National Observatory of Athens Long-Range Lightning Detection System

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The National Observatory of Athens (NOA) owns a low-cost experimental long-range lightning detection system based on a network of six “sferics” receivers deployed in Europe. Sferics is the radio noise emitted by lightning over a broad region of the electromagnetic spectrum, which in the Very Low Frequency (VLF), between 5 and 15 kHz, propagate over thousands of kilometers in the earth-ionosphere wave-guide. The design takes advantage of the latest computing hardware, signal processing algorithms, and communications networking, and improve the state-of-the-art in receiver design at these frequencies. The receivers are situated in Birmingham (UK), Roskilde (Denmark), Iasi (Romania), Larnaca (Cyprus), Mt. Etna (Italy), and Evora (Portugal). For convenience this newly developed sensor network is denoted as ZEUS, named after the mythological Greek God of Gods. Using this sparse network and Internet communication, it is now feasible to operate a lightning detection system covering not only large developed areas in Europe, but also sea/oceans and remote areas (e.g., mountains), which were previously impractical to monitor. The deployment of ZEUS was completed in June 15, 2001. Since then sferics have been measured from the US East Coast to Western Asia and from the Northern Europe to Central Africa. The data will be valuable to air traffic control, flood and flash flood studies jointly with satellite infrared observations, and as a driver for numeric weather prediction models, which will ingest lightning data in their next generation of development. This document describes the ZEUS system specifications and initial performance evaluation.

a) System Overview

ZEUS system is based on radio sferics receivers in the Very Low Frequency (VLF) spectrum between 5 and 15 kHz centered at 9.8 kHz. Each receiver measures the vertical electric field and includes a time stamp synchronized to GPS clock within one microsecond accuracy, where the sferics location is obtained by time differences in the impulsive noise emitted by a lightning strike. These electric field time series represent sferics waveforms of a lightning source that propagates through the ionosphere-earth wave-guide. The time correlation between two-outstation waveform defines an Arrival Time Difference (ATD). The computed ATD represents locations with same time difference between two outstations. Those locations define hyperbolas over the earth’s surface. The intersection of several ATDs (hyperbolas) from a sferics candidate defines a “fix” location. The network configuration has six such receivers located in Birmingham (UK), Roskilde (Denmark), Iasi (Romania), Larnaca (Cyprus), Mt. Etna (Italy), and Evora (Portugal). Below we present a review of ZEUS hardware and software.

System Hardware: The system hardware can be separated in two parts: a number of receivers and a central computer station. A simplified sketch of this system is illustrated in Figure 1. Each receiver consists of an outside VLF antenna and preamplifier, a Global Positioning System (GPS) timing generator and signal converter, and an inside personal computer (PC) with Internet communication access. The central computer station runs on a PC, which receives via Internet in a digital form the electric field signal measured by each receiver. A more detailed diagram of the antenna receiver’s components is shown in Figure 2. The VLF signal is pre-amplified at the antenna located outside the building some 30 meters or more to avoid electrical noise. In a nearby converter box the signals are synchronized to GPS time and encoded by Analog-to-Digital (A/D) converters. The digitized data are then sent inside to a PC with a Digital Signal Processor (DSP). The PC executes the identification algorithm that detects a probable sferics candidate and then sends compressed files to the central station over the Internet. The receiver hardware has a dynamic range exceeding 100 dB with a timing accuracy within one microsecond of GPS time. The noise floor has typically standard deviation of 60 nano-Volts/meter/root-Hertz.

