Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm

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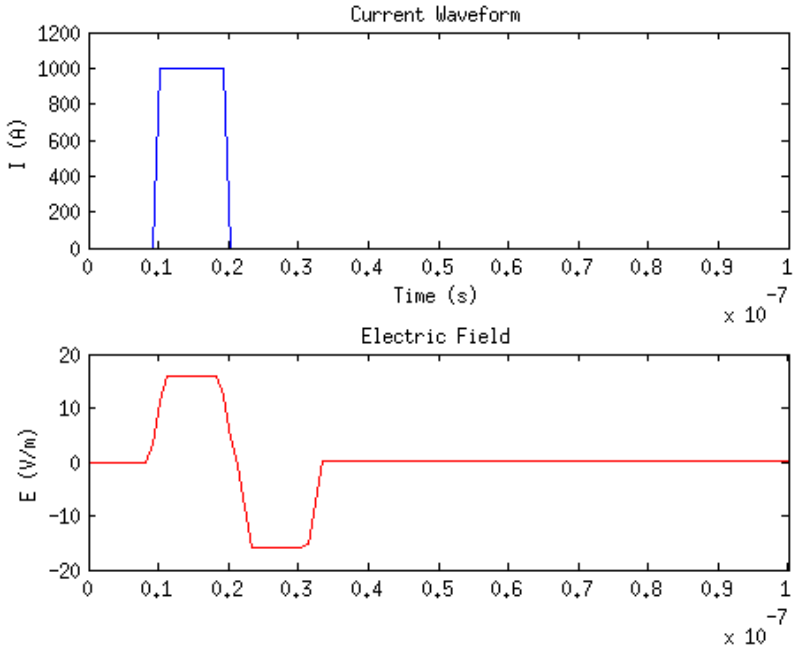
Outline

- Why VHF Radiation?
- Instrument specs
- Data Processing Theory/Techiques
- General Results
- Combination With LMA data

Why Does Lightning Emit VHF Radiation?



VHF radiation is around 40MHz, Period of 2.5×10^{-8} s

Based on radiation calculations from homework 6, a 1×10^{-8} s current pulse down a 1m antenna produces a signal close to this frequency. This likely corresponds to streamer action at the leader tips.

The Broadband Interferometer

Table 1. Table of the Parameters for the Interferometer (INTF) and the Lightning Flash

Sensor Parameters		
Number Antennas	3	
Baselines	10.2	m
Bandwidth	60	MHz
Sampling Rate	180	MS s^{-1}

The three antennas are arranged to form two equal length orthogonal baselines.

The signals are band limited to 20-80 MHz before being digitized.

Source Location

For baseline
d, arrival time difference
τ_d, phase difference $\delta\phi$,
and incident angle α we have

$$d\cos\alpha = c\tau_d = \left(\frac{\Delta phi}{2\pi}\right)\lambda$$

Where λ is the wavelength and
c is the speed of light in air.

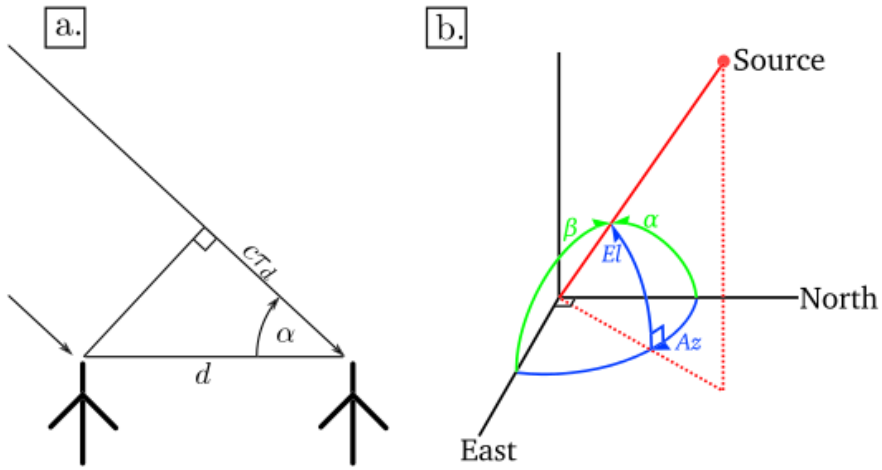


Figure 1. Basic geometry of the interferometer measurements.

Azimuth and Elevation

When time differences are found for the two orthogonal antenna baselines the direction cosines, $\cos\alpha$ and $\cos\beta$ are related to azimuth and elevation (spherical coordinates) by

