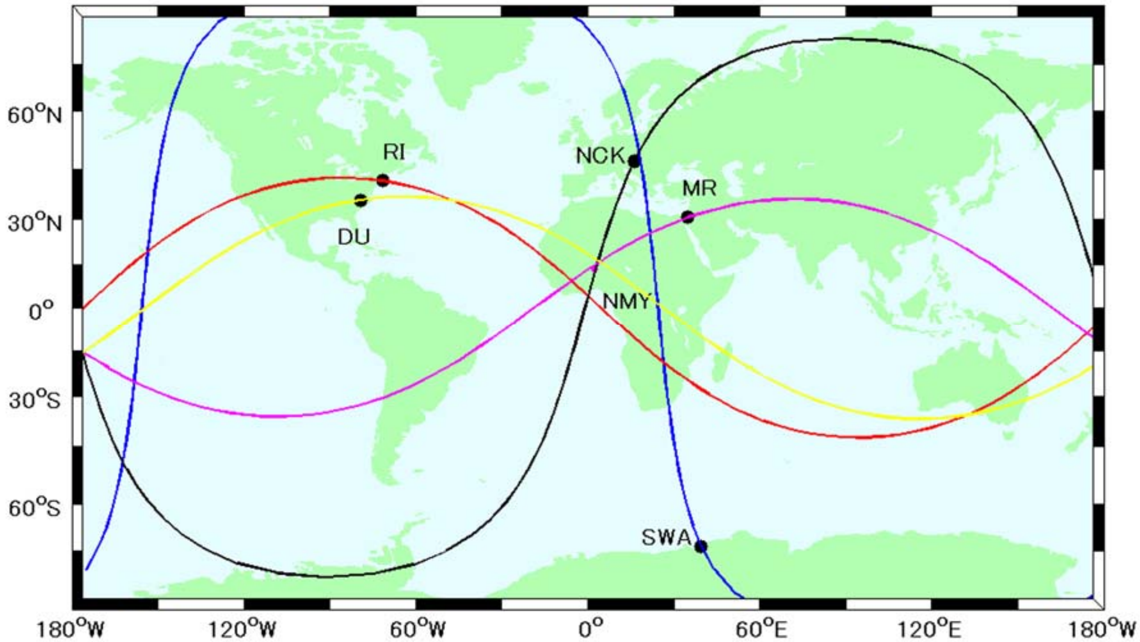

Figure 6   Great circle paths for reception of ELF radiation for a sprite event at 02:27:48.235 UT on September 21, 2005 at five receiving stations.