Software Overview: The system software is divided between the receivers and the central station. The receiver signal processing algorithms are optimized to separate distant, and therefore weak, sferics from the interference that surrounds them. Signal quality control is integrated across the system to eliminate low-quality sferics data that could cause false location reports. The receiver software is capable of capturing ~70 sferics-per-second. The receiver bandwidth is defined by a finite impulse filter (FIR) digital filter extending 3.0 kHz above and below its center at 9.8 kHz. Each sferic waveform is contained in 13.1 millisecond windows. The wave-shape information is heavily compressed to about 160 bits per sferic. This compressed sferic data are accumulated into files of 16 seconds duration, which have a typical size of 5 to 20 kilobytes. These files are backed-up and transmitted to the central station. Once the data reaches the central station two tasks are performed: (a) Decompression and correlation, and (b) locating and optimization. In the decompression task each file is uncompressed and the waveform signal is restored. It follows that same source candidates observed in the different outstations are compared to extract the corresponding Arrival Time Difference (ATD) values. Namely, the 13.1 milliseconds waveform signal from two receivers are analyzed and the time lag with the highest cross-correlation value defines an ATD. Accordingly, ATD values are computed for all possible combinations of receiver pairs. In the present system with six receivers fifteen ATD values are computed. As mentioned earlier, these ATD values represent positions between two outstations with same signal arrival time difference. The intersection between those ATDs defines a sferic fix. In the second task an ATD technique serves as the primary locating algorithm. All the ATDs for a same-source candidate are examined to estimate the strike location and time using a least-squares fit weighted selectively to certain ATDs. The algorithm adaptively compensates for correlation ambiguities, a problem that increases with long propagation distances. This is a consequence of the distortion of the electrical signal traveling the differing propagation paths to the receivers and possible different sferics noise observed at the same time. These effects might contribute to distort the waveform and therefore create several ambiguous peaks. A final optimization takes into account the likely errors associated with each ATD in light of the estimated location and is dependent on the network layout. Proper resolution of these ambiguities is an important task as it increases the system accuracy and sensitivity especially at long distances.

b) Uses of ZEUS Lightning Data

Lightning detection is the fastest meteorological data source. Its greatest value is for real-time thunderstorm monitoring, tracking, and (most recently) weather prediction. Because of its long range this network can provide low cost and accurate monitoring of severe storms that threaten airborne carriers and cause concern for flash floods in river basins. As a monitoring tool, the detection and long-range tracking of severe storms could improve weather prediction and avoid the consequences of inaccurate or incomplete information.

The images of Figure 3 show examples of high clouds with low brightness temperatures. It is noted that some of the cloudiness are non-precipitating cirrus clouds that pose no flood hazards while those clouds with lightning are associated with the most intense convection and thus surface rainfall. Sferics from lightning measured by ZEUS at different time intervals is also presented in the figure. The sferics distributions are binned into 15-minute intervals and overlaid on the 11 μm infrared imagery obtained from METEOSAT. The existence of a continuous and large-scale lightning monitoring system such as ZEUS combined with the satellite imagery is of fundamental importance for atmospheric, hydrologic, and climate research. In particular, real-time quantitative estimation of convective storms from combination of lightning and satellite observations at high spatial (0.1 to 0.2 degrees) and temporal (half hourly to hourly) resolution is of primary interest to both hydro-meteorological research and real-time applications. It has been demonstrated that in lieu of other conventional weather monitoring systems (e.g., weather radar) tracking of lightning activity associated with thunderstorms could improve weather prediction and consequently flood forecasting, and the efficient management of water resources. Furthermore, it has been shown that lightning information can be valuable in improving overland passive microwave (PM) precipitation retrieval where PM observations are limited to scattering frequencies (37 and 85 GHz) only. An example of SSM/I (85 GHz), METOSAT IR, and ZEUS lightning data over Europe is shown in Figure 4, demonstrating the strong coincidence of 85GHz brightness temperature depression and ZEUS lightning location and frequency. Recently, research by Morales and Anagnostou (accepted for publication in the *Journal of Hydrometeorology*, 2002) using a predecessor of ZEUS system operated in US for a limited period (3 months) has shown that combination of lightning and satellite infrared can produce rain retrievals that are superior to any single geo-stationary satellite sensor retrieval.

