

# ZEUS Long-Range Lightning Detection System

Emmanouil N. Anagnostou  
Civil and Environmental Engineering  
University of Connecticut  
Storrs, CT 06250

<http://www.engr.uconn.edu/ZEUS>

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## 1. ZEUS Background

Funded by the *National Science Foundation* (Water Cycle Program), with joint support by the *Hellenic General Secretariat for Research and Development* provided to the National Observatory of Athens collaborating in this project, we have deployed, and been operating an experimental long-range lightning detection system named ZEUS (Anagnostou et al. 2002). The system, built by Resolution Displays, Inc., consists of a network of ten Very Low Frequency (7-15 kHz) radio receivers (named “sferics”) located in the European and African continents. Sferics is the radio noise emitted by lightning over a broad region of the electromagnetic spectrum, which in the VLF band can propagate over thousands of kilometers in the earth-ionosphere wave-guide. The system is designed to take full advantage of modern computing technology, signal processing algorithms, GPS, and communications networking capabilities in order to optimize ground-based receiver design for long-range detection (<http://sifnos.engr.uconn.edu>). ZEUS’ receivers are presently situated in Europe and Africa (see Figure 1). These sites, selected for their low man-made electric noise interferences, include: Birmingham [UK], Roskilde [Denmark], Iasi [Romania], Larnaka [Cyprus], Evora [Portugal], Addis Ababa [Ethiopia], Dar e Salaam [Tanzania], Bethlehem [South Africa], Lagos [Nigeria], and Dakar [Senegal]. *Figure 1* shows the receivers’ locations overlaid on a global map of multi-year lightning climatology derived from the TRMM (Tropical Rainfall Measuring Mission) Lightning Imagine Sensor (LIS) observations. The deployment of the European receivers (henceforth Zeus01 configuration) was completed in June 2001 (Chronis and Anagnostou 2003), while the installation of the African receivers (henceforth Zeus03 configuration) was completed in July 2003 (Chronis and Anagnostou 2006). ZEUS system with its current configuration of stations can be used to monitor lightning activity on a continuous basis over Europe, Africa and surrounding waters (shown by the box of Figure 1). As shown in Figure 2, ZEUS can also detect lightning activity over the U.S. East Coast, South America, the Atlantic Ocean and West Asia, but with decreased locating accuracy (Chronis and Anagnostou 2006).

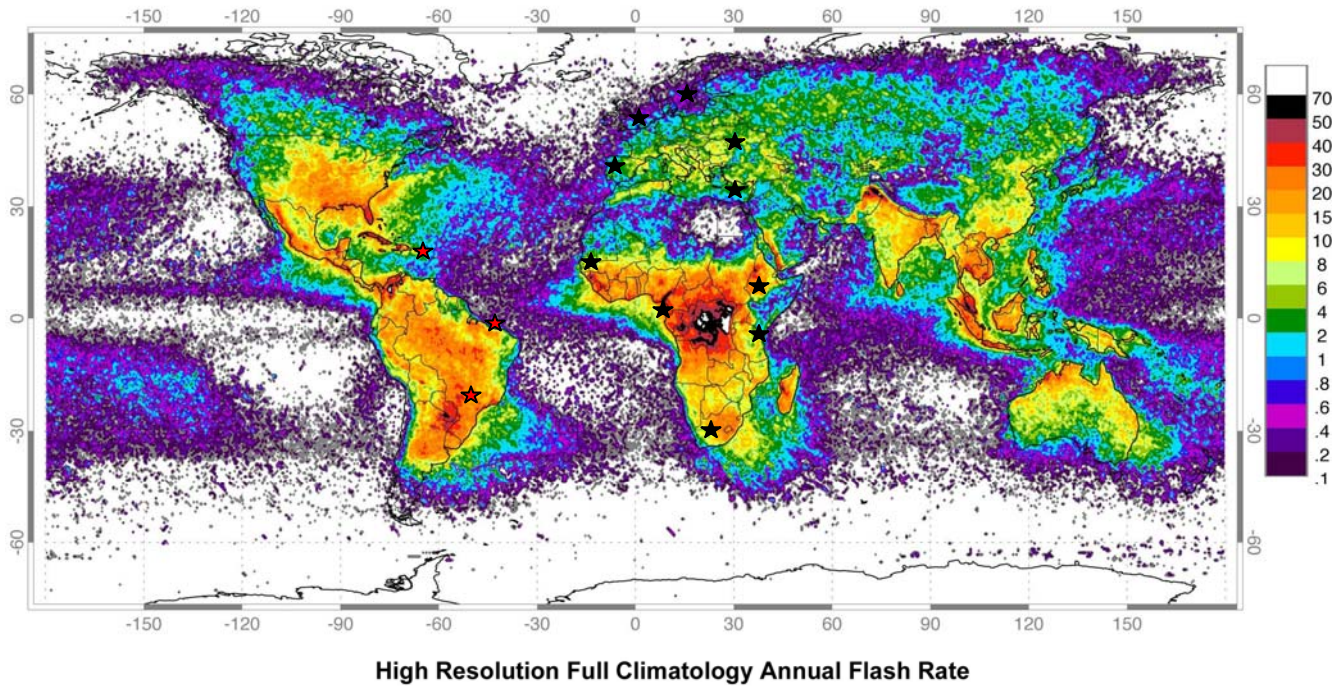
Long-range lightning detection systems based on VLF receivers (like ZEUS) can primarily detect CG lightning strikes (Morales 2001). A typical CG lightning strike excites sferics that propagates along the ground (ground wave) and bounce off between the Earth’s surface and the lower part (D-layer) of the ionosphere (sky wave). Each receiver samples the vertical electric field of the propagating sky wave. The sampled time series from all receivers are synchronized using a time stamp from a GPS clock. The ZEUS’ locating algorithm relies on the Arrival Time Difference (ATD) technique (Lee 1986a,b). Namely, measured ATD values are extracted for every receiver pair by maximizing the temporal cross-correlation of the waveforms sampled by each receiver. Theoretically, an ATD pair between receivers “i” and “j” is defined as:

$$ATD_{i-to-j} = \frac{S_i}{V_i} - \frac{S_j}{V_j} = T_i - T_j \quad (1)$$

where  $S_i$  and  $S_j$  are the distances (km) of the lightning source to the  $i^{th}$  and  $j^{th}$  receiver;  $V_i$  and  $V_j$  are the associated wave propagation velocities (km/sec) and  $T_i$  and  $T_j$  represent the time when the two receivers recorded the signal. An ATD defines a hyperbola of possible lightning source positions over the Earth's surface associated with the same arrival time difference. Combining the hyperbolas of all ATD pairs (40 pairs for the 10-receiver network), we can identify a common point of intersection, which uniquely defines the location of the lightning strike. The inverse solution of locating the intersection point of the hyperbolas is computationally defined by the minimization of the following cost function (Lee 1986a):

$$\chi^2 = \sum_{p=1}^{15} \left\{ \frac{1}{\sigma_p^2} \left( ATD_p^{Measured} - ATD_p^{Simulated}(V, u) \right)^2 \right\} \quad (2)$$

Subscript “ $p$ ” denotes the ATD pair index. “Measured” superscript symbolizes ATD values for a lightning strike recorded by ZEUS system. “Simulated” superscript indicates the theoretical ATD values calculated on the basis of the propagation path (from the strike location ( $u$ ) to the receivers) and the modeled sferics group velocity along that path ( $V$ ) (Chronis and Anagnostou 2003). The  $\sigma^2$  is the measurement and modeling error variance (given in  $\mu\text{secs}^2$ ) of each ATD pair. This error is mostly related to technical specifications of the receiver sensitivity and time resolution. In this application the value of  $\sigma^2$  is typically considered the same for all ATD pairs (i.e., pairs have equal weight in determining Eq. 2).



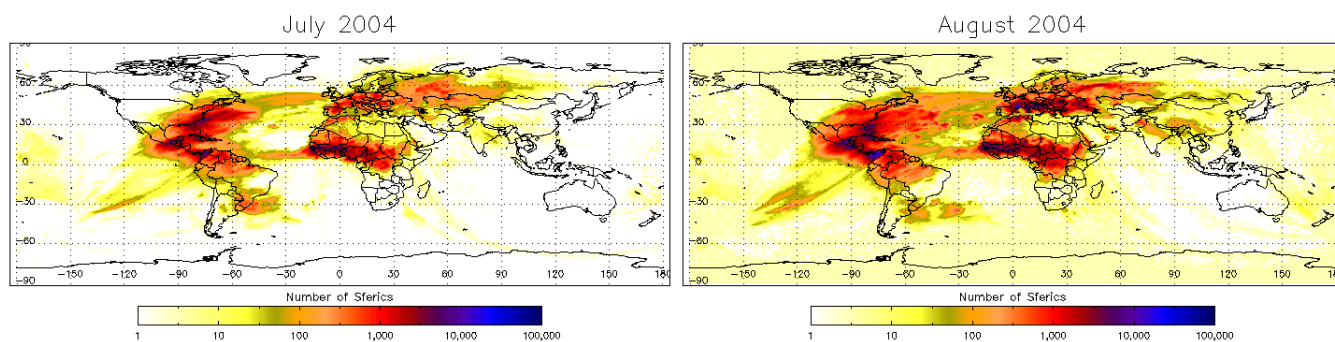
**Figure 1:** Global distribution of lightning (April 1995–February 2003) from the combined observations of the NASA OTD and TRMM-LIS earth orbiting satellite sensors. The stars represent approximate locations of the current (black) and upcoming expansion (red) ZEUS network receivers.