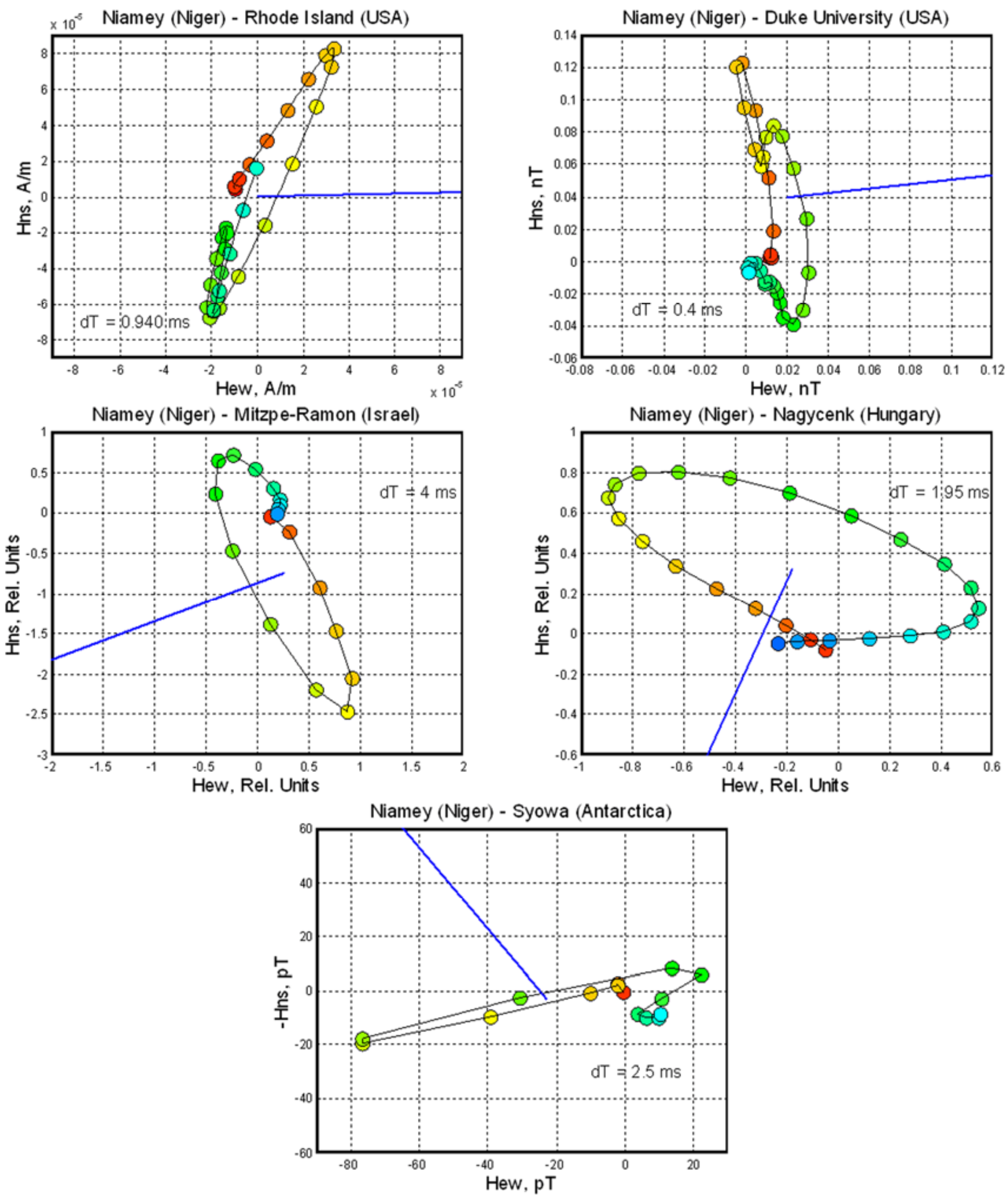

Figure 7 Observed magnetic Lissajous patterns in the horizontal magnetic field at multiple receivers for the strong lightning flash that produced the very bright sprite event at 02:27:48.235 UT on September 21, 2006.