ZEUS, as mentioned above, is designed to measure lightning activity over long ranges that are beyond the network's periphery. For example, the system has measured lightning in the east coast of the US and central Africa with varying degree of accuracy. Lightning location accuracy at those large ranges is primarily affected by errors in modeling the signal's propagation velocity. Significant effort has been put forth to develop a model to accurately simulate the propagation of a sferic wave in the VLF (i.e., wave excited by a lightning stroke) accounting for the phase velocity of propagation, ground electrical conductivity, ionosphere height variations and electron gyro-frequency. The model is designed to account for a number of potential VLF frequencies excited during a lightning stroke in the range of 7 to 18 KHz as suggested from the literature. Validation of this modeling effort has been performed in the US East Coast using as "ground truth" the US National Lightning Detection Network (NLDN). As an example consider Figure 5 showing two thunderstorm cases in the East Coast that plot NLDN (upper panels) and two versions of ZEUS lightning fixes, one (middle panels) using a single (i.e., fixed) propagation velocity and a second (bottom panels) using the modeled sferics propagation velocity at optimum frequency. It is apparent that the modeled propagation ZEUS lightning locations are close to the ones detected by the local NLDN network, while the fixed velocity solutions are associated with large errors. This demonstrates the significance of proper sferics propagation modeling in ATD retrieval. The results from comparing the optimum ZEUS locations to NLDN are very encouraging considering that these lightning fixes are retrieved from just five receivers located over 6,000 km away. Research is conducted to evaluate the location error of ZEUS over a large area ranging from the East Coast to West Asia and North Europe to Central Africa.

In summary, ZEUS--a new Long Range Lightning Detection Network--can provide accurate CG lightning detection within Europe and surrounding waters, so is a dependable continuous monitoring system for storm activity. ZEUS can also detect lightning activity over very long distances (up to ~ 6000 Km) introducing an error due to propagation effects, which can be partly treated through modeling of the sferics propagation velocity using existing formulations for VLF earth-ionosphere propagation and knowledge of ionosphere state and signal frequency. ZEUS has been operating on an experimental basis in the period June 15th to October 20th 2001, while effective June 2002 it is expected to operate continuously. Detailed information about ZEUS and on-line images can be acquired by visiting its web page at http://sifnos.engr.uconn.edu. Compiled historical sferics location and timing data grouped in 15-minute intervals are available upon request. Effort is currently under way to expand the network with three to four additional sensors to be deployed in Central and South Africa, which would extend dramatically the ability of the system to monitor lightning activity at high accuracy over Africa and the Atlantic Ocean's Inter Tropical Convergence Zone (ITCZ).

c) Primary Investigators' Narratives

Dr. Emmanouil N. Anagnostou: Assistant Professor in the Department of Civil and Environmental Engineering of the University of Connecticut and holds Adjunct Scientist appointment with the National Observatory of Athens. He has been Visiting Scientist at the Laboratory of Atmospheres of NASA Goddard Space Flight Center. His research experience and expertise is on remote sensing applications in hydrometeorology and the prediction of natural hazards (floods, hurricanes, severe weather, lightning, etc.). In the past six years he has focused his work on the advancement of our knowledge on precipitation estimation from both space and ground based sensors, and the optimum assimilation of remote sensing data in atmospheric and hydrologic models for the prediction of hazardous floods and flash floods. He is recipient of three prestigious awards in support of his Natural Hazards interdisciplinary research: (1) the NSF CAREER award for research on improving the knowledge on precipitation microphysics for advancing radar rainfall estimation and quantitative precipitation forecasting; (2) the NASA's New Investigator Program Award for research on the quantification of uncertainties associated with satellite remote sensing of rainfall; and (3) the European Union Marie Curie award for studying the propagation of radar rainfall estimation error in runoff forecasting. He is recipient of the 2002 Plinius Medal Award from the European Geophysical Society and the Outstanding Junior Faculty Award from the School of Engineering of the University of Connecticut. He is the Primary Investigator of several research projects in the area of Earth Sciences and Natural Hazards funded by NASA and the US National Science Foundation. He is member of NASA's Tropical Rainfall Measuring Mission science team. He is the author or co-author of 29 journal papers in areas of precipitation remote sensing and hydro-meteorological prediction.

