EPRI Lightning Protection Design Workstation

Tom McDermott
Electrotek Concepts, Inc.
2000 Winter Power Meeting

LPDW v5 Components

- Includes 1988-97 flash data from the National Lightning Detection Network
- CFlash for underground distribution (new)
- DFlash for overhead distribution
- TFlash for overhead transmission
- LPData.exe - manages main database
- On-line reference

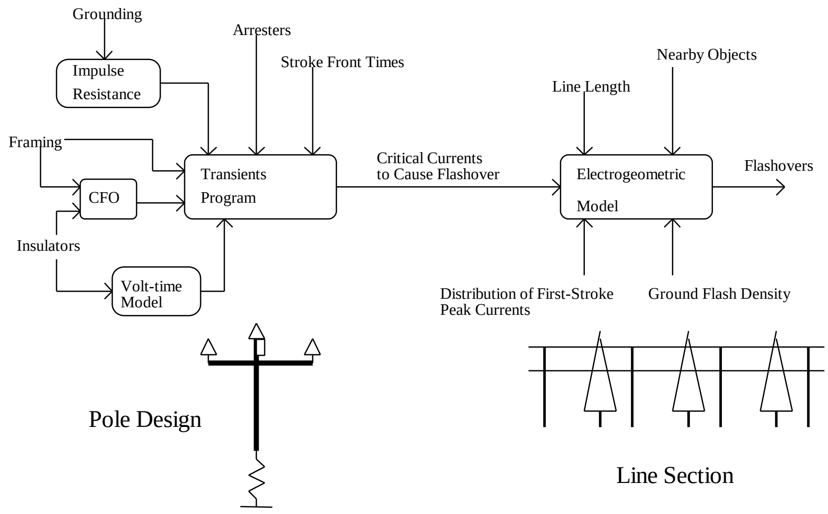
LPDW History

- 1992 v1 Release (DFlash)
- 1994 v2 Release
  - DFlash pole drawing
  - MultiFlash for transmission
- 1997 v4 Release
  - brand new TFlash for transmission
  - multiple circuits in DFlash
- 1999 v5 - brand new CFlash for cables

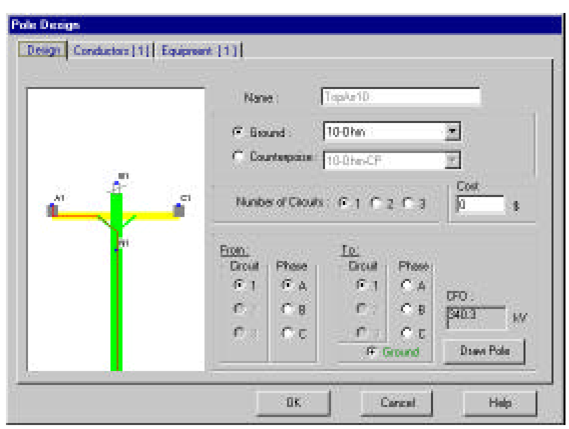
DFlash Features

- Lightning Flash Data (EPRI RP 2431)
  - Ground Flash Density maps
  - Peak currents of the first stroke
- Pole Insulation Strength analysis (EPRI RP 2874)
- Shielding
  - Overhead shield wires
  - Nearby trees and houses
- Surge Arresters at various spacings
- Pole Ground Resistance
- Transformer Protection (lead length, low-side surges)
- Equipment Inventory

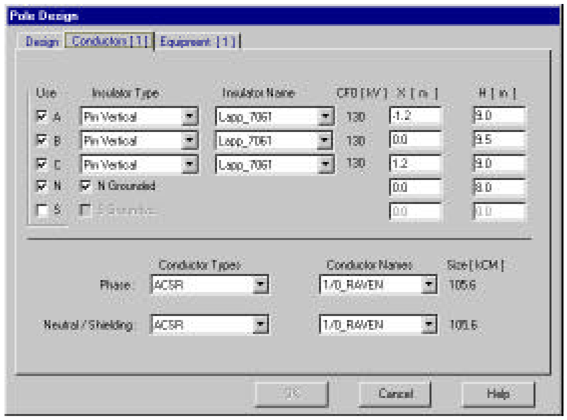
DFlash Line Flashover Calculation



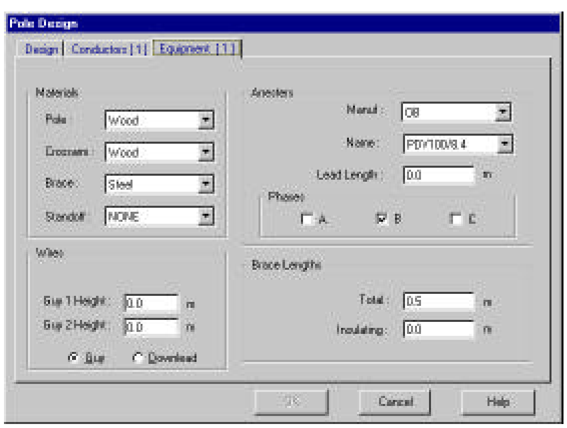
DFlash Pole Design Dialog



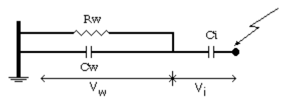
DFlash Conductor and Insulator Specification

