**1995**

**NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM**

**MARSHALL SPACE FLIGHT CENTER**
**THE UNIVERSITY OF ALABAMA IN HUNTSVILLE**

# VLF LONG–RANGE LIGHTNING LOCATION USING THE ARRIVAL TIME DIFFERENCE TECHNIQUE (ATD)


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# VLF LONG-RANGE LIGHTNING LOCATION USING THE ARRIVAL TIME DIFFERENCE TECHNIQUE (ATD)

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August 1995

## Introduction

A new network of VLF receiving systems is currently being developed in the USA to support NASA's Tropical Rain Measuring Mission (TRMM). The new network will be deployed in the east coast of the US- including Puerto Rico- and will be operational in late 1995. The system should give affordable, near real-time, accurate lightning locating capabilities at long ranges and with extended coverage (Kriz, 1995). It is based on the Arrival Time Difference (ATD) method of Lee (1986; 1990). The ground system results will be compared and complemented with satellite optical measurements gathered with the already operational Optical Transient Detector (OTD) instrument and in due course with its successor the Lightning Imaging Sensor (LIS) (Christian, et al., 1992).

Lightning observations are important to understand atmospheric electrification phenomena, discharge processes, associated phenomena on earth (e.g. whistlers, explosive Spread-F) and other planets. In addition, lightning is a conspicuous indicator of atmospheric activity whose potential is just beginning to be recognized and utilized . On more prosaic grounds, lightning observations are important for protection of life, property and services.

Lightning is observed with a variety of methods and here we focus on ground based RF techniques for the study of ground to cloud lightning. The field may be divided in close range ($\leq$ 100 km, say) and long range ($\geq$ 250 km) techniques. Close range measurements have used several procedures: (a). Interferometry at VHF to construct RF images of the lightning channel (Richard and Auffray, 1985), (b). Radar (or active) UHF observations of physical properties of the hot ($5000°K$) and overdense plasma channel (William et al., 1989), (c). Magnetic Directional Finder (MDF) at VLF to establish angle of arrival and fixing via triangulation (Volland, 1995 and references therein). VLF Long range measurements include: (a) The single station Group Time Delay Difference (GDD) system (Volland, 1995), (b). Arrival Time Difference (ATD) at VLF to overcome polarization and timing errors. Arguably, the ATD offers the best prospects for accurate (sometimes to within a few kms!), efficient and inexpensive system for lightning observations at thousands of kilometers distance (Lee, 1990). It is pertinent to note that here we are mostly concerned with Cloud to Ground (CG) lightning. Other forms include cloud to cloud (encompassing intra-cloud and inter-cloud), cloud to stratosphere. The systems above are fairly insensitive to the latter types of lightning, due to the horizontal (perpendicular) polarization characteristics of the emitted radiation.

The organization of this work is as follows. First we review some basic concepts of the theory of long range VLF propagation. Second we discuss the modernized version of the ATD system as proposed by Kriz (1995). Next, we offer some comments aimed to shed some light on peculiar VHF satellite observations known as Trans-Ionospheric Pulses (TIPPs). Finally, the main conclusions are summarized.

## VLF wave propagation in the earth-ionosphere waveguide

It is convenient to begin the discussion of sferics propagation in the earth- ionosphere waveguide considering first the ideal case of perfectly reflecting top (height $h$) and bottom walls (Budden, 1961; Wait, 1968). The waves supported by such a structure are proportional to $\sim e^{-ik(x\cos\theta \pm z\sin\theta)}$ where the positive (negative) sign preceding the $z$ coordinate indicates upward (downward) propagation in the positive $x$ direction. The wavevector $\vec{k}$ lies in the $x$-$z$ plane. The angle $\theta$ is measured relative to the abscissa $x$. The waveguide supports the combination of these two waves or $\sim \cos(kz\sin\theta)e^{-ikx\cos\theta}$. Maxwell's boundary conditions ensure that $kh\sin\theta = 2n\pi$, where $n$ is an integer $\geq 0$. The waves above are known as *progressive plane waves*; they must be augmented with *inhomogeneous plane waves* to constitute a set of functions- or modes- whose superposition reproduces the original radiation. Inhomogeneous plane waves are captured in the description above by simply allowing that $\sin\theta > 1$. In this case we have, from $\cos\theta = \sqrt{1-\sin^2\theta}$, that the latter attenuate in the $x$ direction and that evanescent waves arise even though the guide is lossless.

