Very High Frequency broadband interferometer for lightning monitoring

An instrument which determines the direction to a lightning-produced radio point source with microsecond time resolution by correlating the signal received at two or more antennas

Alternative terminology

Lightning Very High Frequency radiation location system based on short-baseline time-difference of arrival (TDOA) technique

Система УКВ локации молнии, основанная на разности времен прибытия и использующая короткую базу

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Why Very High Frequency ?

Cannot see inside storm at optical frequencies, but clouds are fully transparent at radio frequencies. Therefore ‘image’ and study processes at these frequencies, rather than optically.

Very High Frequency (VHF)

is the range of radio frequency electromagnetic waves from 30 MHz to 300 MHz with corresponding wavelengths of 10 m to 1 m

Leaders

❖Lightning Research Group of Osaka University, Japan
❖Langmuir Laboratory, New Mexico Institute of Mining and Technology, USA

Recent achievements

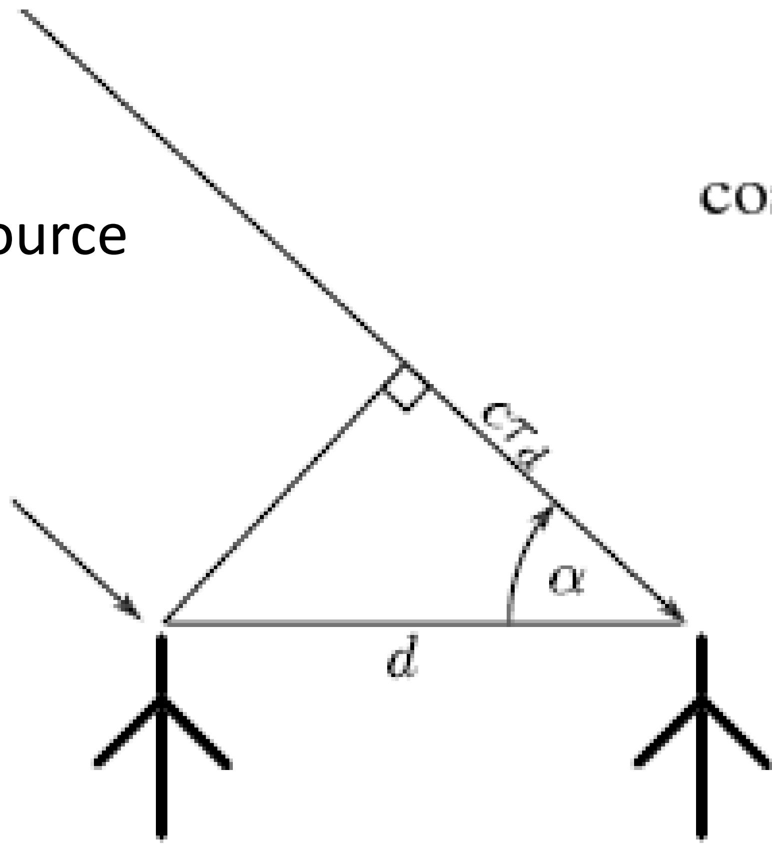
•M. Stock, M. Akita, P. Krehbiel, W. Rison, H. Edens, Z. Kawasaki, and M. Stanley (2014), "Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm", JGR -Atmospheres, 119(6), 3134–3165.

•W. Rison, P. R. Krehbiel, M. Stock, H. Edens, X.Shao, R. Thomas, M. Stanley , and Y. Zhang, "Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms" Nature Communications, 2016 , DOI: 10.1038/ncomms10721

•M.Stock (2014), "Broadband interferometry of lightning", Ph.D. thesis
•http://lightning-interferometry.com/index.php/videos/
•https://vimeo.com/lightninginterferometry

Basic principle

Source



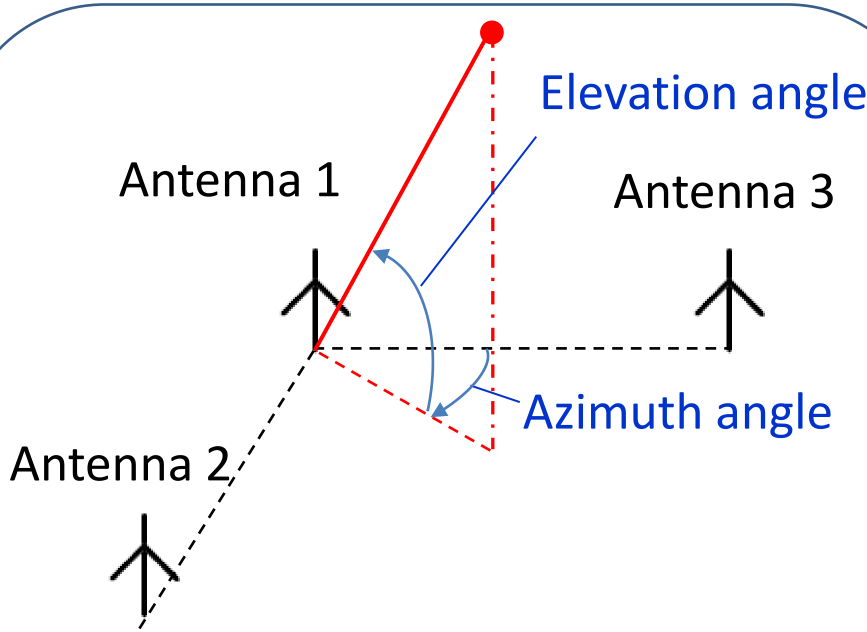
Antenna 1 Antenna 2

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

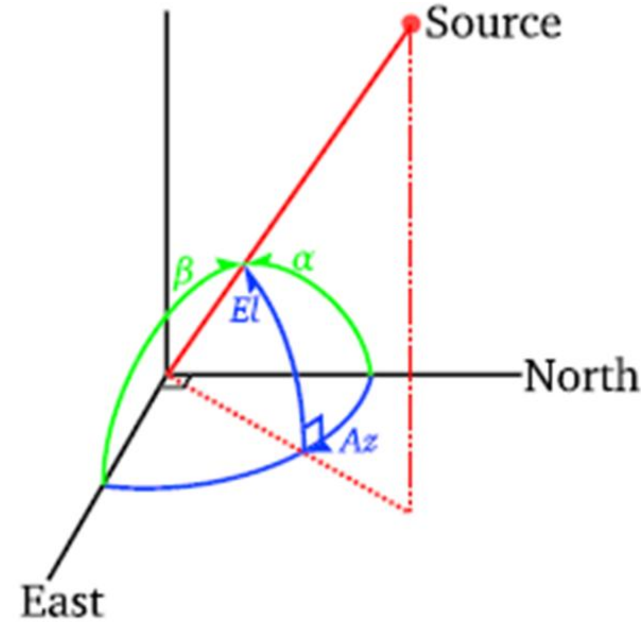
λ is the wavelength of the radiation,
c is the speed of light in air

The time delay τ_d or the phase difference ΔΦ determines the direction cosine of the source

Basic geometry of the measurements



Three antennas are arranged to form two orthogonal horizontal baselines of equal length



From spherical trigonometry

$$\cos\alpha = \sin(\mathrm{Az})\cos(\mathrm{El})$$

$$\cos\beta = \cos(\mathrm{Az})\cos(\mathrm{El})$$

$$\mathrm{Az} = \arctan\left(\frac{\tau_{d1}}{\tau_{d2}}\right)$$

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

τ_{d1} and τ_{d2} are time differences of arrivals for two baselines

Computational methods

Two dominate computational methods are used

- **Phase fitting** which analyses the phase difference vs frequency

- **Cross correlation** which estimates the time delay

Ultimately, both computational methods measure the time delay between antennas, and so the two techniques are equivalent. However, there are subtle differences in the details of algorithms.