To attain a unique solution from Equation (2) minimum of four receivers are required to record the same event. Furthermore, due to multiple sferic reports from lightning strikes occurring over greatly varying

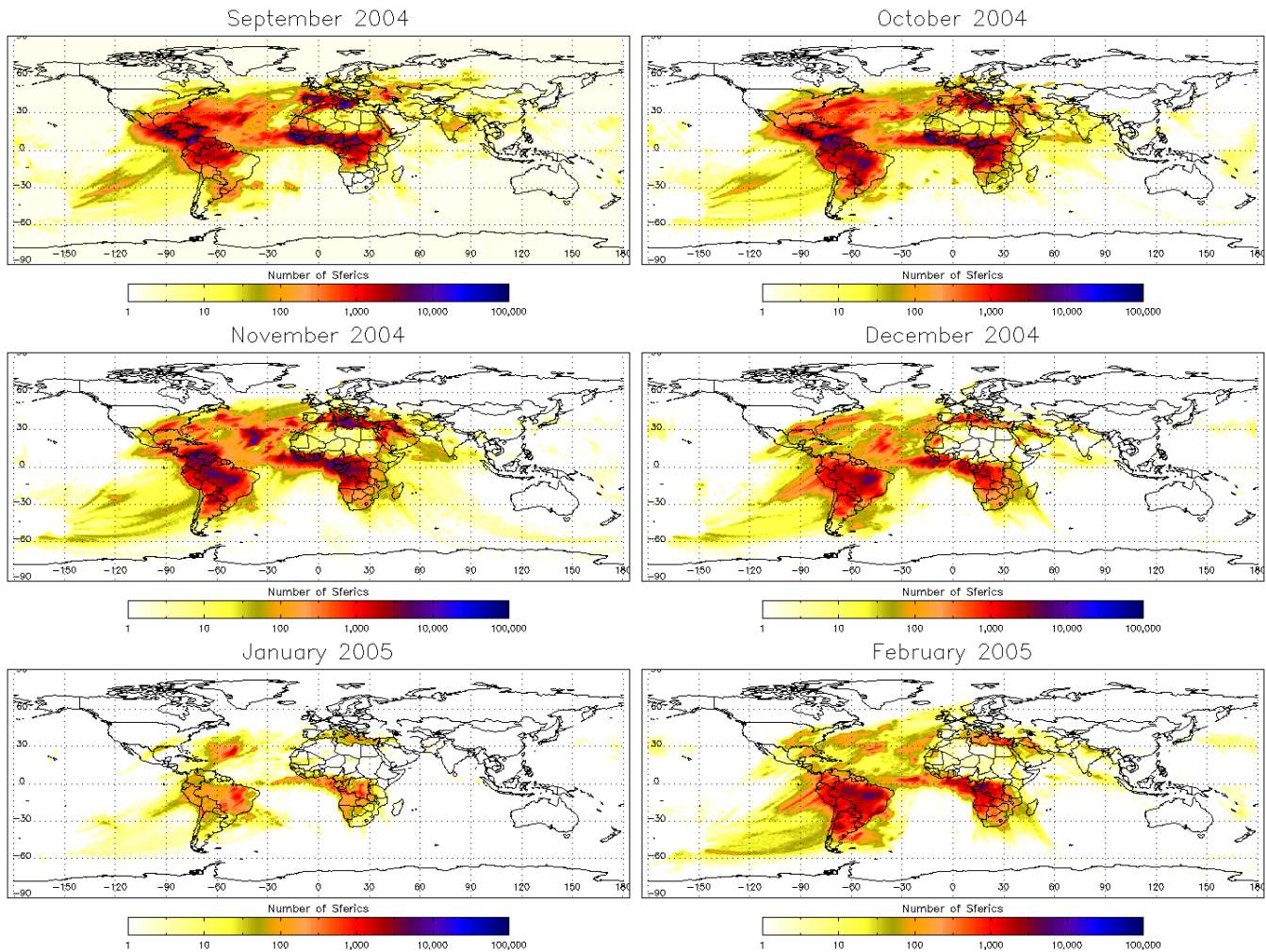
distances from each receiver, the sferic report for any particular strike is often interspersed with reports from other strikes in a non-sequential manner. To address this issue, the locating algorithm searches for reports from among the receivers that are likely same-strike candidates and then confirm their relationship. This process suffers a “combinatorial explosion” when the network area is large. To handle this problem ZEUS network is divided into two continent-sized regions (Europe and Africa), containing seven receivers each. The European cell consists of the five European receivers plus two receivers located in Africa (Ethiopia and Senegal). The African cell consists of the five African receivers plus the Cyprus and Portugal receivers of Europe. The candidate data from those cells are then combined and the final strike location is optimized according to Eq. 2. This allows a satisfactory compromise in computational load versus desired accuracy. The locating procedure described in Equation (2) can be ill posed. This issue arises particularly when the lightning event is located outside the network’s periphery. Under these circumstances, the minimization problem suffers from the so-called multiple minima convergence. Namely, solutions for Equation (2) located outside the periphery (main solution domain) tend to be non-unique. At the same time,  $\chi^2$  is no longer defined by a unique point but rather a group of points defining an area of “multiple local minima”. Below we present measurements and discuss error characteristics of the system.