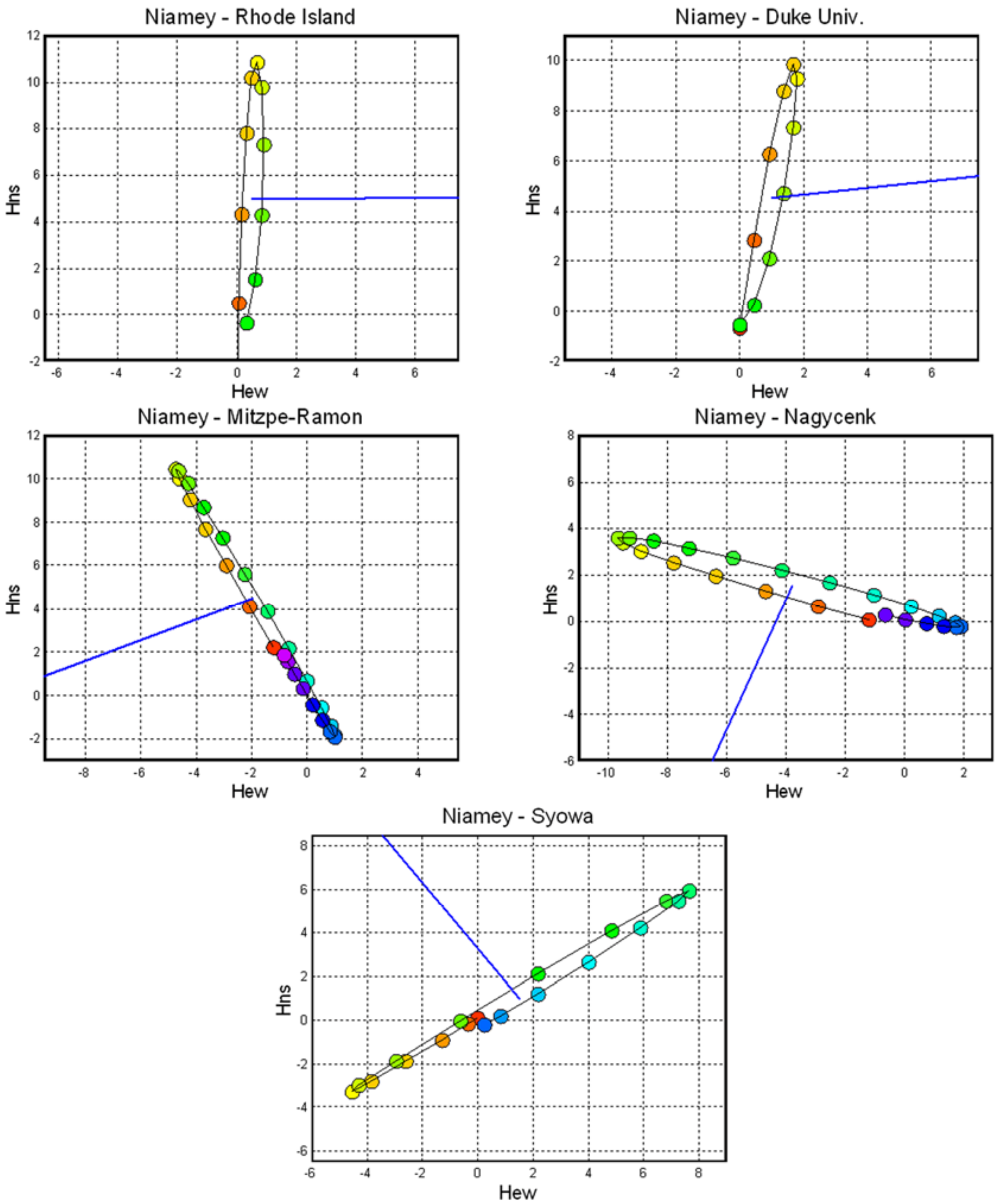

Figure 8 Simulated magnetic Lissajous patterns in the horizontal magnetic field on the basis of a transmission line model of the Earth-ionospheric cavity that includes the effect of the day-night asymmetry of the ionosphere.

4. Conclusions

The main conclusions in this study are as follows:

Sprites have been documented for the first time from the surface of the African continent, over mesoscale convective systems in Nigeria.

As many as six ELF stations have detected the radiation from the sprite parent lightning flashes. The polarities of all sprite events are positive. The polarity of one presumed halo event is negative.

The simultaneous locations of lightning flashes by two VLF networks show excellent agreement in both space and time. These accurate locations provide a sound basis for further analysis of these events at ELF.

Vertical charge moment estimates show good agreement among ELF receiving stations in most cases. The magnitudes of the charge moments are consistent with dielectric breakdown in the mesosphere as the cause for the sprites.

Analysis of the magnetic field polarization at ELF provides good evidence that the departure from linear polarization is caused primarily by the day-night asymmetry of the Earth-ionosphere cavity.

Appendix: Analysis of Magnetic Polarization Behavior for a Single Sprite-Related ELF Lightning Transient on September 21, 2006

One of the frequently observed features of ELF transient signals emanating from strong lightning flashes is their non-linear magnetic polarization. Figure 7 presents the magnetic Lissajous patterns (the time-domain plots of the north-south magnetic component versus the east-west one) simultaneously observed at five of the ELF stations (also listed in Table 1) and generated by a strong, reliably located (by both the WWLLN and ZEUS VLF networks) sprite event occurring east of Niamey (Niger, West Africa) at 13.46^{o}N, 5.09^{o}E on September 21, 2006 at 02:27:48.2408509 UT. The geographical locations of the source and the globally distributed observers are shown in Figure 7.

The general polarization pattern observed at all stations is a quasi-elliptical initial stage (its temporal dynamics is illustrated by the rainbow sequence of colors) followed by several less structured quasi-elliptical stages of smaller amplitudes (not shown in the plots). Another characteristic feature of each observed Lissajous pattern is a more or less pronounced deviation of the major axis orientation from the direction perpendicular to the source-observer great circle, indicated in each plot by a blue line.

The magnetic polarization behavior was discovered in the 1970's when a new technique for the global location of lightning discharges based on their ELF signatures had been suggested and applied (Kemp and Jones, 1971). In particular, Kemp (1971) considered the polarization effects in the frequency domain and found that the bearing determined from the ratio of orthogonal magnetic components critically depends on frequency and had to be averaged over the equipment's frequency range to obtain a reasonable bearing accuracy. (When analyzing a series of transients events generated at the Rhode Island ELF station by ground-true (optically located) sprites in Northern Australia (Williams et al., 2003), it was found that the bearing deviations estimated in the frequency and time domains are close to each other within a couple of degrees, which additionally confirms the objectivity of the findings.)

While there is a general agreement in the ELF community that the polarization behavior is attributable to the “desymmetrization” of the classical, spherically symmetrical model of the Earth-ionosphere waveguide (for which a linearly polarized Lissajous is predicted for a vertical lightning source), the actual hierarchy of “desymmetrizating” factors is yet to be established. While it is widely believed that the major factor is the ionospheric anisotropy resulting in the waveguide’s asymmetry due to the eccentricity of the geomagnetic dipole (Bliokh et al, 1980; Fullekrug and Sukhorukov, 1999), the theoretical simulations carried out by Nickolaenko and Hayakawa (2002) show that the geomagnetic hypothesis alone fails to interpret some well established polarization features – in particular, the temporal change in the sense of the magnetic ellipticity of the background Schumann resonance signal (Sentman, 1989). Sentman (1987, 1989) suggested an additional factor is the changeability of the ionospheric height due to the electrodynamic difference between the day- and nighttime hemispheres.