Dr. Dimitri P. Lalas: Professor and Director of the National Observatory of Athens (N.O.A.), and President of its Governing Board. He has held the chair of Meteorology at the University of Athens and has been Professor of Engineering at two U.S. Universities. He has long experience in PBL and turbulence research. He has published more than a hundred papers and co-authored several books on various aspects of dynamic meteorology, air pollution and wind energy. He has been in charge of more than twenty-five international and EU-funded research projects, totaling over 10M Euros plus numerous other national research related projects. He is member of EAG on Global Change and Biodiversity of DGXII and has been the Head of the Greek Delegation in Climate Negotiations.

d) Support Team

Dr. Yiannis Kalogiros: Research Scientist in the National Observatory of Athens.

Mr. Themis Chronis: Ph.D. candidate in the Civil and Environmental Engineering Department of the University of Connecticut and recipient of the NASA Earth Science Graduate Fellowship.

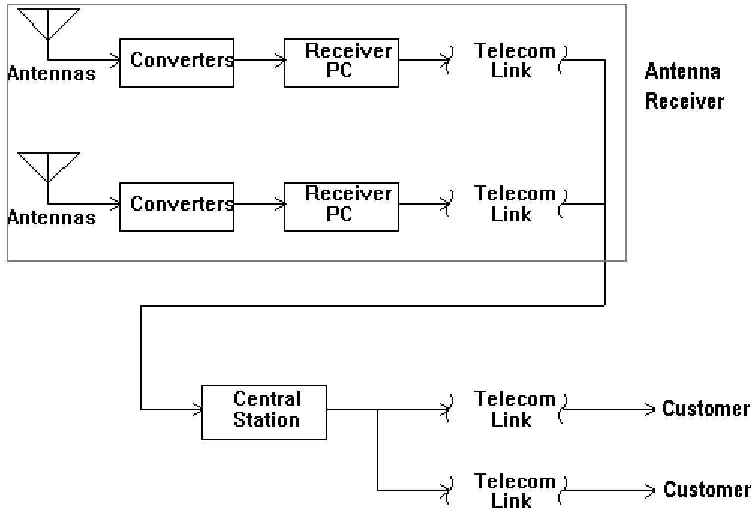

Figure 1. Overview of ZEUS network architecture.

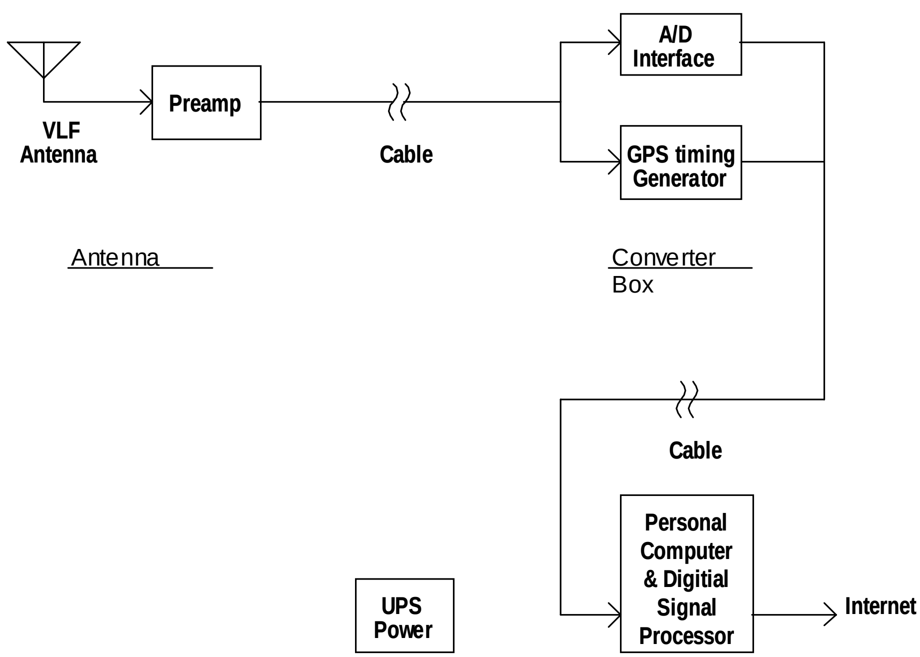

Figure 2. Sketch of ZEUS antenna receiver's component.