Estimates of the time delay by cross correlation method

$$x_1(t) = v(t) + n_1(t)$$
$$x_2(t) = v(t - \tau_d) + n_2(t)$$

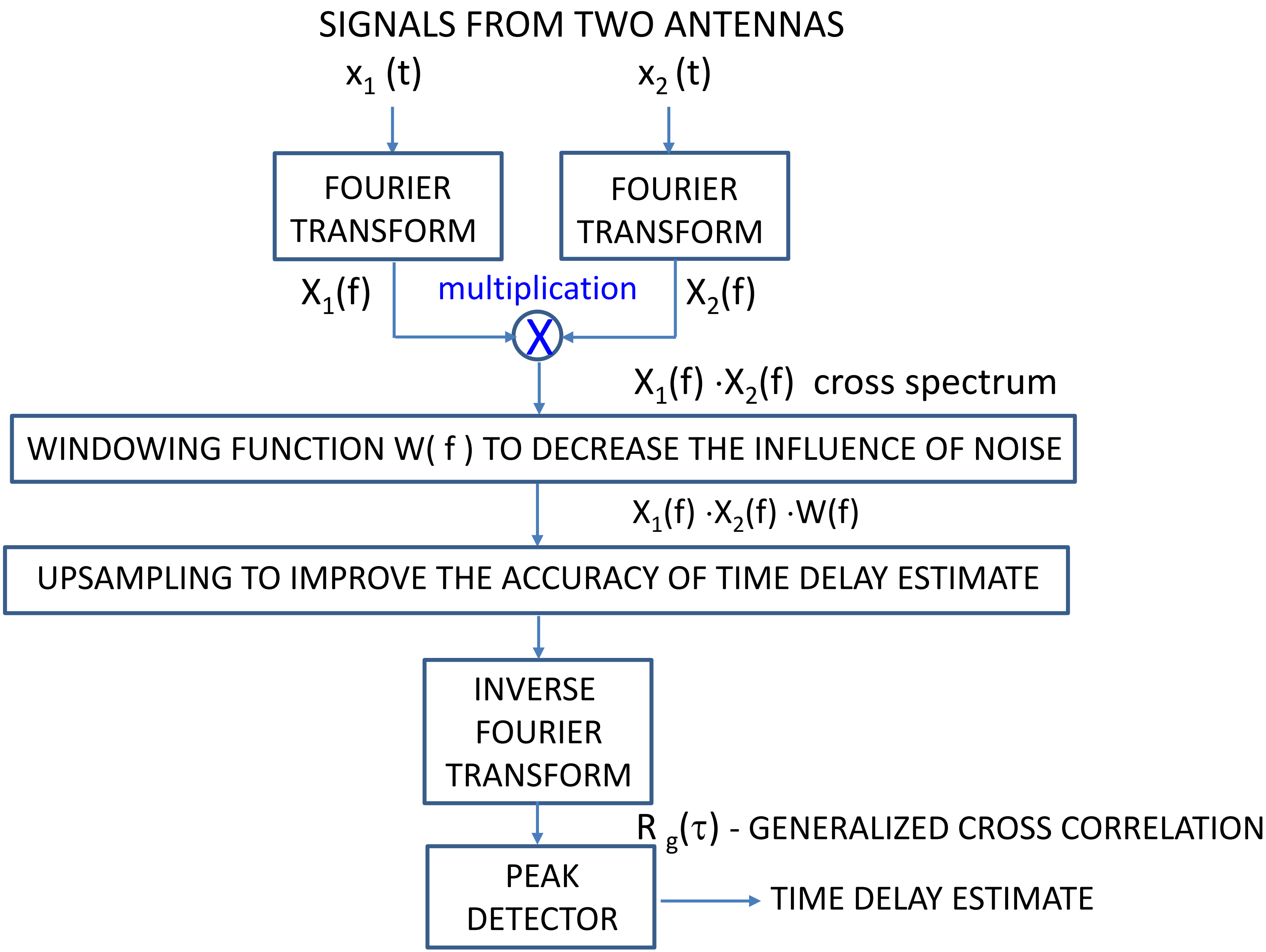
$x_1(t)$ and $x_2(t)$ - signals from two antennas
$v(t)$ and $v(t-\tau_d)$ - signals from the coherent source
$n_1(t)$ and $n_2(t)$ - uncorrelated noise sources.

The time delay τ_d can be determined from the maximum value of the cross correlation

$$R(\tau) = \int x_1(t) \cdot x_2(t - \tau) dt$$

Computing the cross-correlation directly is computationally expensive.
It is both faster and simpler to utilize fast Fourier transforms
to transform into the frequency domain, where the convolution becomes
simple multiplication, and then transform back to the time domain.

Implementation of cross correlator in the frequency domain



Windowing function

The role of windowing (frequency weighting) function W(f) is to emphasize frequency components that have good signal-to-noise ratio, thereby improving the time delay estimation.

$$W(f) = \frac{\Phi_v(f)}{\Phi_{n1}(f) \cdot \Phi_{n2}(f) + \Phi_v(f) \cdot \left(\Phi_{n1}(f) + \Phi_{n2}(f)\right)}$$

(Maximum Likelihood windowing function [*Hassab and Boucher* ,1979])

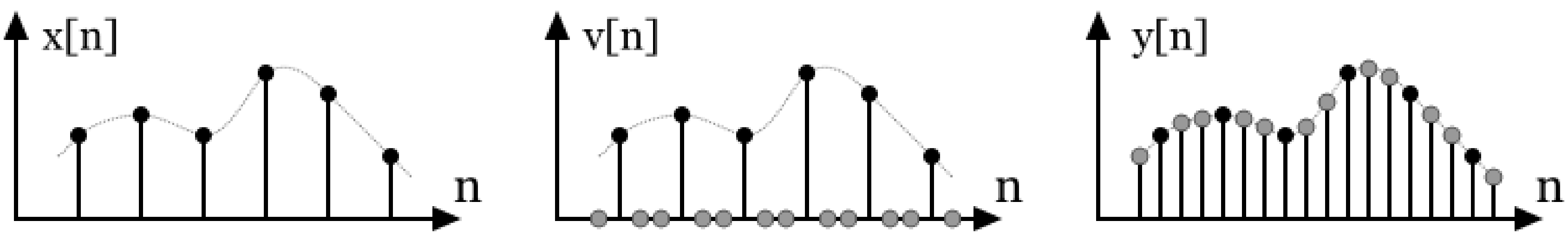
where $\Phi_v(f)$ is the signal spectrum
$\Phi_n(f)$ is the noise spectrum

“The noise spectrum is readily obtained from portions of the record that contain no signal from lightning. The signal spectrum is estimated by differencing the cross spectrum of the current window and the cross spectrum of noise”(Stock et al., 2014).