To explore the importance of the latter factor, simulations have been carried out using the two-dimensional telegraph equation (TDTE) method developed specifically for treating the irregularities and asymmetries of the ionosphere (Madden and Thompson, 1965; Kirillov, 2002). This method, based on a transmission line analogy (Madden and Thompson,1965), consistently follows the idea planted by Greifinger and Greifinger (1987) to consider two complex characteristic altitudes - $H_C(f)$ and upper $H_L(f)$ - that present in a condensed form the frequency-dependent electrodynamic properties of two dissipation layers within the lower ionosphere (Kirillov, 2002; Mushtak and Williams, 2002). In these simulations, the Grefinger et al. (2007) model of the lower characteristic altitude $H_C(f)$ has been exploited. The upper characteristic altitude $H_L(f)$, more complicated for modeling, has been derived so that the frequency dependences of the general ELF propagation parameters (the phase velocity and the attenuation factor) agree with their full-wave values computed directly from representative day- and nighttime ionospheric profiles (Galejs, 1972).

The simulated polarization patterns for the five ELF observers for this sprite-producing lightning flash are presented in Figure 8. Qualitatively, the simulations demonstrate the same features as the observations– non-linear polarization forms and deviations from the “geometrically-optical” orientations of the major axes, clear evidence that the day/night asymmetry plays a fundamental role in the polarization effects. To understand the physical cause for these effects, it is advisable to compare the ELF expressions for the magnetic components in a spherically symmetrical (uniform) and an asymmetrical (non-uniform) models of the Earth-ionosphere waveguide.

In the uniform model, the field is expressed via the Legendre function P_ν and the characteristic altitudes as (Mushtak and Williams, 2002)

$$H_\varphi^{SYMM}(f,\theta) \sim \frac{IdS(f)}{H_C(f)} \frac{1}{\sin[\nu(f)\pi]} \frac{dP_\nu[\cos(\pi-\theta)]}{d\theta}$$

(1)

where $IdS(f)$ is the current moment of the lightning source, θ and φ are the observer’s coordinates in a spherical system with the pole at the source’s location, the eigenvalue $\nu(f)$ is related to the ratio of the characteristic altitudes as

$\nu(f)[\nu(f)+1]=(ka)^2 H_L(f)/H_C(f)$, with k and a denoting the wave number and the Earth's radius, respectively.

In a non-uniform waveguide, the TDTE magnetic components generated at the observer's location $O \equiv \{a;\Theta_O,\Phi_O\}$ by a lightning source located at $S \equiv \{a;\Theta_S,\Phi_S\}$ can be symbolically presented as combinations of propagation factors dependent on the source-local (denoted by *S*), observer-local (denoted by *O*) and global (put in square brackets and denoted by $S \to O$) electrodynamic properties of the waveguide:

$$H_\Phi^{ASYMM}(f;S\to O) \sim IdS(f)\frac{H_L(f;S)}{H_C(f;S)}\frac{1}{H_L(f;O)}[\frac{\partial U(f;S\to O)}{\partial\Theta}],$$

(2)

$$H_\Theta^{ASYMM}(f;S\to O) \sim IdS(f)\frac{H_L(f;S)}{H_C(f;S)}\frac{1}{H_L(f;O)}[\frac{\partial U(f;S\to O)}{\partial\Phi}],$$

(3)

where $U(f)$ if the solution of the proper two-dimensional telegraph equation. (The specific form of the equation is of no principal importance in the present consideration but can be found, for instance, in the Kirillov (2002) work.) Generally, expressions (2)-(3) are formulated in an arbitrary spherical system of coordinates, but when treating the day/night asymmetry, it is both natural and convenient to use a coordinate system with its pole coinciding with the sub-solar point at the Earth's surface.

The comparison of (1) with (2)-(3) shows clearly the reason for the non-linear magnetic polarization of the observed ELF transient signals. In a hypothetical uniform waveguide, the magnetic field's (1) projections on any two orthogonal directions (including the NS and EW configuration) would be in phase with each other, and the resulting time-domain Lissajous pattern would be linear. In a real, non-uniform waveguide, the propagation of the Θ -component (normal to the day-night boundary) obviously differs from that of the Φ -component (tangent to the boundary), due to principal difference in the global propagational factors - $\frac{\partial U(f;S\to O)}{\partial\Phi}$ and $\frac{\partial U(f;S\to O)}{\partial\Theta}$, respectively. As a result, there is always a phase - and, generally, an amplitude - difference between these components (resulting in a non-linear time-domain polarization) that would be transferred to any other pair of orthogonal antennae, including the NS and EW configuration. (Of course, there are special scenarios – with one of the components being negligible in comparison with the other - when the non-linear polarization would degenerate into a linear one.) The same factor is responsible for to the deviation of the polarization ellipse's orientation from the "geometry-optical" one; a more detailed insight on this effect can be found in Williams et. (2007, 2008) where sprite-lightning-generated signals from a reliably located Australian storm are monitored, along with the temporal dynamics of their polarization features, for about four hours. Despite the qualitative agreement between theory and experiment shown here, both the ellipticities and to a lesser measure the deviations from "geometrically-optical" orientations of the simulated patterns, are generally less pronounced than the observed ones. This circumstance suggests a larger contrast between the day- and night-time conditions than that assumed in the simulations. No doubt, the exploited models – and that of the upper characteristic altitude, in the first place, - are yet to be carefully “tuned”, and the signals from ground-true sources (like the one considered in this section) do provide invaluable information for this inverse task. At the same time, both the data and especially the attendant conditions, are to be critically considered. In addition to the diversity of the experimental techniques exploited at different stations, deviations are evident between features observed at pairs of closely located (in the global ELF sense) stations: i.e., in the major axis’ orientation between the Rhode Island and Duke locations, and in the ellipticity between the Mitzpe-Ramon and Nagycenk stations. A more critical analysis of these observations is yet to be undertaken.