## 2. ZEUS Measurements

In Figure 2 we present global distributions of monthly lightning accumulation measured by ZEUS system for the period July 2004 to February 2005. Points to note are that ZEUS system with current receiver configuration can detect lightning activity over Europe, Africa, Central-South America and surrounding waters (Atlantic Ocean). The geographic regions exhibiting erroneous patterns in the lightning data (e.g., Northern South America, Central America, Pacific Ocean, South Asia) are associated with poorly defined minima in the  $\chi^2$ -surface. This causes the locating algorithm’s optimization scheme to converge to locations that are distant from the “true” lightning location ( $\chi^2$ -problem—Chronis and Anagnostou, 2003 and 2006). This  $\chi^2$ -problem is mostly apparent in the Northwestern South America, Central America, Northern Atlantic, East Pacific and parts of Indian Ocean. Those are regions where the network receiver-pairs’ ATD hyperbolas become almost parallel, thus significantly decreasing the sensitivity of  $\chi^2$  surface around the minimum. In such situations measurement noise and errors in modeling the signal’s wave velocity would make the locating algorithm to converge to sub-optimal solutions that as mentioned above can be far from the “true” lightning source location. Experimental and simulation based evaluations of the location retrieval error of ZEUS network for different regions have been described in Chronis and Anagnostou (2003 and 2006). To optimize ZEUS accuracy in the Western Atlantic/East Pacific we plan to supplement ZEUS network with three new receivers (two to be located in Brazil) and one in Puerto Rico (see Figure 1). Details on this design are discussed in the subsequent section.







**Figure 2:** Monthly ZEUS measured lightning accumulation for the period July 2004 to February 2005.

### 3. Current Status of the Network

The network was operational till June 2005. Currently the African network is taken down to repair problems that occurred in three of the African receivers (Ethiopia, Nigeria and Tanzania), establish a new 3-year term agreement with the Institute of Environmental Research and Sustainable Development of the National Observatory of Athens (IERSD-NOA) that owns the European receivers, and to re-negotiate Internet contracts with local Internet providers for the next three years. The system continuation is contingent upon the availability of funds by the National Science Foundation (proposal is currently under review by the Climate Dynamics program).

Currently, we are reprocessing ZEUS lightning location retrievals on the basis of the combined Europe-Africa ZEUS network observations in the period August 2003 to May 2005. Reprocessing is needed to include receiver station measurements that were not used during the real-time processing of the system due to delays in data transferring. Completion of ZEUS data reprocessing is expected by May 2006. At that time a CD containing ZEUS lightning retrievals over a two-year period (Aug 03-May 05) will be produced and distributed to scientific community.

## 4. Network Expansion

To optimize the locating accuracy of ZEUS system over Central-South America, Western Atlantic and the Southwest Asia region we plan to relocate one of the African receivers (Nigeria) to Bangladesh, and deploy three new receivers to augment the existing network. Two of the new receivers will be located in Brazil (Sao Paolo and Fortaleza), and the third in Puerto Rico. The two new receivers to be located in Brazil are contributed by Prof. Carlos Morales through a Brazilian Science Foundation grant, while the third receiver to be located in Puerto Rico is contributed by Prof. Phanord of the University of Nevada in Las Vegas (UNLV). The timeframe of the expected new sensor deployment is **May to July 2006**. Following the new sensor deployment will be the system integration and testing of the new ZEUS lightning locating algorithm. This will improve ZEUS lightning monitoring capabilities over the Atlantic and East Pacific Oceans, Central-South America, and Southwest Asia. Error simulations conducted based on a hypothetical 20- $\mu$ sec-time measurement error at each receiver, combined with a hypothetical 0.05% error in the estimated speed-of-light along each propagation path (Morales 2001; Chronis and Anagnostou 2006, 2003), have shown an expected average location accuracy of 20 km, and no directional preference, for the expanded network over the longitudinal / latitudinal zone of 90°E-90°W 50°N-40°S.