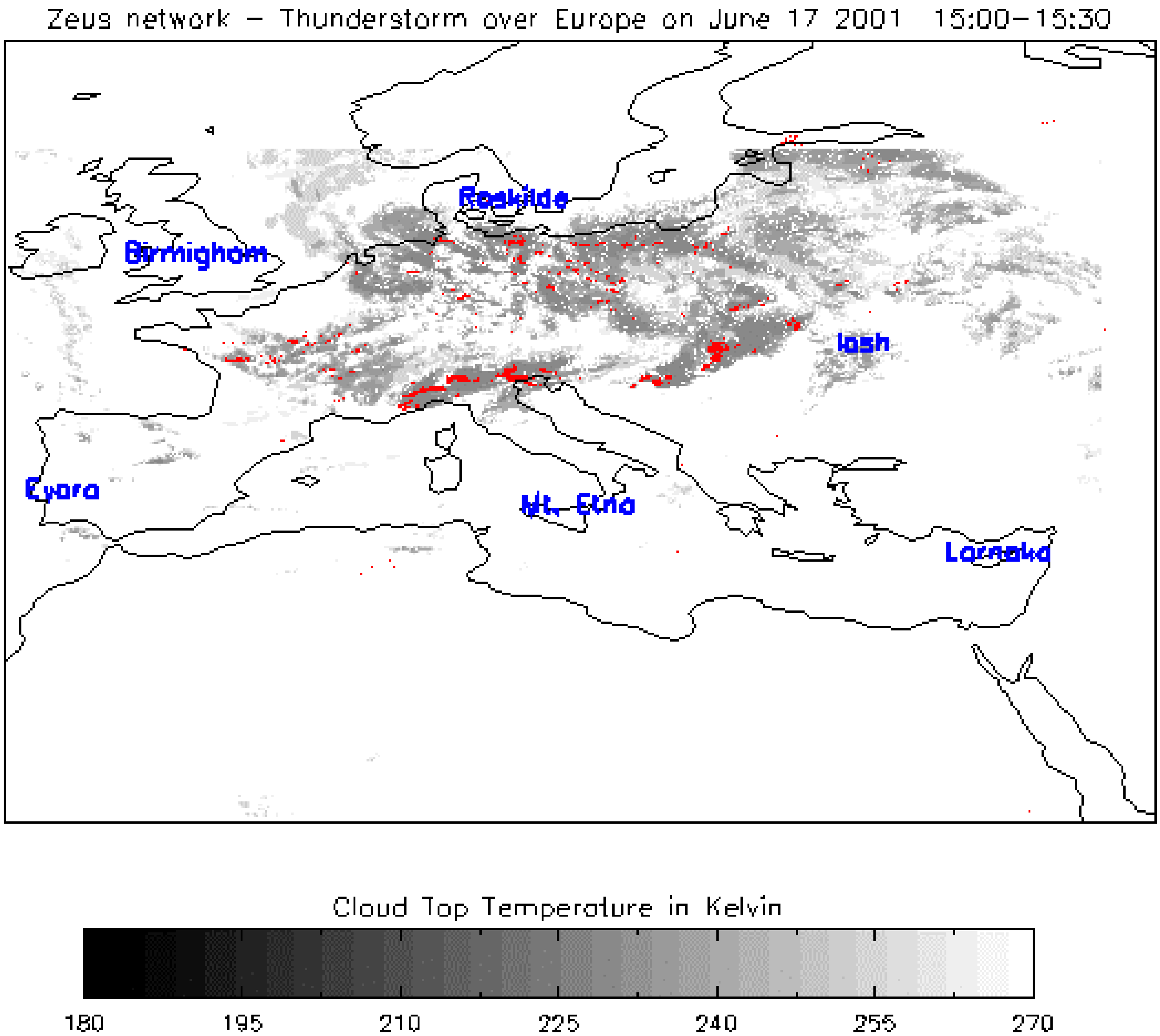

Figure 3: ZEUS sferics receivers' locations and an example of ZEUS lightning measurements overlaid with satellite infrared. The IR images correspond to the nearest half-hourly snapshot, while lightning fixes are presented in 15-minute intervals.