These observations and comparisons with theory provide a litmus test for considering what propagation factor – the ionospheric anisotropy or the general contrast between the day- and nighttime conditions – plays the major role in the polarization behavior. If the anisotropic factor were predominant, the polar Syowa station in Antarctica (as the one located in the most anisotropic section of the waveguide) would register the most pronounced effect. This prediction is not supported here, however. From the theoretical point of view, this finding is of little surprise: while the day/night contrast has a global hemispherical scale, the strongly pronounced ELF anisotropic effect (that depends only on the vertical projection of the geomagnetic field) is confined to the comparatively close proximity (10^{o} to 20^{o}) of the pole. Nevertheless, this preliminary consideration does not exclude the further exploration of the geomagnetic factor in future research.

Acknowledgements

Moustafa Boukari provided access to the Niamey control tower for video camera observations, ASECNA forecasters provided access to MeteoSat imagery to plan favorable camera pointing directions, and Les Pompiers at ASECNA and the DMN meteorologist in charge gave assistance in maintaining dark conditions for observations at the Airport. Nathalie Nathou, Alhassane Tidjani, Chaibou Oubandawaki, Eyal Freud, Abdou Ali, Adamou Mahamadou, and Guillem Lebel provided radar support for the sprite observations. Walt Lyons contribution to this study was partially supported by the U.S. National Science Foundation, Grant ATM-0649034 to Colorado State University and FMA Research, Inc. Jonathan D. Meyer analyzed the Niger videotape records. Dr. Jared Entin at NASA Hydrology supported the MIT radar operation in Niamey that ultimately allowed for the sprite observations reported here. Chris Thorncroft strongly supported this effort. The work on the sprite observations and attendant electromagnetic analysis was supported by the Physical Meteorology Program at NSF under Grant ATM-0734806. The contribution from Hungary was supported by grants NI 61013 and K72474 from the Hungarian Scientific Research Fund.

References

Ando, Y, P. Maltsev, A. Sukhynyuk, T. Goto, T. Yamauchi, Y. Hobara, M. Sekiguchi, Y. Ikegami, M. Sera, V. Korepanov, and M. Hayakawa, New ELF observation system at Moshiri, Japan and assessment of acquired data, J. Atmos. Electr., 25, 29-39, 2005.

Betz H.-D., K. Schmidt, P. Oettinger, M. Wirz, Lightning detection with 3-D discrimination of intracloud and cloud-to-ground discharges, Geophys. Res. Lett., 31, L11108, doi:10.1029/2004GL019821, 2004.

Bliokh, P.V., A.P.Nickolaenko, and Yu.F. Filippov. *Schumann resonances in the Earth-ionosphere cavity*. Peter Perigrinus, London, 1980.

Boccippio, D.J., E. Williams, S.J. Heckman, W.A. Lyons, I. Baker and R. Boldi, Sprites, ELF transients and positive ground strokes, Science, 269, 1088-1091, 1995.

Boeck, W.L., O.H. Vaughan, Jr., R.J. Blakeslee, B. Vonnegut, M. Brook and J. McKune, Observations of lightning in the stratosphere. J. Geophys. Res., 100, 1465-1475, 1995.

Boeck, W.L., O.H. Vaughan Jr., R. Blakeslee, B. Vonnegut and M. Brook, The role of the space shuttle videotapes in the discovery of sprites, jets and elves, J. Atmos. Solar-Terr. Phys, 60, 669-77, 1998.

Chen, A.B., C.-L. Kuo, Y-.J. Lee, H-.T. Su, R-.R. Hsu, J-.L. Chern, H. U. Frey, S. B. Mende, Y. Takahashi, H. Fukunishi, Y-.S. Chang, T-.Y. Liu, and L-.C. Lee, Global distributions and occurrence rates of transient luminous events, J. Geophys. Res., VOL. 113, A08306, doi:10.1029/2008JA013101, 2008

Christian, H.J., R.J. Blakeslee, D.J. Boccippio, W.L. Boeck, D.E. Buechler, K.T. Driscoll, S.J. Goodman, J.M. Hall, W.J. Koshak, D.M. Mach, and M.F. Stewart, Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, J. Geophys. Res., 108, 4005, doi: 10.1029/2002JD002347, 2003.