The first algorithm upgrade involves handling the increase in the ZEUS network dimension. The algorithm will need to accommodate multiple sferic reports from receivers that are located over ranges that are up to five times longer than the current ZEUS system. Because lightning strokes occur over greatly varying distances from each receiver, the sferic report for any particular stroke is often interspersed with reports from other strokes in a non-sequential manner. The locating algorithm would search for reports from among the receivers that are likely same-stroke candidates and then confirm their relationship. This process suffers a “combinatorial explosion” when the network area roughly quadruples due to our expansion. To handle this problem the expanded network will be divided into several continent-sized regions, containing six or seven receivers each. The candidate data from the regions would then be combined and the final stroke location optimized. This allows a satisfactory compromise in computational load and desired accuracy/detectability. This algorithm upgrade will be completed in approximately three to six months from the time we start collecting data.

The second algorithm upgrade involves examining and improving the mathematical methods for retrieving lightning locations. This involves assessing both the *analytic methods* for obtaining a first estimate of the source location, and the subsequent *nonlinear numerical methods* applied to iteratively improve upon the first estimate. The location retrieval process, which is formally a problem in mathematical inversion theory, will be examined by Dr. Koshak (NASA/MSFC). For the past 20 years, Dr. Koshak has played an active role in analyzing a wide variety of lightning retrieval problems at various lightning source frequencies (electrostatic, VLF/LF/VHF radio, and optical frequencies). He has developed locating algorithms applicable to several different types of networks that use radio arrival time technology [e.g., Lightning Detection and Ranging (LDAR), Advanced Lightning Direction Finder (ALDF), and North Alabama Lightning Mapping Array (LMA)]. In this work effort, Dr. Koshak will apply the latest long-range retrieval theory provided in Koshak and Solakiewicz (2001) to the ZEUS system. Variable wave propagation velocities will be considered. Both Monte Carlo computer simulations and standard chi-squared Curvature Matrix theory statistical inferences will be used to assess algorithm retrieval errors. A location error map for the entire ZEUS Analysis Region (ZAR) will be generated showing regions of both optimum accuracy and those regions containing source location ambiguity. Application of the retrieval theory in Koshak and Solakiewicz (2001) and a finalized error map for the

ZAR will be completed in 2006-07 timeframe. To verify many portions of the expansive ZAR error map, location errors will also be evaluated experimentally on the basis of local networks in the US (NLDN) and South America (Brazil, West Amazon and Costa Rica), and by using airborne data and LIS (if available). Qualitative (visual) comparisons will also be performed by overlaying lightning fixes on VIS/IR cloudiness observations from geo-stationary satellites. These are studies we have successfully performed with past sferics data in North Atlantic (Morales and Anagnostou 2003; Morales 2001) and currently in Europe and Africa (Chronis and Anagnostou 2006, 2003).