Upsampling
(increasing the sampling rate of the signal)

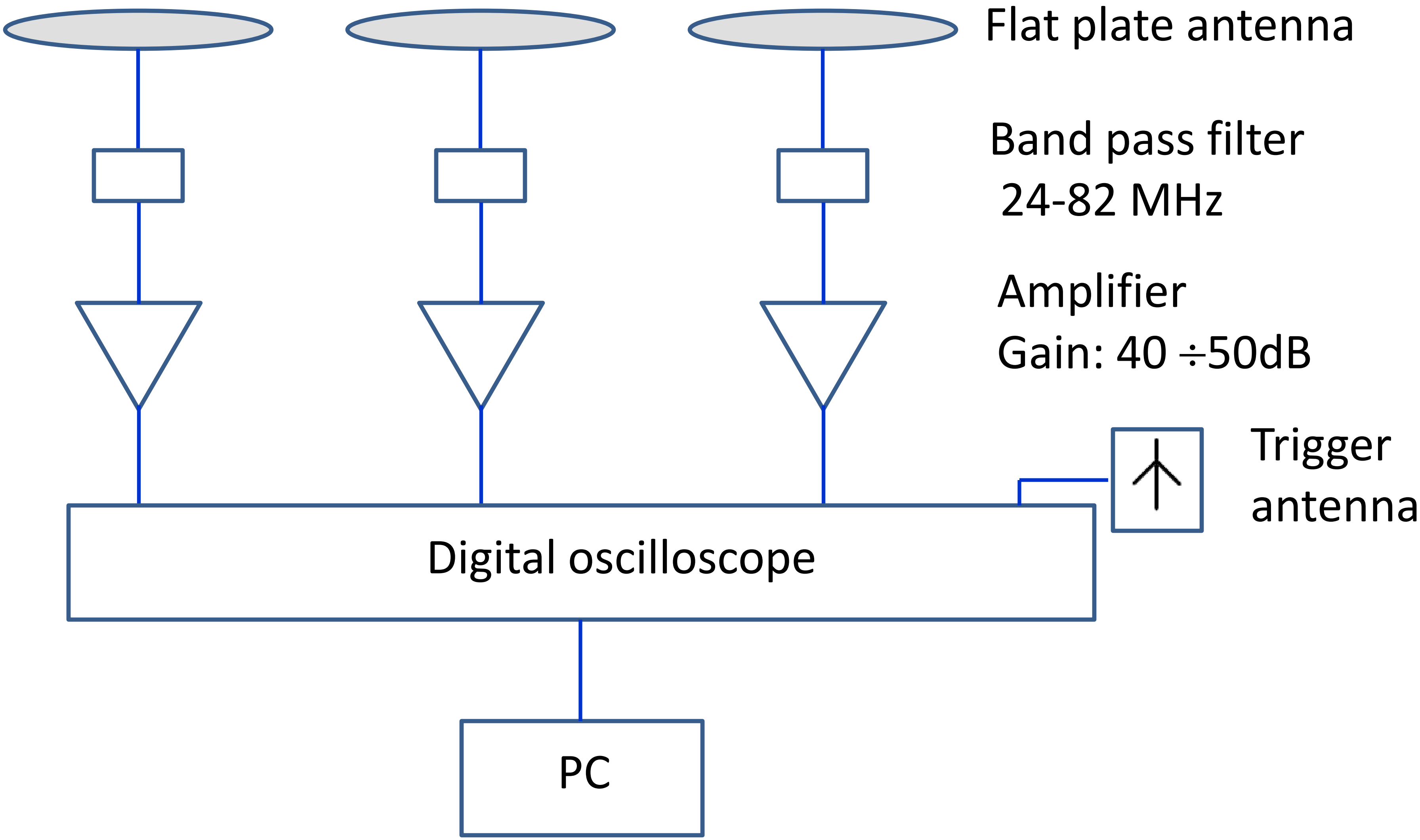
Because the cross correlation is computed discretely, the maximum of the correlation function is an integer multiple of the sampling period. To obtain a more accurate value of time delay, the cross spectrum is upsampled before transforming back to the time domain.

Example: Upsampling by a factor of 3.
Sampling interval becomes 3 times smaller



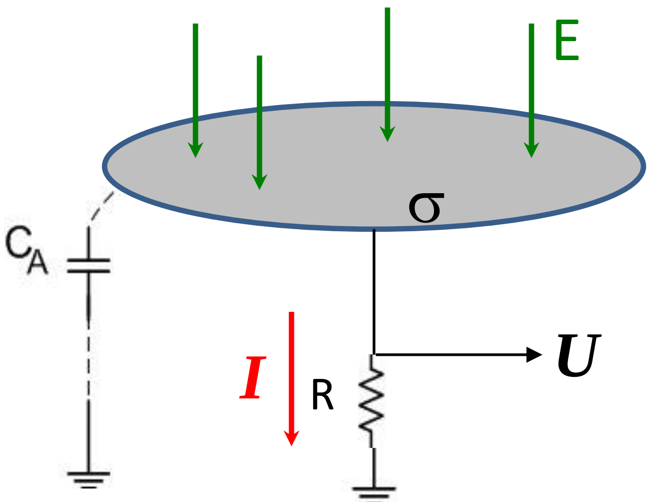
Upsampling produces an approximation of the sequence that would have been obtained by sampling the signal at a higher rate

Hardware



Flat plate antenna
Band pass filter
24-82 MHz
Amplifier
Gain: 40 ÷50dB
Trigger
antenna
Digital oscilloscope
PC