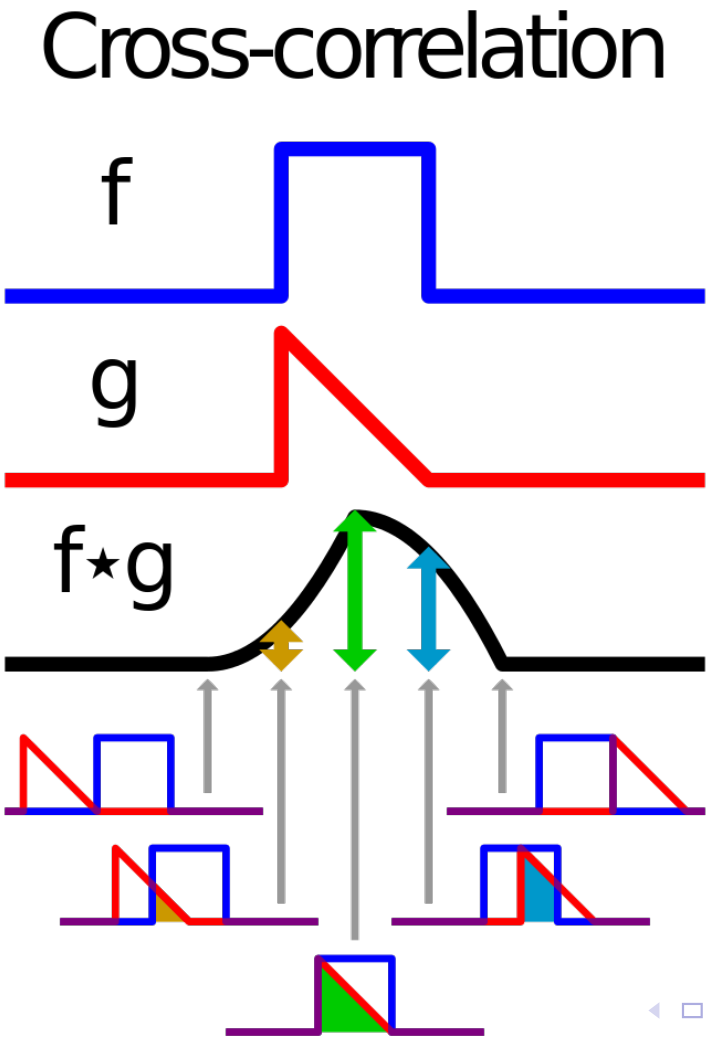
$$\cos\alpha = \sin(Az)\cos(El)$$
$$\cos\beta = \cos(Az)cos(El)$$

Which can be inverted to get

$$Az = arctan\left(\frac{\tau_{d1}}{\tau_{d2}}\right)$$
$$El = arccos\left(\frac{c}{d}\sqrt{\tau_{d1}^2 + \tau_{d2}^2}\right)$$

for the special case of orthogonal baselines aligned north-south and east-west.

Cross Correlation Basics



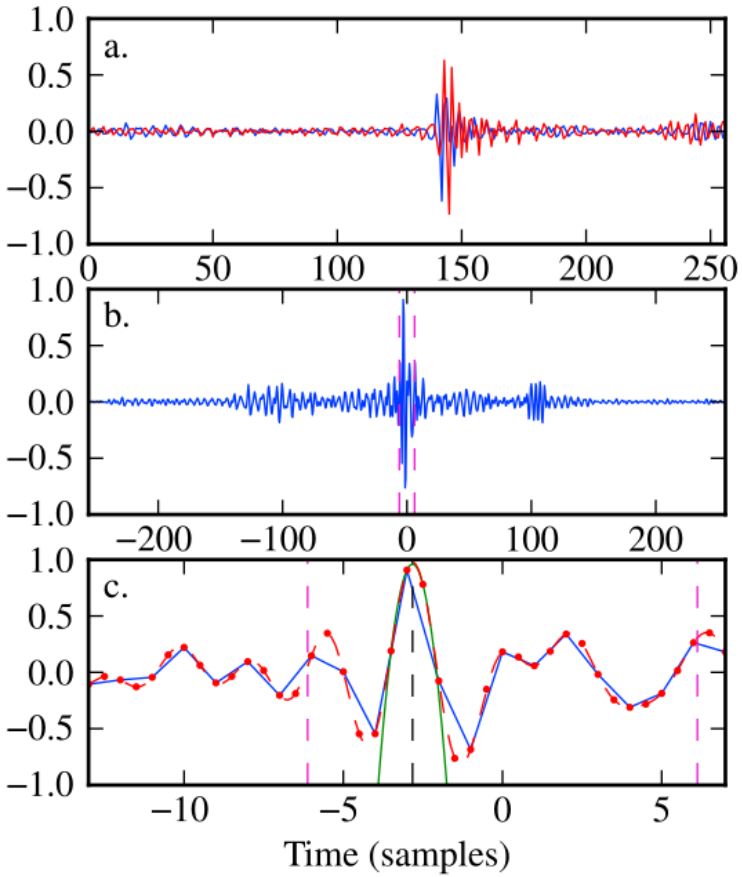
Generalized Cross Correlation Technique

Computing the cross-correlation directly is computationally expensive.
Instead Fourier transforms can be used,

$$x_1(t), x_2(t) \leftarrow \mathcal{F} \rightarrow X_1(f), X_2(f)$$
$$\vdots \quad \downarrow$$
$$R_g(\tau) \leftarrow \mathcal{F} \rightarrow X_1(f)X_2(f)W(f)$$

Where $X_1(f), X_2(f)$ are the Fourier transforms of $x_1(t), x_2(t)$, $R_g(\tau)$ is the generalized cross-correlation, and $W(f)$ is a windowing function used to decrease the influence of noise.