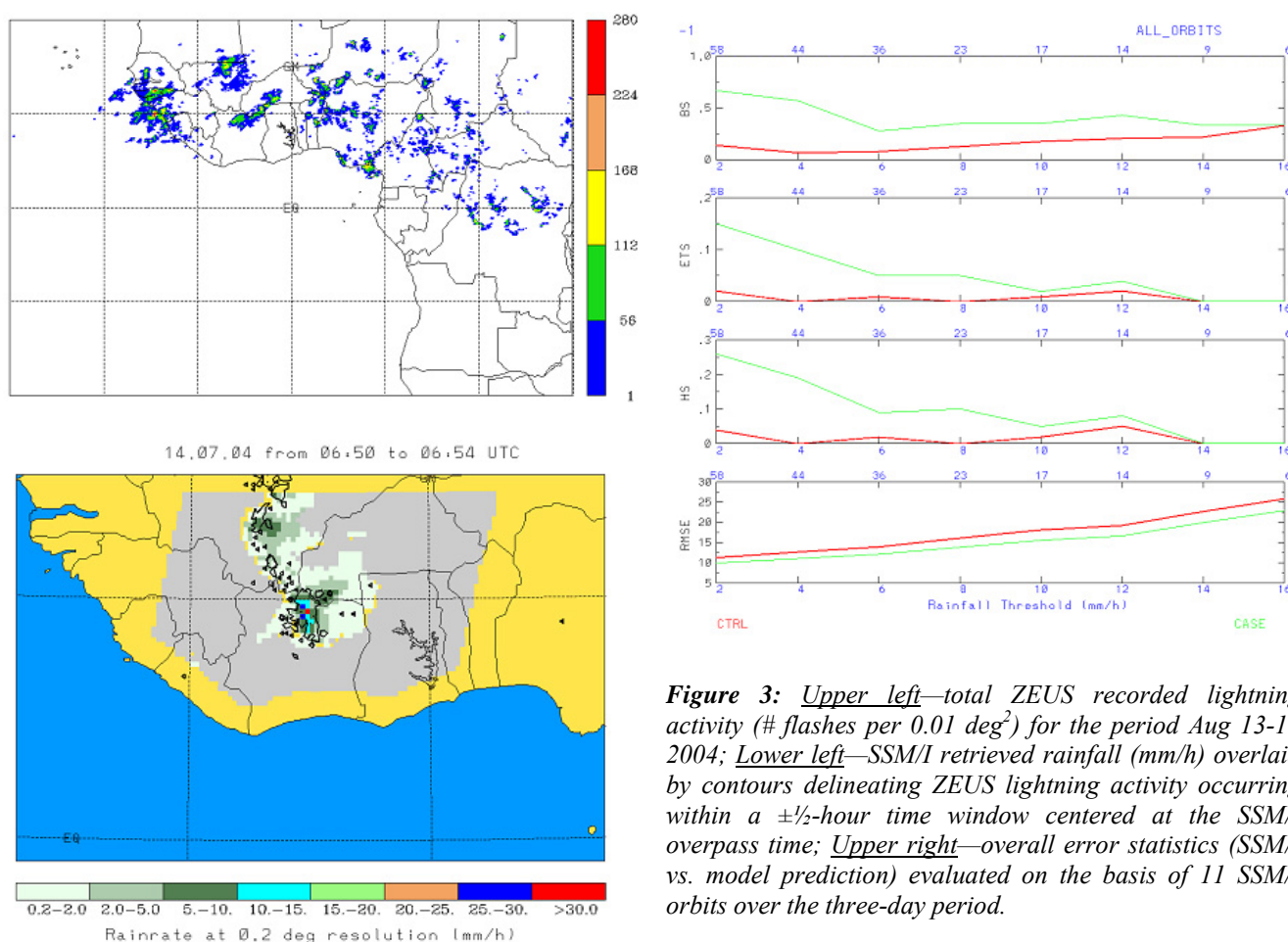
## 4. Contributions to Science

ZEUS system is unique in the sense that it provides continuous measurements of CG lightning activity over a very large region (almost half of the globe) with high locating accuracy (~20 km mean error global) and detection efficiency (~60% of CG flashes). Summary of ZEUS contributions to science and hydrologic / meteorological applications is provided below.

Hydrology & Continental Water Cycle: A critical aspect in investigating water and energy cycle is the need to resolve the continental-scale land surface hydrological processes at high temporal (hourly to 3 hours) and spatial (1-10 km) resolutions. This is important as the physical processes that dictate land-vegetation-atmosphere interactions occur at these fine space-time scales. Although, Land Surface Models (LSMs) are capable of modeling land-atmosphere interactions at resolutions down to 1-km, the most current attempts to estimate rainfall near those scales have relied on proxy data (e.g., Infrared-IR, from Geo-stationary satellites) merged with that of infrequent but more physically-based passive microwave estimates (e.g., Todd et al. 2000; Huffman et al. 2003; Turk et al. 2003; Tapiador et al. 2004; Marzano et al. 2004). Unfortunately, the desired progression to finer scales in satellite rain retrieval is counter-balanced by the increasing multi-dimensionality of error, which has a consequentially complex effect on propagation through land surface-atmosphere interaction simulations (Anagnostou, 2006; Hossain and Anagnostou, 2006a,b; 2005a,b; 2004; Hossain et al., 2004a,b,c). In essence, this represents a competing trade off between lowering the rain retrieval error and modeling land-vegetation-atmosphere processes at the finest scale possible. Fortunately, recent studies have shown that the inclusion of continuous lightning observations (proxy to convective precipitation) in satellite observations improves the physical basis of the retrieval facilitating higher resolution rain estimates (<0.1 deg) and improved accuracy in the estimation of higher (convective) rain rates (Morales and Anagnostou 2003; Chronis et al. 2004). This advancement in high-frequency satellite rain estimation was further corroborated by Anagnostou et al. (2004a) to have consequential improvements on the accuracy of LSM simulations.

Numerical Weather Prediction: Outputs from regional/mesoscale numerical weather prediction (NWP) models are used to issue short-to-medium-range (up to 6-48 hours) quantitative precipitation forecasts (QPF) to support floods and other severe weather management systems. At the scales typically used by regional NWP, numerical models exhibit low skill at forecasting highly variable convective precipitation events. Collective evidence from past studies indicates that improved initialization of the local environment in NWP models (particularly those of moisture and temperature) is an avenue for potentially improving QPF as it relates to simulated convective precipitation. To this end, continuous lightning observations provide wealth of information about the growth, location, lifecycle and ice microphysics of convection in MCS regimes. Charge separation leading to lightning is a physical process that takes place in regions of a thunderstorm associated with rigorous vertical forcing. Arguably, developing a way to modify model-generated variables (e.g., humidity and temperature profiles) on the basis of lightning location and intensity could result in more accurate parameterizations of the convective environment. Making use of the sound link between lightning occurrence and convection, a technique was recently developed by Papadopoulos et al. (2005a) to amend the initialization data inadequacies and limitations in formulating sub-grid scale processes using continuous regional lightning observations from ZEUS network. The study has shown that nudging model humidity profiles to empirical profiles related to flash rates, leads to more realistic model soundings and consequential improvements in convective precipitation forecasts. This study was recently expanded to demonstrate the assimilation capabilities in different regions (Europe, US, and Africa). Example from an application (Papadopoulos et al. 2005b) of the ZEUS