Antenna



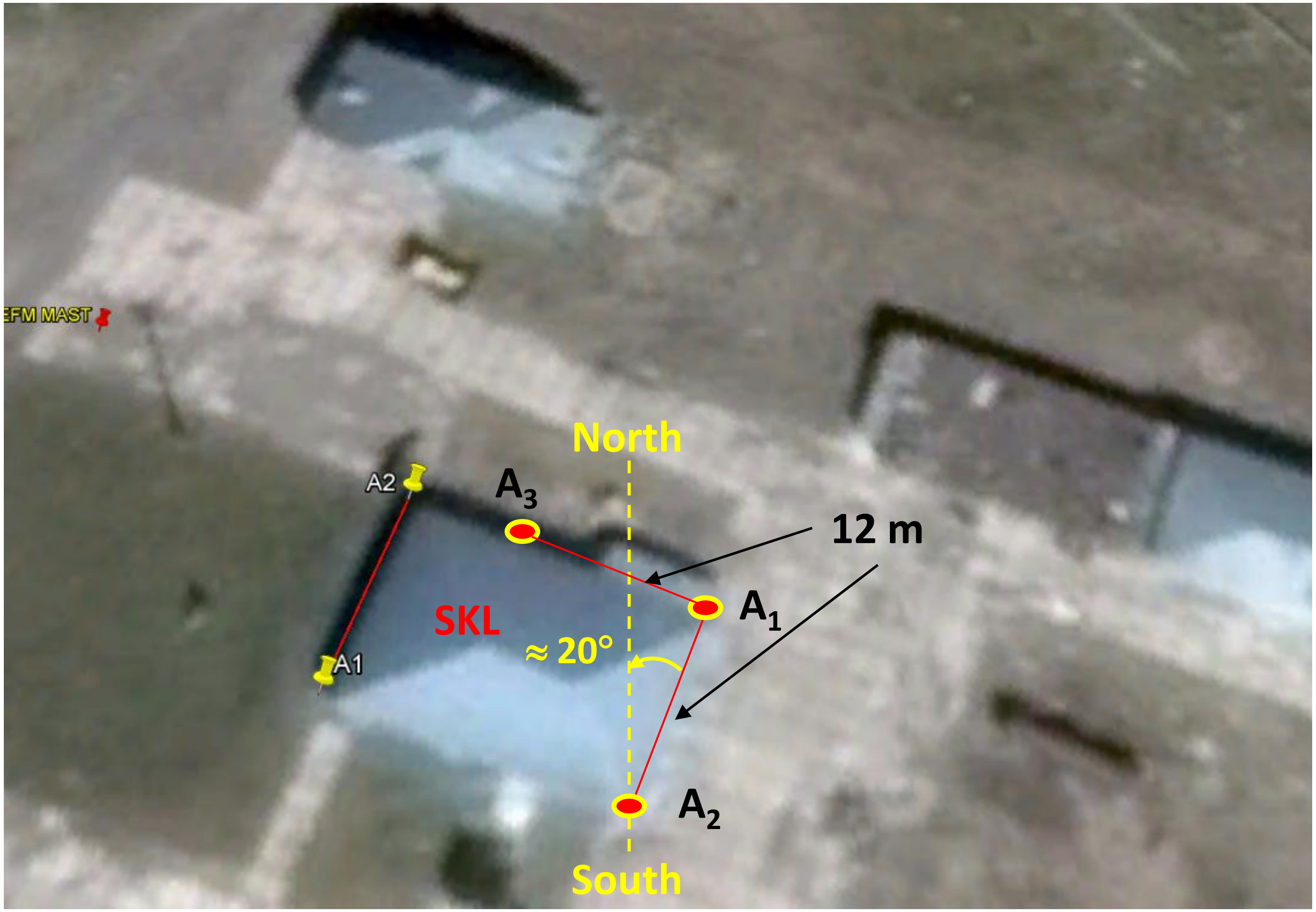
Diameter D=30 cm, $C_A \approx$ 30pF, R =50 Ohm.
The resistively coupled antenna is a low pass filter with cut-off frequency f=1/(2πRC)≈100MHz

$$E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{A\varepsilon_0}; \quad I = \frac{dQ}{dt} = A\varepsilon_0 \frac{dE}{dt}; \quad U = RA\varepsilon_0 \frac{dE}{dt}$$

σ is the surface charge density on the sensor plate,
A is the area of the plate, and $\varepsilon_0 = 8.854 \cdot 10^{-12}$ *F/m*

The resistively coupled antennas sense the time derivative of the incident electric field, dE/dt, and hence partially compensate for the falloff of lightning's VHF spectrum with increasing frequency

Antenna placement



Digital oscillosope

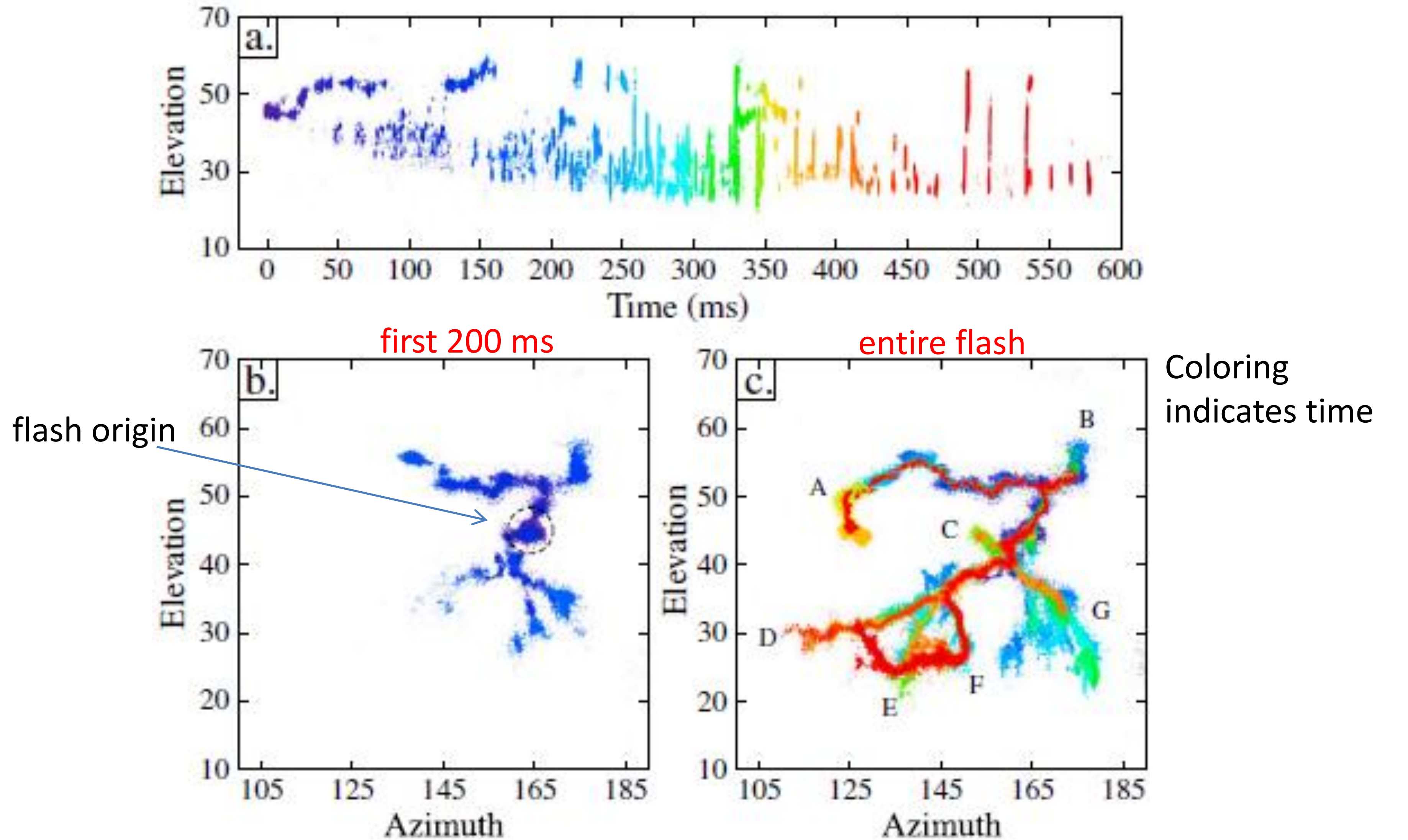
- Number of channels 3 (max 4)
- Sampling rate 200 MS/s (max 1.25 GS/s)
- Sampling interval 5 ns (min 0.8 ns)
- Record length 1 s
- Number of samples per channel 200 MS
- Memory required for 1 s recoding of three channels 600 MS (max memory 1 Gs)
- File size for 1-s record with 5 ns sampling interval: 120-130 MB (estimated size in Picoscope format)
- File size in 'mat' format about 1 GB. File splitting required