Cummer, S. A. and U. S. Inan, Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics, Geophys. Res. Lett., 24, 1731–1734, 1997.

Cummer, S. A., and U. S. Inan, Modeling ELF radio atmospheric propagation and lightning currents from ELF observations, Radio Science, 35, 385-94, 2000.

Cummer, S.A. and W.A. Lyons, Lightning charge moment changes in sprite-producing and non-sprite producing lightning, J. Geophys. Res., 110, A04304, doi:10.1029.2004JA010812, 2005.

Dowden, R., R.H. Holzworth, C.J. Rodger, J. Lichtenberger, N.R. Thomson, A.R. Jacobson, E. Lay, J.B. Brundell, T.J. Lyons, S. O'Keefe, Z. Kawasaki, C. Price, V. Prior, P. Ortega, J. Weinman, Y. Mikhailov, O. Veliz, X. Qie, G. Burns, A. Collier, O. Pinto, Jr., R. Diaz, C. Adamo, E.R. Williams, S. Kumar, G.B. Rada, J.M. Rosado, E.E. Avila, M.A. Cliverd, T. Ulich, P. Gorham, T.J.G. Shanahan, T. Osipowicz, G. Cook and Y. Zhao, World-wide lightning location using VLF propagation in the Earth-ionosphere waveguide, IEEE Antennas and Propagation Magazine, 50, 40-60, 2008.

M. Füllekrug and A.I. Sukhorukov, The contribution of anisotropic conductivity in the ionosphere to lightning flash bearing deviations in the ULF/ELF range, Geophys. Res. Lett., 26(8), 1109, 1999.

Füllekrug, M. and C. Price, Estimation of sprite occurrences in Central Africa, Meteorologische Zeitschrift, 11, 99, 2002.

Galejs, J., *Terrestrial propagation of long electromagnetic waves*. Pergamon Press, Oxford-New York-Toronto-Sydney-Braunschweig, 1972.

Greifinger, C. and P.Greifinger, Approximate method for determining ELF eigenvalues in the Earth-ionosphere waveguide. Radio Science, ***13***, 831-837, 1978.

Greifinger, P. S., V. C. Mushtak, and E. R. Williams (2007). On modeling the lower characteristic ELF altitude from aeronomical data, *Radio Science,**42***, RS2S12, doi:10.1029/2006RS003500.

Heckman, S., E. Williams and R. Boldi, Total global lightning inferred from Schumann resonance measurements, J. Geophys. Res., 103, 31775-31779, 1998.

Hobara, Y., N. Iwasaki, T. Hayashida, N. Tsuchiya, E.R. Williams, M. Sera, Y. Ikegami and M. Hayakawa, New ELF observation site in Moshiri, Hokkaido, Japan and the results of preliminary data analysis, Journal of Atmospheric Electricity, 20, 99-109, 2000.

Hobara, Y., N. Iwasaki, T. Hayashida, M. Hayakawa, K. Ohta and H. Fukunishi, Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves, Geophys. Res. Lett., 28, 935-938, 2001.

Hobara, Y., M. Hayakawa, E. Williams, R. Boldi and E. Downes, Location and electrical properties of sprite-producing lightning from a single ELF site, in *Sprites, Elves and Intense Lightning Discharges*. Ed. M. Fullekrug, E.A. Mareev and M.J. Rycroft, NATO Science Series, II. Mathematics, Physics and Chemistry 225, Springer, 398 pp., 2006.

Hu, W., S. Cummer, W.A. Lyons, and T.E. Nelson, Lightning charge moment changes for the initiation of sprites, Geophys. Res. Lett., 29, doi 10.1029/2001GL014593, 2002

Hu, W., and S. A. Cummer, An FDTD model for low and high altitude lightning-generated EM fields, IEEE Transactions on Antennas and Propagation, 54, 1513–1522, 2006.

Hu W., S. A. Cummer, and W. A. Lyons, Testing sprite initiation theory using lightning measurements and modeled EM fields, J. Geophys. Res., 112, D13115, doi:10.1029/2006JD007939, 2007.

Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson and C. Wong, Criteria for sprites and elves based on Schumann resonance observations, J. Geophys. Res., 104, 16943-16964, 1999.

Jacobson, A. R., R. Holzworth, J. Harlin, R. Dowden, and E. Lay, Performance assessment of the World Wide Lightning Location Network (WWLLN), using the Los Alamos Sferic Array (LASA) as Ground Truth, J. Atmos. Ocean Tech., 23, 1082-1092, 2006.

Kemp, D.T., The global location of large lightning discharges from single station observations of ELF disturbances in the Earth-ionosphere cavity. Journal of Atmospheric and Terrestrial Physics, ***33***, 919-927, 1971.

Kemp, D.T., and D.Ll. Jones, A new technique for the analysis of transient ELF electromagnetic disturbances within the Earth-ionosphere cavity. Journal of Atmospheric and Terrestrial Physics, ***33***, 567-572, 1971.