lightning assimilation technique to predict convective storms over a period of three days (13-15 August) in West Africa is presented in *Figure 3* below. In this experiment, control (CTRL) and ZEUS-lightning-nudged (CASE) mesoscale model runs were performed using NCEP reanalysis initial and boundary condition fields. Model predictions are compared against corresponding instantaneous 0.2-deg gridded rainfall fields derived from SSM/I observations (Dinku and Anagnostou 2005). The following points are noted: The intense rainfall observed by SSM/I is well correlated with regions of ZEUS-detected lightning activity. Significant improvement is demonstrated comparing CTRL and CASE rainfall field error statistics: Bias Score—BS, Equitable Thread Score—ETS, Hiedle Score—HS, and Root-Mean-Square Error—RMSE. The collective evidence from the Papadopoulos et al. (2005a,b) studies indicate the capability of lightning data nudging to trigger and enhance convection in mesoscale models.

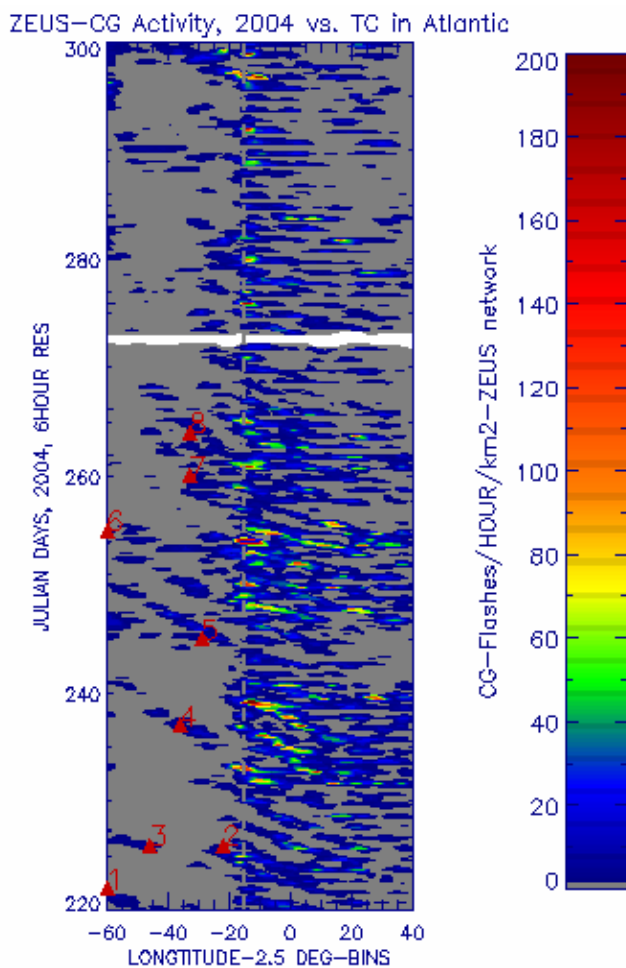


**Figure 3:** *Upper left*—total ZEUS recorded lightning activity (# flashes per 0.01 deg<sup>2</sup>) for the period Aug 13-15 2004; *Lower left*—SSM/I retrieved rainfall (mm/h) overlaid by contours delineating ZEUS lightning activity occurring within a  $\pm 1/2$ -hour time window centered at the SSM/I overpass time; *Upper right*—overall error statistics (SSM/I vs. model prediction) evaluated on the basis of 11 SSM/I orbits over the three-day period.

**Tropical Convective System Characteristics:** ZEUS data can be used in synergy with satellite observations (TRMM and Global IR) to study the life cycle of tropical mesoscale convective systems (MCS), the associated precipitation intensity and variability, convective precipitation fraction, and associated lightning dynamics. This would facilitate the study of relationships between convective dynamics (in terms of convective precipitation intensification and storm kinematics) and storm microphysics as related to the production of flash rates within an MCS for different meteorological conditions. The availability of continuous large-regional lightning observations from ZEUS network would uniquely facilitate this investigation in tropical regions like Africa and Amazon.