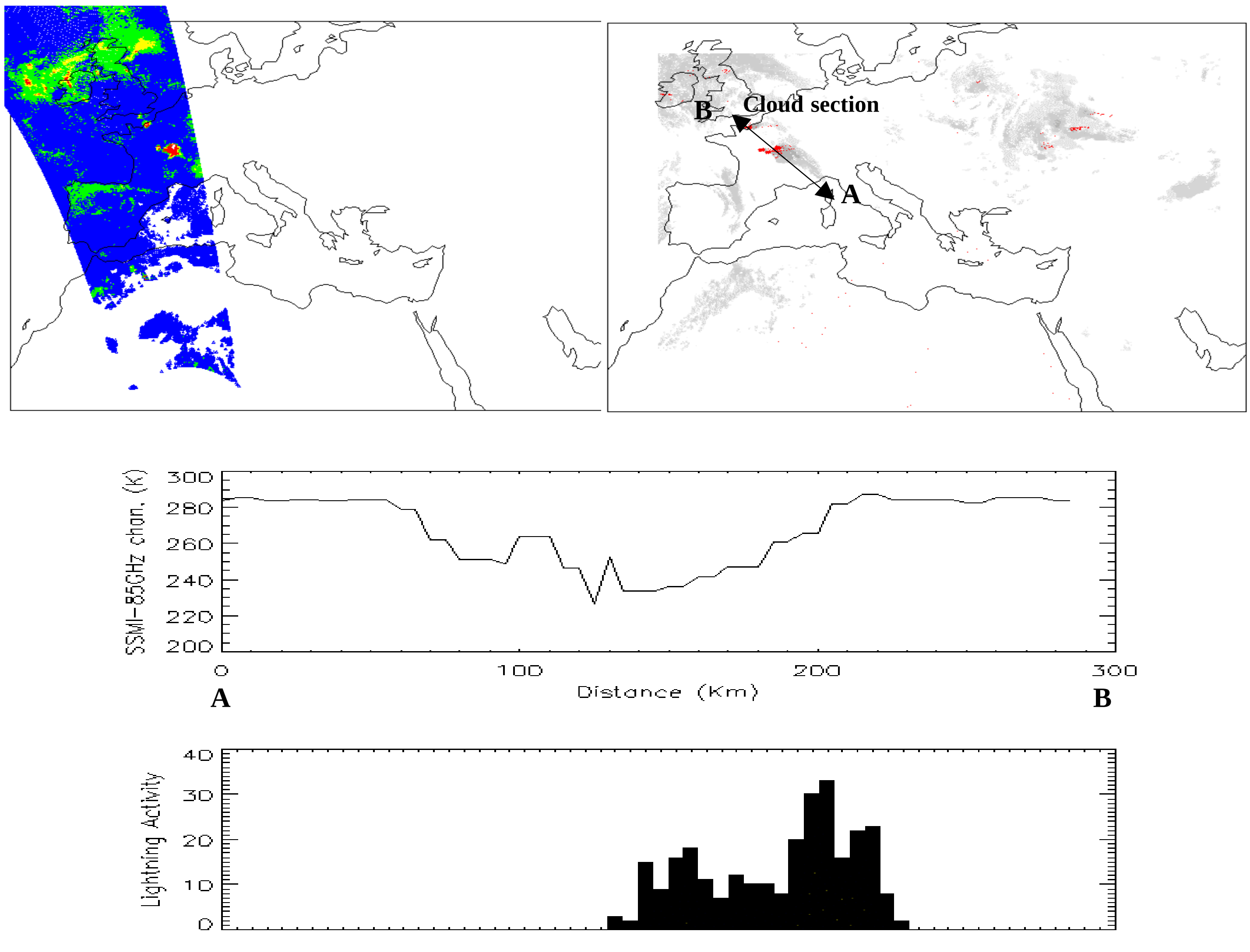

Figure 4: Example of a storm case with coincident SSM/I 85 GHz brightness temperatures, METOSAT IR temperatures and ZEUS lightning frequency observations.