Kirillov, V.V., Solving a two-dimensional telegraph equation with anisotropic parameters. Radiophysics and Quantum Electronics, ***45***, 929-941, 2002.

Kotroni V., and K. Lagouvardos, Lightning occurrence in relation with elevation, terrain slope and vegetation cover over the Mediterranean. J. Geophys. Res. -Atmospheres, *(in press)*, 2008.

Lagouvardos, K.; Kotroni, V. Betz, H.; Schmidt, K., Assessment of the ZEUS lightning detection network over Europe by comparison with lightning data from LINET. 10th EGU Plinius Conference on Mediterranean Storms, Nicosia, Cyprus, 22-24 September 2008.

Laing, A.G. and J.M. Fritsch, Mesoscale convective complexes in Africa. Mon. Wea. Rev., 121, 2254-2263, 1993.

Lay, Erin H, A. R. Jacobson, R. H. Holzworth, C. J. Rodger, and R. L. Dowden, Local time variation in land/ocean lightning flash density as measured by the World Wide Lightning Location Network, J. Geophys. Res., 112, D13111, doi:10.1029/2006JD007944, 2007.

Lyons, W.A. and E.R. Williams, Preliminary investigations of the phenomenology of cloud-to-stratosphere lightning discharges. Preprints, Conference on Atmospheric Electricity, American Meteorological Society, St. Louis, MO., 8 pp., 1993.

Lyons, W.A., Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, J.Geophys. Res., 101, 29,641-29,652, 1996

Lyons, W.A., T.E. Nelson, E.R. Williams, S.A. Cummer and M.A. Stanley, Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems. Mon. Wea. Rev., 131, 2417-2427, 2003.

Lyons, W.A., The Meteorology of Transient Luminous Events – An Introduction and Overview, Chapter 1, NATO Advanced Study Institute, in *Sprites, Elves and Intense Lightning Discharges*, NATO Science Series II (Mathematics, Physics and Chemistry), Vol. 225, Springer Publishing House. M. Füllekrug, Ed., Corte, Corsica, 19-56 pp., 2006.

Lyons, W.A., S.A. Cummer, M.A. Stanley, K. Wiens and T.E. Nelson, Supercells and sprites. Bull. Amer. Meteor. Soc. , 1165-1174, doi: 10.1175/BAMS2439.1, 2008.

Lyons, W.A., M.A. Stanley, J.D. Meyer, T.E. Nelson, S.A. Rutledge, T.L. Lang and S.A. Cummer, The meteorological and electrical structure of TLE-producing convective storms, In, *Lightning, Principles, Instruments and Applications*, H.D. Betz et al. (eds). 389-417, Springer Science and Business Media B.V., doi: 10.1007/978-1-4020-9079-0_17, 2009.

Malan, D, Sur les décharges orageuses dans la haute atmosphere, Academie des Sciences, November 3 Session, 1937.

Madden, T., and W. Thompson, Low frequency electromagnetic oscillations of the Earth-ionosphere cavity. Reviews of Geophysics, ***3***, 211-254, 1965.

Miller, M.A. and A. Slingo, Atmospheric Radiation Measurements (ARM) Mobile Facility (AMF) and its first international deployment: Measuring radiation flux divergence, Bull. Am. Met. Soc., 88, 1225-1244, 2007.

Morel, C. and S. Senesi, A climatology of mesoscale convective systems over Europe using satellite infrared imagery, I. Methodology, Quart. J. Roy. Met. Soc., 128, 1953-1971, 2002.

Mushtak, V.C., and E.R. Williams, ELF propagation parameters for uniform models of the Earth-ionosphere waveguide, J. Atmos. Sol. Terr. Phys., ***64***, 1989-2001, 2002.

Nickolaenko, A., and M. Hayakawa, *Resonances in the Earth-ionosphere cavity*. Kluwer Academic Publishers, Dordrecht/Boston/London, 2002.

Ogawa, T., Y. Tanaka, M. Yasuhara, A.C. Fraser-Smith, and R. Gendrin, Worldwide simultaneity of occurrence of a Q-type ELF burst, J. Geomag. Geoelec., 19, 377-384, 1967.

Redelsperger et al., African Monsoon Multidisciplinary Analysis (AMMA): An international research project and field campaign, Bull. Am. Met. Soc., 88, No. 2, February, 2007.

Rodger, C. J., S. W. Werner, J. B. Brundell, N. R. Thomson, E. H. Lay, R. H.Holzworth, and R. L. Dowden, Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study, Ann. Geophys., 24, 3197- 3214, 2006.

Sátori, G., J. Szendrői, J., and J. Verő, Monitoring Schumann Resonances-I. Methodology, J. Atmos.Terr. Phys., 58 (13), 1475-1481, 1996.

Sátori, G., Schumann resonance observations, in Geophysical Observatory Reports of the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences, Nagycenk Geophysical Observatory, Year 2005-2006, Hillbrand nyomda Kft, ISBN 798-963-8381-22-4, 2007.