**Tropical Cyclone Monitoring:** The enhanced ZEUS lightning detection over the African continent and the Eastern Atlantic Ocean allows the continuous monitoring of CG lightning activity during the period of amplified Tropical Cyclogenesis (TC) during the summer months and the AEW activity. The AEW are westward propagating disturbances, with varying periods (3-6 days) and typical wavelengths ranging from 2,500-3,000 km. Although AEW are known to modulate West African rainfall they are also known to have a significant impact on Atlantic tropical TC activity (Burpee 1976). The AEW activity on an annual basis depicts repetitive characteristic, varying from 30-60 waves per boreal warm season or an average between 6-10 waves per month, May-November). An approximate 10% of these disturbances serve as “seeds” for the genesis of TC and potential hurricane formation off the West African Coast, especially in the latitudinal band between 10N-15N (Carlson 1969). Figure 4 illustrates the ZEUS recorded CG activity for the region as well as the TC formations recorded between August and September 2004. ZEUS shows ability to monitor the AEW tracks, their lifecycle starting from the inland continent reaching the coast of West Africa and either cease or intensify into TC along their Eastern Atlantic path. The same figure indicates that despite the comparably low frequency of oceanic CG activity, the TC formations highly coincide with the birthplace of oceanic thunderstorms. Lightning activity has been documented as a trustworthy precursor for severe weather (Williams et al 1998) and potential tornadic activity. Our goal with ZEUS measurements is now to investigate in depth the implications between CG activity trends and formation and/or intensification of TC events. (“Lightning as a Potential Precursor of Tropical Cyclogenesis”, manuscript to be submitted to *Science*).



**Figure 4:** Zeus CG activity AEW-related (100 days in 2004) over Africa and East Atlantic. Dotted vertical line represents the rough longitudinal (17W-15W) location of the West African coastline around the latitudinal band 0-15 N. The red-colored numbers represent the TC formed during that period according to CIMSS. '1' Charley, '2' Danielle, '3' Carl, '4' Frances, '5' Ivan, '6' Jeanne, '7' Karl and '8' Lisa.

Monitoring the Impact of Traveling Global Planetary Waves on Tropical Convection: The modulation of synoptic convective regimes by planetary waves has been demonstrated by numerous studies with the majority having turned the focal point on the modulation of the monsoon period over the Indian Ocean by the Madden-Julian Oscillation (MJO) (Martyn 1992; Madden and Julian 1994). The 73-year sea-level pressure time series analysis by Madden and Julian (1972) has provided evidence of a direct implication of the role of the 5-day wave in the planetary circulation and synoptic weather patterns. Lightning activity and specifically the CG lightning flashes is one of the strongest indicators of both cloud microphysics and synoptic convective regime (Williams and Renno, 1993; Goodman et al., 2005). This is especially the case when propagating disturbances of even smaller wavelength are targeted (Petersen and Boccippio 2004). Along these lines, Burpee (1976) investigated possible 4-6 day modulation of synoptic convective regime over the tropical belt extending from eastern Africa to the western Caribbean using sea level and upper air datasets. By using precipitation and thunder counts as a proxy variable of synoptic weather pattern, he concluded that the percent of measured precipitation and observed thunder activity increased (decreased) relative with the passage of the 5-day wave's trough (ridge), despite the existence of very low wind-divergence magnitudes. Complimentary studies involve lightning-emitted Schumann resonances as the main weather-pattern proxy parameter (Castro 2000; Patel 2001), also agreed with past findings on the 5-day wave. Most of the previously cited studies use harmonic analysis to reconstruct the spatial and temporal features of the 5-day wave. They have also revealed periods of lightning activity modulation by the phase wave number 1 Fourier component over the African continent and/or the Caribbean (Castro 2000; Patel 2001; Burpee 1976). ZEUS measurements can support studies that extend the investigation of the synoptic convective regime modulation by the 5-day wave by taking advantage of ZEUS continuous and high-resolution measurements. The NCEP surface-pressure products are used in conjunction with ZEUS data to track and identify the 5-day wave characteristics along the Inter Tropical Convergence Zone (ITCZ). We have incorporated harmonic analysis (Fourier and Wavelet Transforms) to describe and identify the modulation of the African CG lightning activity on a daily basis in terms of the 5-day-wave features (amplitude-phase) and its linkages to the spectral signatures of the lightning activity over the continent. The Zeus' monitored CG activity over Africa reveals a strong signal over a 4-6 day window while the harmonic analysis on the wave number 1 of the 5-global day wave reveals CG activity modulation by the wave's phase ("Evidence of African Lightning Activity Modulation by the Global 5-Day Wave", manuscript to be submitted to *Journal of Atmospheric Science*).

#### **4. Contributions to Research Programs**

ZEUS data may contribute to a number of research and applied projects. Some of the centers or programs that can make use of ZEUS data are:

- African Monsoon Multidisciplinary Analyses (AMMA, <http://www.joss.ucar.edu/amma/>)
- Global Precipitation Measurement (GPM) Mission (<http://gpm.gsfc.nasa.gov/>)
- National, Regional and/or International Weather Forecast Offices and Water Resources Management Agencies in Africa.
- US agencies responsible for flood and drought monitoring in Africa (e.g., NOAA, USGS, USAID).
- NOAA Hurricane Prediction Center.

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The European ZEUS network receiver data were contributed by IERSD-NOA under Memorandum of Agreement between NOA and the University of Connecticut.

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