The theory just reviewed suffices to establish the existence of a cutoff frequency $f_n$ for mode $n$. Here, $f_n = nc/2h$ with $c$ the speed of light. A radio signal of frequency $f < f_n$ attenuates with coefficient $k\sqrt{(f_n/f)^2 - 1}$. The phase velocity $v$ of a particular mode is given by $v = c/\sqrt{1-(f_n/f)^2}$ and the group velocity $u$ satisfies $uv = c^2$. Note that $v \geq c$ and $u \leq c$. This model captures some interesting observed features of atmospherics. For example, when the height $h$ decreases from about 85 km to 65 km (due to regular day to night ionospheric changes or in response to sudden disturbances) $f_n$ increases. This behavior agrees with diurnal or sudden absorption events measurements at frequencies near cutoff. A second example is the propagation of mode $n$, with $n \geq 1$, to long distances. For the sake of argument let's consider the radiation source (or lightning event) as a vertically oriented electric dipole that discharges instantaneously. (The dipole will have an infinite number of images at the top and bottom walls). The current associated with this event is a delta function whose Fourier components are equal to a constant. The time response of mode $n$ can be calculated by re-synthesizing the frequency spectra subject to the constraint that $\omega/c\ \sin\theta = n\pi/h$ (Budden, 1961). The response in the time domain shows several measured characteristics: the waveform is distinctly oscillatory, the frequency diminishes with time eventually reaching the cutoff frequency, the intensity decreases due to dipersion in the waveguide.

However, the lossless model just described fails to explain several features. Notably, mode $n = 0$ has no attenuation hence it should reach the receiver as an impulse of radiation contrary to actual measurements. The theory must be improved by allowing for lossess in the walls. The new boundary condition for mode $n$ becomes, $R(\theta)e^{-i2kh\sin\theta} = e^{-i2\pi n}$, with $R(\theta)$ an effective reflection coefficient that incorporates ionospheric and surface-of-the earth effects. The reflection coefficients of importance here correspond to vertical (or parallel) propagation,

$$R(\theta) = \frac{\aleph^2 \sin\theta - \sqrt{\aleph^2 - \cos^2\theta}}{\aleph^2 \sin\theta + \sqrt{\aleph^2 - \cos^2\theta}}$$

where $\aleph$ is the index of refraction, $\aleph^2 = \epsilon - i\sigma/w\epsilon_0$, with $\epsilon$ the relative permittivity of the medium, $\sigma$ its conductivity, and $\epsilon_0$ the permittivity of vacuum. The earth's surface conductivity is regarded as a constant while the ionospheric conductivity is given by, $\sigma = \epsilon_0 Ne^2/m\nu$, where $N$ is the electron density, $e$ and $m$ the electron's charge and mass respectively, and $\nu$ is the collision frequency. Here the geomagnetic field has been ignored; however it can influence the reflection process by depolarizing the radiation and also, specially for equatorial paths, by introducing zonal asymmetries wherein west to east reflection coefficients are larger than east to west ones (Volland, 1995). Another simplification employed here has been to treat the ionosphere as sharply bounded. The ATD technique predictions should not be unduly influenced by these approximations.

The lossy walls model just described predicts radio atmospherics propagation fairly well. One of its main virtues is that only one mode needs to be considered for each frequency. This mode (possibly a hybrid) has been referred as the *least attenuated mode*. This special mode is introduced to allow for the re-synthesizing of Fourier components by considering only those modes (usually the zero or one) that have minimal attenuation characteristics versus frequency. Here lies the convenience of the mode theory of propagation over the ray theory. Namely, the least attenuated mode is sufficient to describe wave signatures at long distances. In contrast, ray theory requires the superposition of the line-of-sight and of the multiply-reflected rays.

## The modernized ATD technique

The ATD technique is based on the estimation of the time of arrival of sferics detected over an 18 kHz bandwidth. The receiving system includes a VLF whip antenna and a GPS system to locate in time the incoming radiation. This system is complemented with two crossed loop aerials for the estimation of angles of arrival to remove ambiguities in lightning fixing- specially useful for high flashing rates. The signals are digitized with substantial dynamic range- equivalent to 16 bits- leading to superior detection efficiencies. The measured signals are correlated with a synthetic waveform to determine time of arrival - based on the complete waveform, not just its leading part. Each station relays this parameter to a server station whose location engine uses least square fitting to establish lightning position. To our knowledge this procedure has not been documented in easily accessible form.