Sentman, D.D., Magnetic elliptical polarization of Schumann resonances. Radio Science, ***22***, 595-606, 1987.

Sentman, D.D., Detection of elliptical polarization and mode splitting in discrete Schumann resonance excitations. J. Atmos. Terr. Phys., ***51***, 507-519, 1989.

Tomasini, M., J.-P. LaFore, C. Pirou, R. Roca, K. Ramage, H. Laurent, C. Morel, and S. Senesi, Atlas on a climatology of West African mesoscale convective systems, AMMA-EU report Du 2/1/3/a., 2006.

Toracinta, E.R. and E.J. Zipser, Lightning and SSM/I-Ice-scattering mesoscale convective systems in the global tropics, J. Appl. Met., 40, 983-1002, 2001.

Vaughan, Jr., O.H., R. Blakeslee, W.L. Boeck, B. Vonnegut, M. Brook and J. McKune, Jr., A cloud- to-space lightning as recorded by the Space Shuttle payload bay TV cameras. Mon. Wea. Rev.,120, 1459- 1461, 1992.

Williams, E.R., Sprites, elves and glow discharge tubes, Physics Today, November, 41-47, 2001.

Williams, E.R. and G. Sátori, Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys, J. Atmos. Sol. Terr. Phys., 66, 1213-1231, 2004.

Williams, E. and Y.Yair, The microphysical and electrical properties of sprite-producing thunderstorms, in *Sprites, Elves and Intense Lightning Discharges*, (Ed., M. Füllekrug) NATO Science Series, II. Mathematics, Physics and Chemistry 225, Springer, Dordrecht, Netherlands, 398 pp., 2006.

Williams, E., E. Downes, R. Boldi, W. Lyons and S. Heckman, Polarity asymmetry of sprite-producing lightning: A paradox?, Radio Sci., 42, RS2S17, doi:10.1029/2006RS003488, 2007.

Williams, E.R., V.C. Mushtak, R. Boldi, R.L. Dowden, and Z.-I. Kawasaki, Sprite lightning heard round the world by Schumann resonance methods. Radio Science, ***42***, RS2S20, doi:10.1029/2006RS003498, 2007.

Williams, E.R., V.C. Mushtak, R. Boldi, R.L. Dowden, and Z.-I. Kawasaki, Reply to comment by A. P. Nickolaenko and M. Hayakawa on "Sprite lightning heard round the world by Schumann resonance methods". Radio Science, ***43***, RS3009, doi:10.1029/2007RS003778, 2008.

Wilson, C.T.R, The electric field of a thundercloud and some of its effects, Proc. Roy. Soc. London, 37, 32D, 1925. 1925

Yair, Y., P. Israelevich, A.D. Devir, M. Moalem, C. Price, J.H. Joseph, Z. Levin, B. Ziv, A. Sternlieb and A. Teller, New observations of sprites from the space shuttle, J. Geophys. Res., 109, D15201, doi:10.1029/2003JD004497, 2004.

Tables and Figures

Table 1 Summary of 14 sprite events detected from Niamey, Niger, on August 30 and September 21, 2006, together with documentation on ELF and VLF detections from multiple sites, including the estimated vertical charge moment for the parent lightning flashes.

Figure 1 MeteoSat imagery for 23:30 UT on August 30, 2006 showing large MCS east of Niamey, and the location (green star) of the parent cloud-to-ground lightning flash for the sprite at 23:20:47.101932 UT determined by the WWLLN.

Figure 2 MeteoSat imagery for September 21, 2006 at 02:30 UT nearest the time of the sprite observed from Niamey at 02:27:48.235 UT. The green star shows the location of the parent ground flash located by the VLF networks WWLLN and ZEUS, which are within about 20 km of each other (and small compared to the size of the star).

Figure 3 Sprite image recorded in Niamey, Niger for the event at 02:27:48.235-268 UT (Table 1) on September 21, 2006.

Figure 4 Comparisons of charge moments from different ELF receiving sites for all 14 events in Table 1.

Figure 5 Pairwise comparison of vertical charge moments for common sprite lightning events recorded in (a) Hungary and the USA (Duke) on both days, and in (b) Israel and in Japan for sprite events on August 30. The diagonal line represents the line of perfect agreement.

Figure 6 Great circle paths for reception of ELF radiation for a sprite event at 02:27:48.235 UT on September 21, 2005 at five receiving stations.

Figure 7 Observed magnetic Lissajous patterns in the horizontal magnetic field at multiple receivers for the strong lightning flash that produced the very bright sprite event at 02:27:48.235 UT on September 21, 2006.

Figure 8 Simulated magnetic Lissajous patterns in the horizontal magnetic field on the basis of a transmission line model of the Earth-ionospheric cavity that includes the effect of the day-night asymmetry of the ionosphere.