For two antennas separated by d =12 m the time difference of arrival is in the range $0 \div 40$ ns. Recorded waveforms are split into 256 sample windows and the time difference of arrival is found for each of these windows. The time resolution is determined by the window length and is (255x5) ns =1275 ns $\approx$1.3 μs.

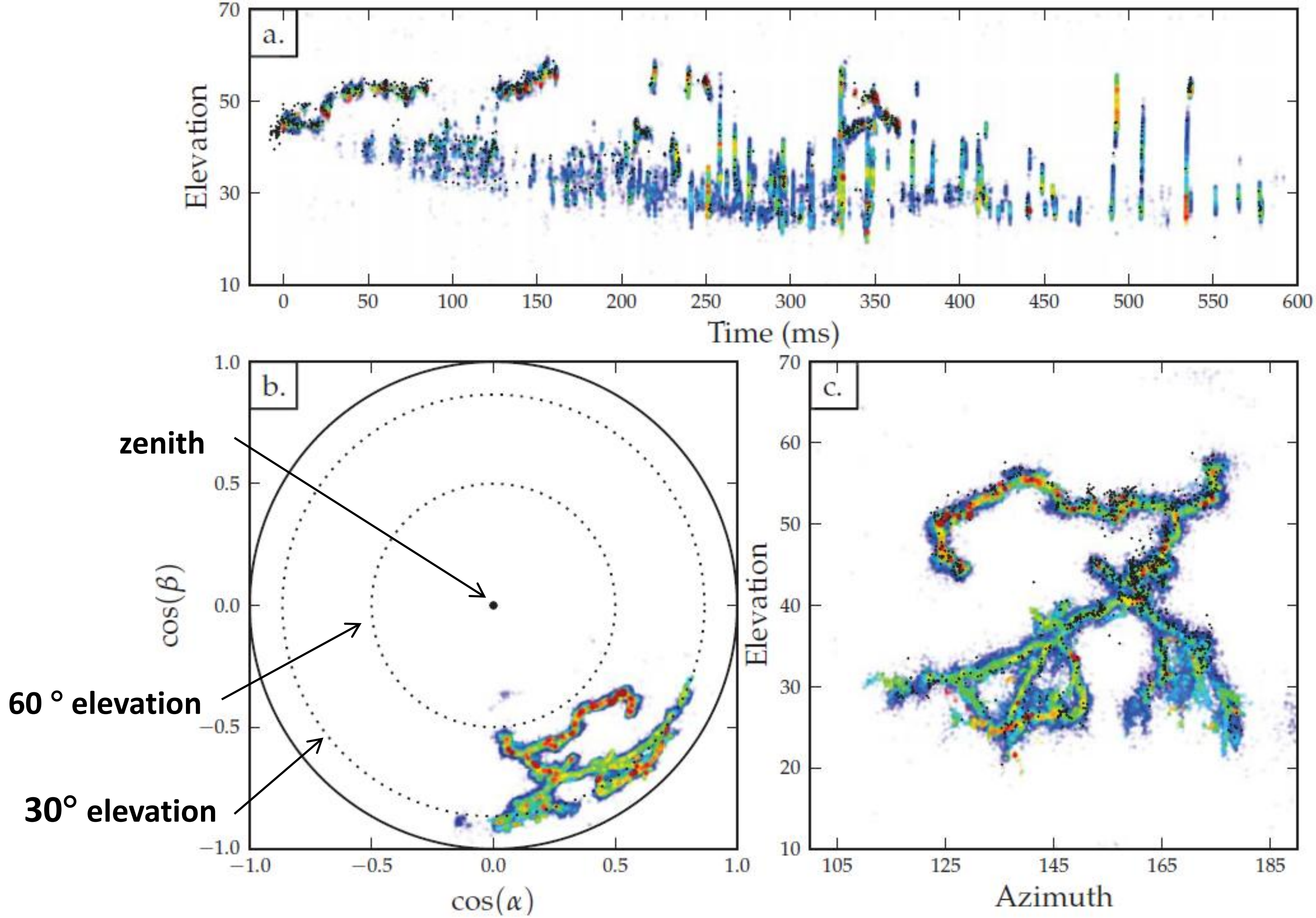
Observations of a “Classic Bilevel Intracloud Flash”

(normal polarity IC between mid-level negative and upper positive charge)

M. Stock, M. Akita, P. Krehbiel, W. Rison, H. Edens, Z. Kawasaki, and M. Stanley (2014), “Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm”, JGR -Atmospheres, 119(6), 3134–3165