The cross-correlation waveform is up-sampled by a factor of 2 or more to increase precision.
Parabola fit
to three points closest to peak.
Parabolic fit is more precise and less computationally costly than increased up-sampling.
Pink dashed lines show baseline limit to time difference.



Results

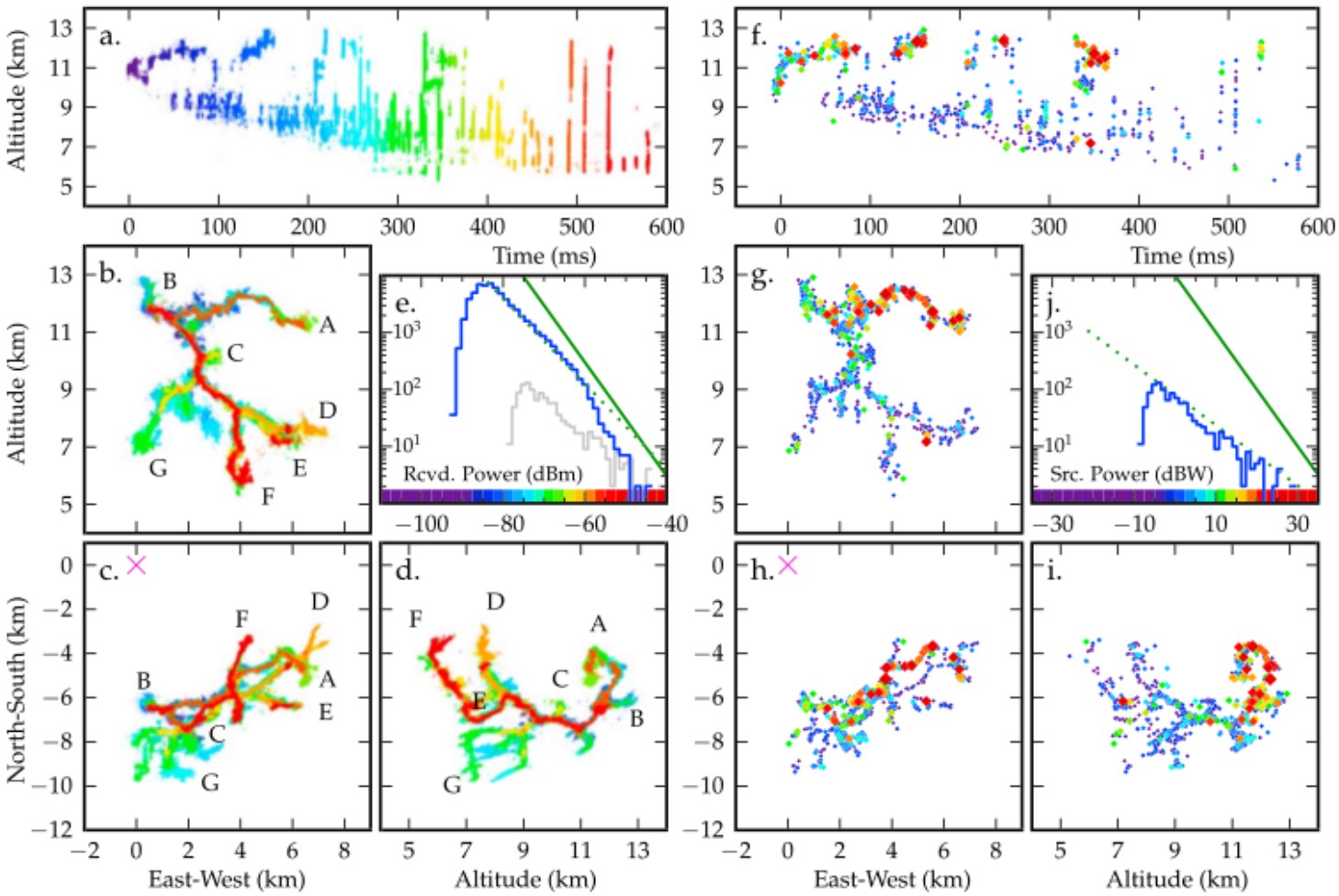
Flash Parameters		
Time	03:08:10.390	UT
INTF sources	62598	
LMA sources	1092	

Due to wide-bandwidth detection and faster digitizing the interferometer is able to detect significantly more radiation sources than the LMA.
The continuous nature of interferometric measurements also allow for better detection of continuous events such as positive leaders and dart leaders.
See gif for animation.

Quasi Three Dimensional Conversion

Interferometer (INTF) data is 2D in spherical coordinates, making it difficult to make direct measurements from the data.
3D LMA data from the same flash can be used to estimate the range to each INTF point.
LMA data is converted into Azimuth and Elevation coordinates, and INTF points are matched with the closest LMA points. This tends to lead to strong radial smearing.
Weighted averages can be used to reduce the radial artifacts.

3D Converted INTF and LMA Comparison



Citations

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All figures taken from Stock et.al. 2014, wikipedia, google maps, or produced by myself.