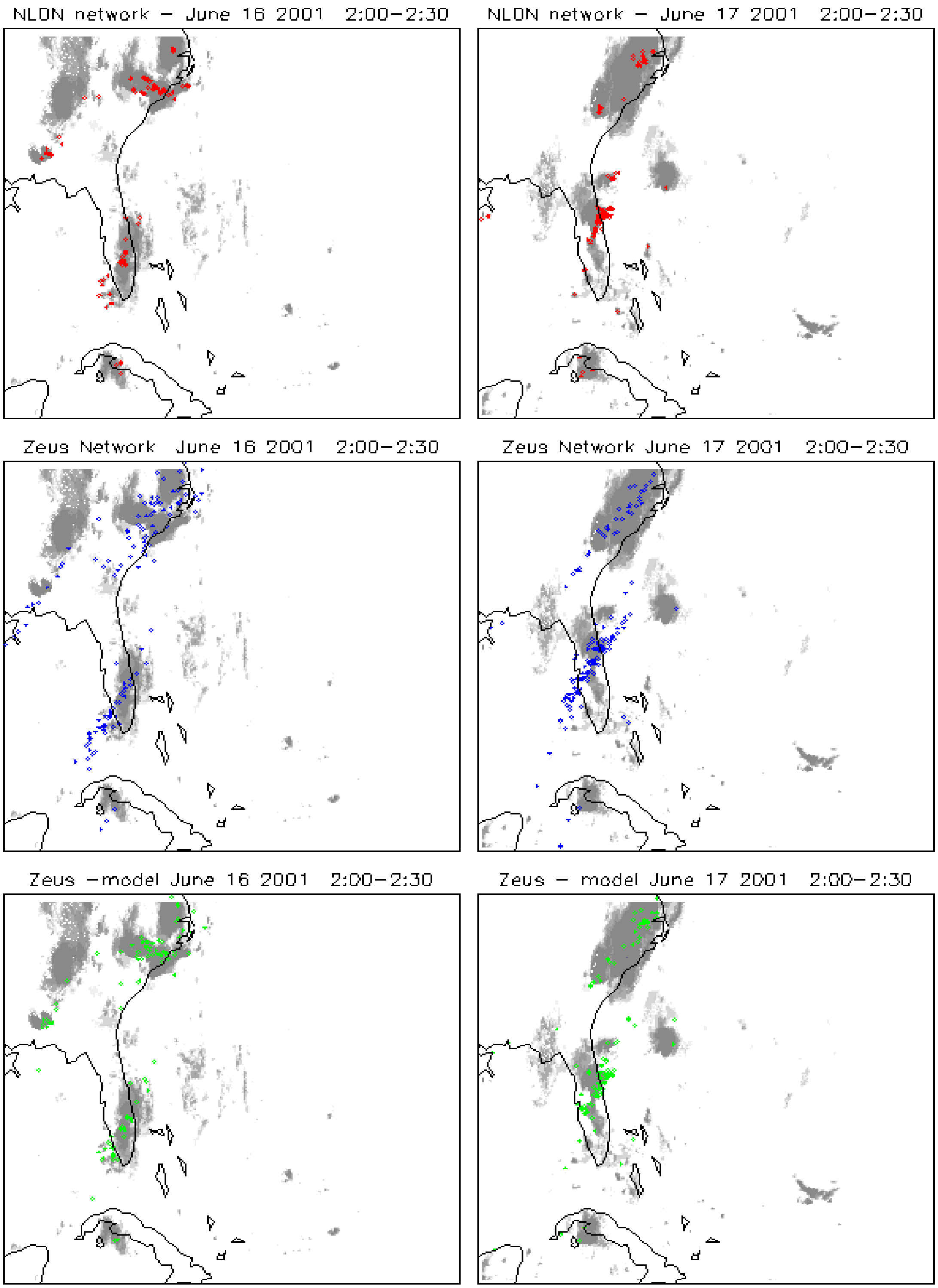

Figure 5. Two thunderstorms recorded by NLDN (upper panel) and Zeus (middle and bottom panels) networks overlaid IR cloudiness. The bottom panel represents the corrected sferics locations via modeling the propagation of the VLF wave.