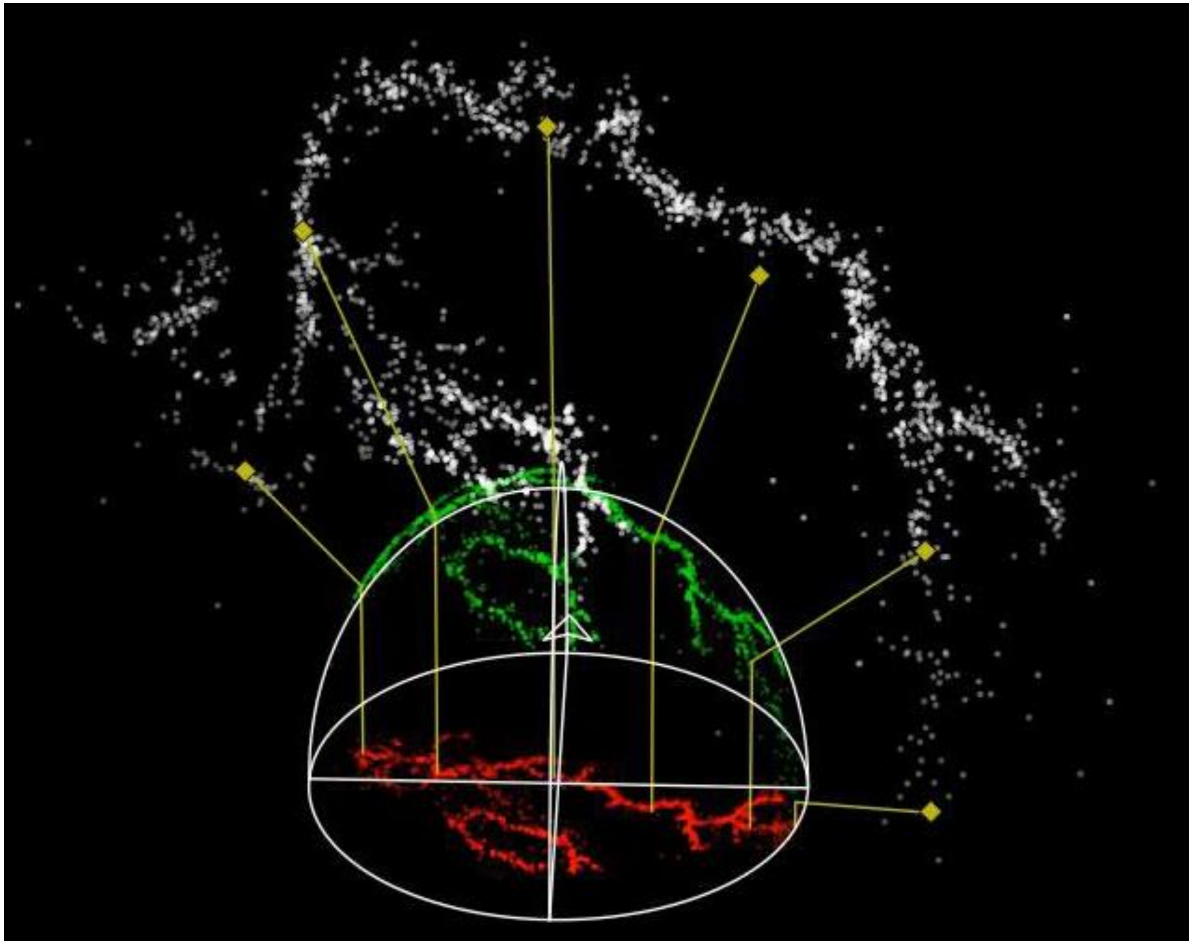


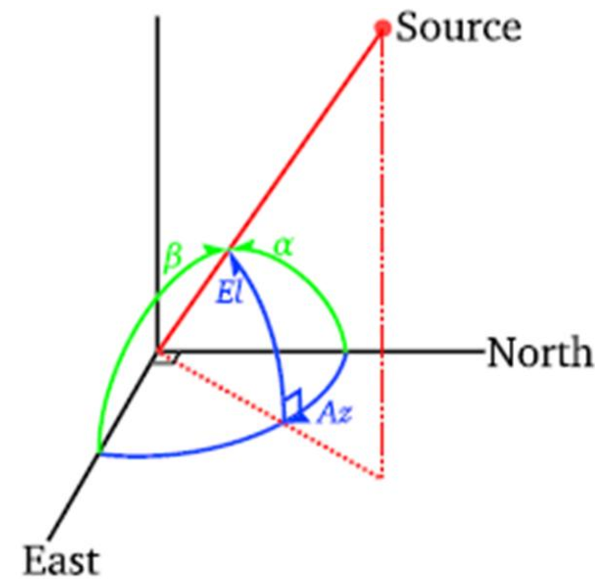
Upper level channels A and B correspond to negative leaders propagating into upper Positive storm charge. Lower level channels D, E, F, and G are formed by positive breakdown propagating into midlevel negative charge. Channel C is a negative-polarity side channel that resulted from negative charge temporarily being unable to propagate up the vertical connecting channel, partway into the discharge.



Same as in previous slide except with the sources colored by power, and showing the sources in the direction cosine plane of the measurements (b). LMA observations of the flash are overlaid as small black dots in a and c.

Image projection





$$\cos\alpha = \sin(\mathrm{Az})\cos(\mathrm{El})$$

$$\cos\beta = \cos(\mathrm{Az})\cos(\mathrm{El})$$

The direction cosines cos (α) and cos (β) represent the projection of the sources from a unit celestial hemisphere down onto the horizontal plane of the antennas.

(cosα, cosβ) - projection: error is constant over the entire cosine projection plane

(Az,El) - projection : **error in elevation increases as one approaches the horizon**

error in azimuth increases towards the zenit

Summary for hardware

- Flat plate antennas: ready
- Picoscope: purchase in progress
- Band pass filter: purchase in progress
- Amplifier: purchase postponed, subject to discussion
- Double shielded (tri-shielded, quad-shielded) coaxial cable (3x30 m) would be preferable to decrease the influence of noise

details

Coaxial cables

CCTV Cables

CCTV CABLE CONSTRUCTION:
CCTV CABLES utilize a copper center conductor. The dielectric is foamed or solid insulation. The shield construction is always a high percentage copper braid.

SDI - Digital Cables

PRO-VIDEO (DIGITAL) CABLE CONSTRUCTION:
PRO-VIDEO CABLES utilize a copper center conductor. The dielectric is foamed or solid insulation. The shield construction is always an aluminum foil + a high percentage tinned copper braid.