Each system has several carefully designed and computer controlled filters. Contaminating VLF signals (usually transmitters) are removed with the help of notch filters. The whole receiving section and the time of arrival algorithms are calibrated and tested locally with the injection of a pseudo-noise code 1023 elements wide and with 10 $\mu$sec baud. A station is capable of inferring the relative position of the code to within 0.1 $\mu$sec. This accuracy does not conflict with the 18 kHz bandwith of the receiving chain.

The proposed network of outstations around the east coast of the USA, linked via the Internet, should be capable of monitoring the North Atlantic area and part of the continental USA. Expected detection rates are in excess of 50 strokes per second with locations accuracies of better than 10 km (Lee, 1990; Kriz, 1995). There are plans to extend geographical coverage with the installation of more stations in the western part of Europe, the west coast of the USA, Hawaii, Australia and other locations.

**On the nature of TIPPs**

Recent VHF (25 to 95 Mhz) satellite observations with a multichannel receiver have documented the occasional presence of pairs of pulses of radiation $\approx 5\ \mu$sec wide separated by upto 50 $\mu$sec (Holden et al., 1995). The radiation apparently has sub-ionospheric origin because it is distinctively affected by ionospheric dispersion.

Next, we argue in favor of the hypothesis that Trans-Ionospheric Pulse Pairs may be due to ground to cloud lightning. (Note however that the arguments below may be applied to the case of cloud to cloud lightning.) Recall that the radiation emitted from thin wires effectively originates at each end of the filament (Schelkunoff, 1952; Le Vine and Meneghini, 1978 hereafter referred to as L&M). Figure 1 below shows a vertical wire aerial over the earth's surface and two spherical waves propagating outwardly. We discuss reflection effects later. The transmission line model of lightning assumes a discharge electric current waveform with a steep leading edge $\leq 5\ \mu$sec and with a gentle tail (e.g. see Fig. 1 of L&M). Note now that the steep edges translate into pulse shaped emitted radiation (see top panel of L&M's Fig. 2). The width of this pulse is given by the separation between the regions 1 and 3 in Fig. 1. The width is also determined by the length of the lightning channel and by the speed of propagation of the discharge current along the channel. In the absence of dispersion by the ionosphere the satellite's receiver would detect two bursts of radiation (one from each edge of the pulse) separated by a, of course, constant delay- independent of frequency- and equal to the width of the radiated pulse.

Coming now to the topic of reflections on the ground we suggest that reflections can be ignored. Fig. 1 shows rough estimates for the vertical reflection coefficient $R_v(\theta)$. In region III, $R_v \approx 0.6$. This value can be substantially lowered by invoking the relative roughness of the terrain at the frequencies of interest. Region II is about the Brewster's angle where $R_v \approx 0$. In region I, $R_v \approx -1$ which in turn means that there is no space wave. The surface wave on the other hand is heavily attenuated at VHF. Region I is therefore a quiet spot.

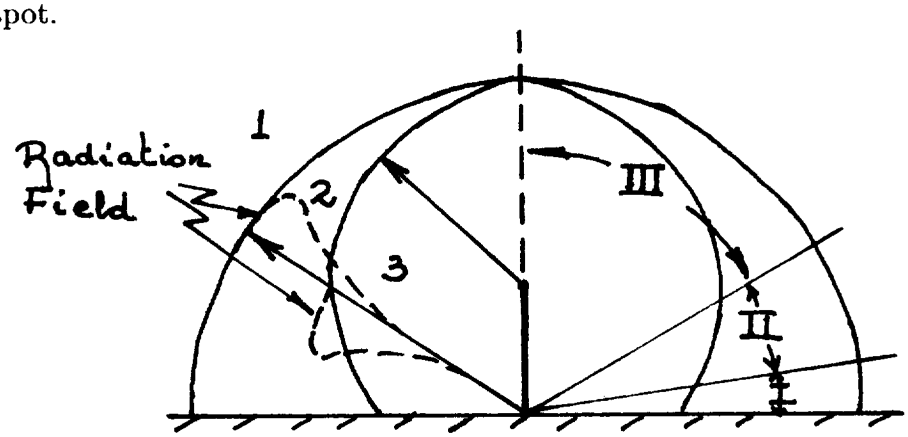


Figure 1