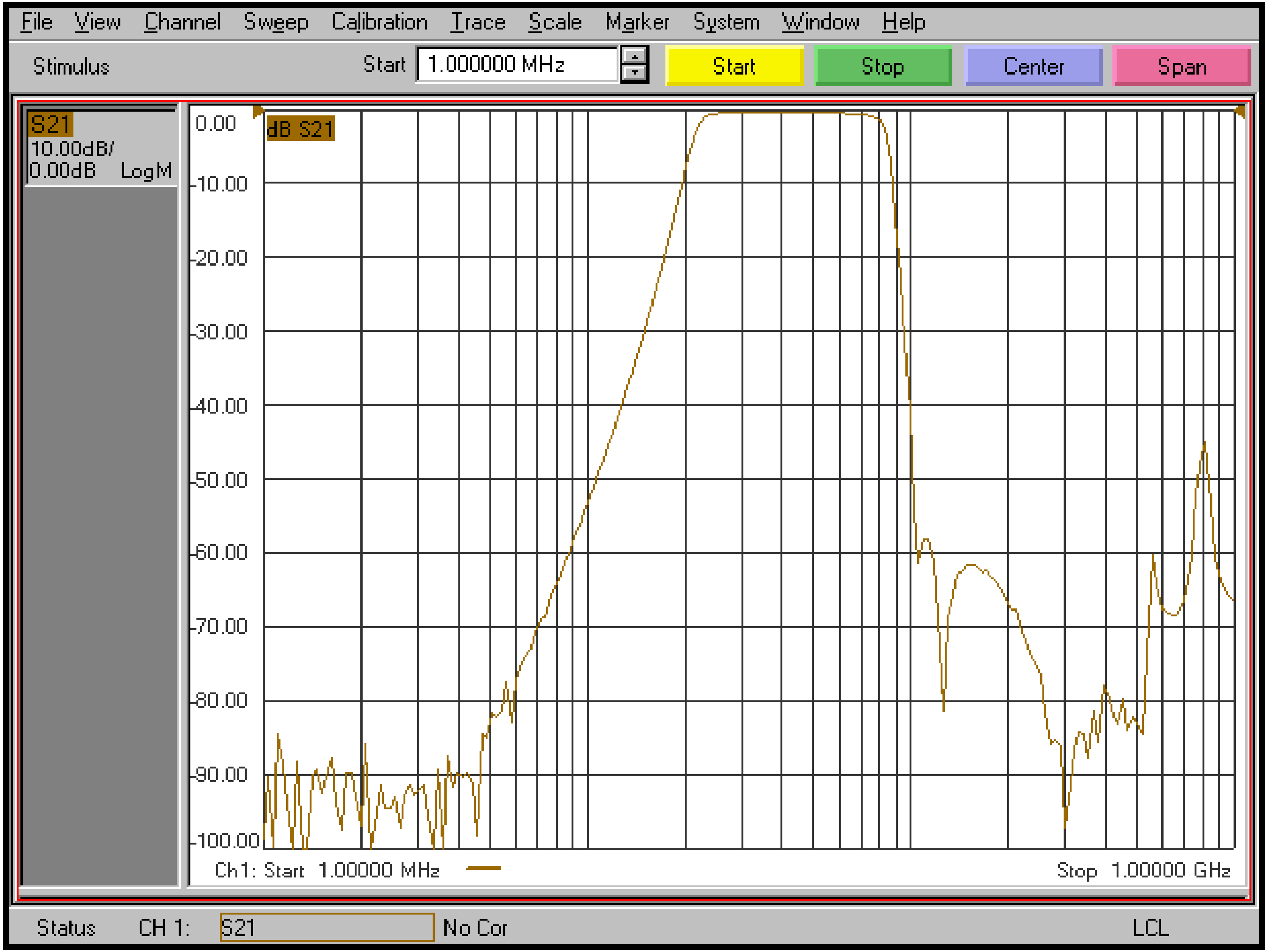
CATV Cables

CATV CABLE CONSTRUCTION:
CATV CABLES utilize a copper center or Copper Covered Steel conductor. The dielectric is always foamed insulation. The shield construction is always an aluminum foil + a aluminum braid.

Quad-Shielded CATV Cables

Other Constructions:
Tri-Shield- *Aluminum Foil + Aluminum Braid + Aluminum Foil*
Quad-Shield- *Aluminum Foil + Aluminum Braid + Aluminum Foil + Aluminum Braid*

24 MHz to 82 MHz band pass filter



24 MHz to 82 MHz band pass filter

KR Electronics, Inc.
www.krfilters.com

KR Electronics 2804-SMA

Specifications

Parameter	Specification	Notes
Filter type	Bandpass	
Center Frequency	53 MHz	
Insertion Loss	1 dBa max	0.5 dBa typical
2 dBc Bandwidth	58 MHz min	24 MHz to 82 MHz
Rejection at 10 MHz & below	40 dBc min	
Rejection at 103 MHz	40 dBc min	
Source and Load	50 Ω	

Amplifier

HD Communications Corp.

HD25116

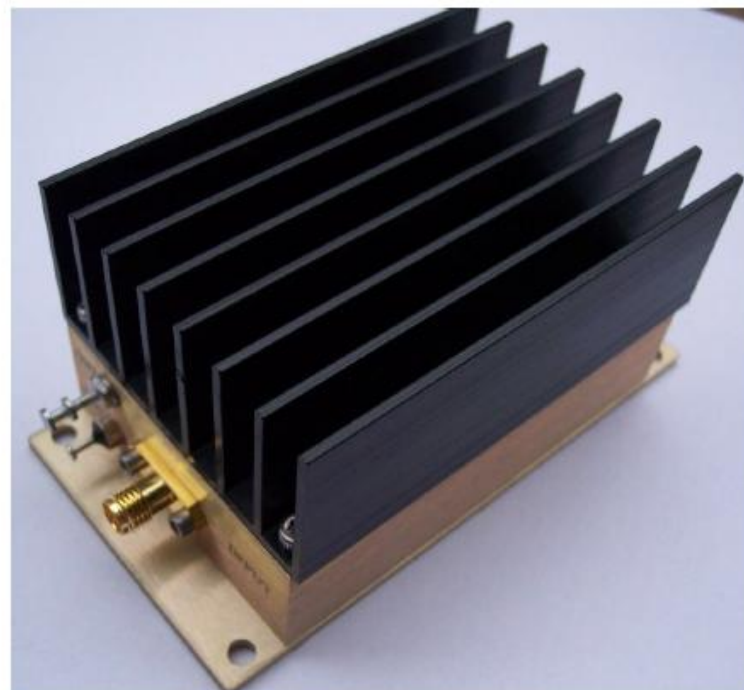
MPA Series

1-1000MHz 1W Power RF Amplifier

Features

- Frequency Range: 1-1000MHz
- Gain: 40dB
- P_{1dB}: +30dBm
- IP3: +40dBm
- Noise Figure: 3.3dB
- DC Power: 12V
- SMA Connector

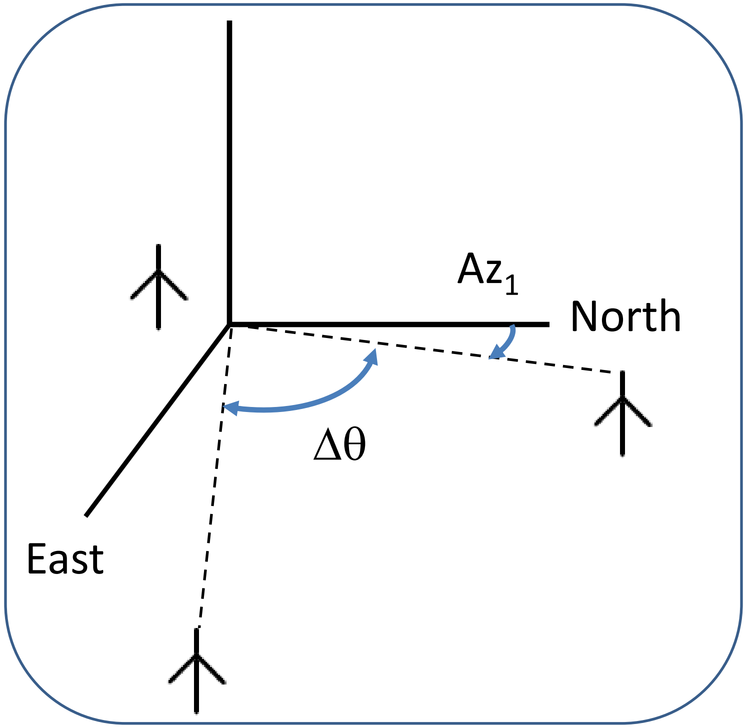
Performance measured @ 500MHz



Description

HD25116 is a 40dB gain, +30dBm (1 Watt) output Medium Power RF Amplifier, operating frequency range from 1 - 1000MHz with single 12V DC power supply.

Basic geometry of the interferometer measurements



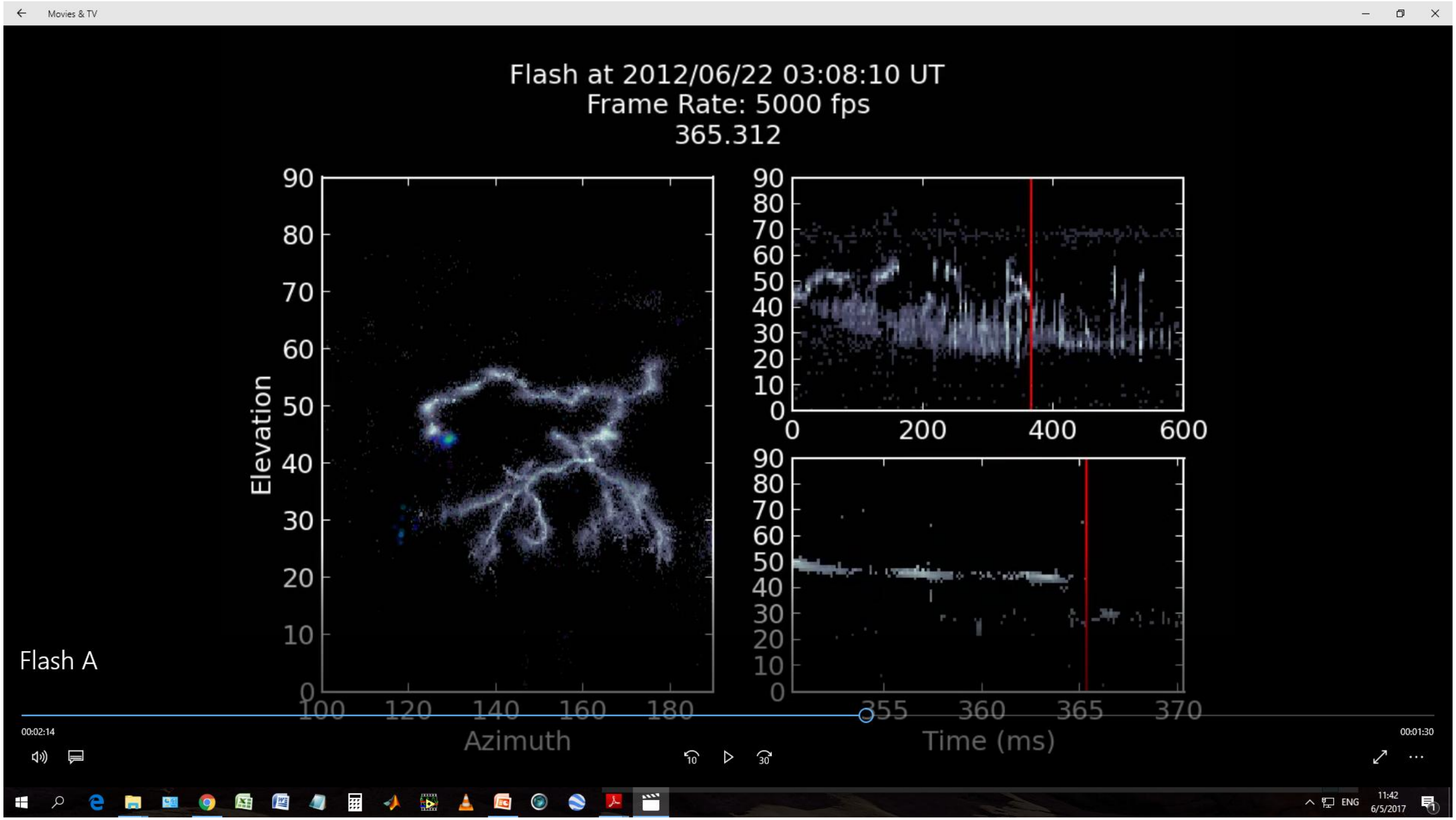
$$Az = Az_1 + arctan\left(\frac{\tau_{d1}\cos(\Delta\theta) - \tau_{d2}}{\tau_{d1}\sin(\Delta\theta)}\right)$$

$$El = arccos\left(\frac{c}{d}\sqrt{\frac{\tau_{d1}^2 + \tau_{d2}^2 - 2\tau_{d1}\tau_{d2}\cos(\Delta\theta)}{(\sin(\Delta\theta))^2}}\right)$$

Nonorthogonal baselines $\Delta\theta = Az_1 - Az_2 \neq 90°$
and arbitrary azimuth angle Az_1 of baseline 1

This flash is a good example of a fairly normal, everyday intra-cloud lightning flash (a flash which stays inside the cloud). If we had photographed this flash, all we would have seen was a diffuse glow in the cloud. One of the major benefits of using the VHF to map the lightning is that we can see through the cloud. By good fortune, the flash is oriented almost face on to the interferometer. When lightning leaders move towards or away from the interferometer site, there's a lot of perspective distortion in the maps. In this case, there is almost none.

The flash initiates with an upward propagating leader which carries negative charge (a negative leader). This leader is propagating into a region of the thunder cloud which carries positive charge, since opposites attract. After a short delay, there are several branched channels carrying positive charge which propagate downward into a region of the thunderstorm carrying negative charge. As the channels carrying positive charge get longer, they destabilize and stop being conductive. When this happens, a fast breakdown process travels back along the channel, warming up the air and making it conductive again.



http://lightning-interferometry.com/index.php/videos/