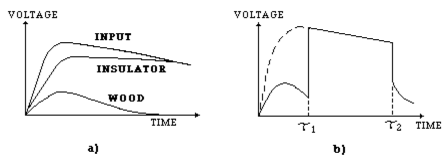


DFlash Arrester and Pole Material Specification



Distribution of Total Voltage Across Pole Insulation





CFO Added Values

Table 2. CFO Added by Second Components

Second Component of:	With first component of:	Adds to the CFO:
Wood crossarm	Vertical pin insulator	250 kV/m
Wood crossarm	Vertical suspension insulator	160 kV/m
Wood crossarm	Horizontal suspension insulator	295 kV/m
Wood pole	Vertical pin insulator	235 kV/m
Wood pole	Suspension insulator	90 kV/m
Fiberglass Crossarm	Insulator	250 kV/m
Fiberglass Standoff	Insulator	315 kV/m

Table 3. CFO Added by Third Components

Third Component of:	Adds to the CFO:
Wood pole	65 kV/m
Fiberglass Standoff	200 kV/m

Sample Pole CFO [kV]

Phase	No Arrester	Phase B Arrester
A	370	340
B	439	130
C	370	340

Time to Flashover

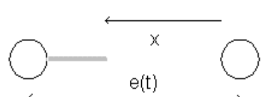
- CFO is based on a 1.2 x 50 μs standard laboratory test waveshape
- Destructive Effect (Dflash v1-4.1):

$$DE = \int (e - V_b)^b \, dt$$

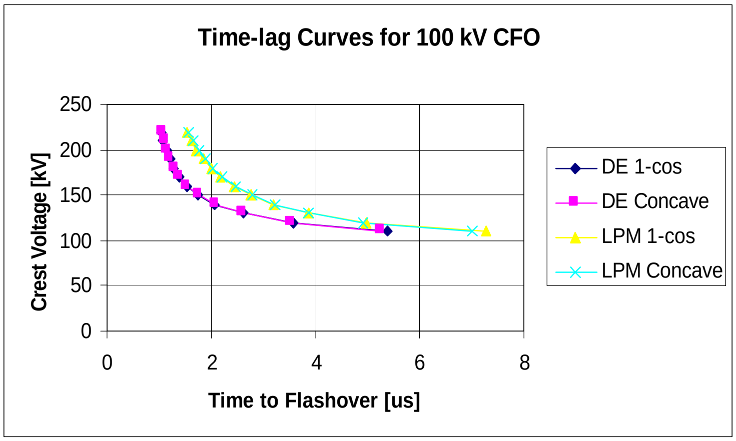
- Leader Progression Model (Dflash v5):

$$dx/dt = Ke(t)\left[\frac{e(t)}{x} - E_0\right]$$

where K = propagation constant
E_0 = breakdown gradient
x = unbridged gap length
e(t) = voltage across gap



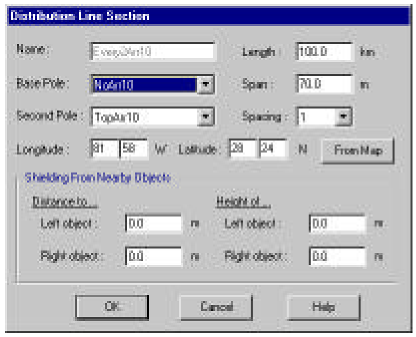
Air-Porcelain Volt-Time Curves



CFO Guidelines for Dflash

- Large impact on flashovers from induced voltages - want CFO at least 300 kV
- Not much effect on direct-stroke flashovers (it’s hard to make overhead shield wires work on distribution lines)
- Steel and concrete structural elements hurt
- Guy wires, downleads, fuse cutouts, and switches also hurt

DFlash Line Section Dialog



DFlash Line Section Flashovers

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**** Line Section Flashover Performance ****

Line Section Name       :  15kV
Global flash density    :  6.68 flashes/sq.km/yr

Exposed             Events    Arresters Exceeding          Direct-Stroke
Conductor(s)            On    Energy Rating/yr             Flashovers/yr
                                1ph   2/3ph   Mckt         1ph   2/3ph   Mckt

Phase A, Ckt 1        Ckt1    0.000  0.000  0.000      12.621  0.000  0.000
                      Ckt2    0.000  0.000  0.000       0.000  0.000  0.000
                      Ckt3    0.000  0.000  0.000       0.000  0.000  0.000

Phase B, Ckt 1        Ckt1    0.000  0.000  0.000       0.682  0.000  0.000
                      Ckt2    0.000  0.000  0.000       0.000  0.000  0.000
                      Ckt3    0.000  0.000  0.000       0.000  0.000  0.000

Phase C, Ckt 1        Ckt1    0.000  0.000  0.000       5.300  0.000  0.000
                      Ckt2    0.000  0.000  0.000       0.000  0.000  0.000
                      Ckt3    0.000  0.000  0.000       0.000  0.000  0.000

                                                       Ckt1   Ckt2   Ckt3
Equivalent shadow widths                         =    27.85   0.00   0.00 meters
Flashes to line in open ground                   =    78.65   0.00   0.00 /yr
Flashes to line with nearby objects              =    18.60   0.00   0.00 /yr
Shielding factor due to nearby objects           =     0.76   0.00   0.00
Direct-stroke flashovers                         =    18.60   0.00   0.00 /yr
Nearby-stroke flashovers                         =    36.63   0.00   0.00 /yr
Arresters with excess energy discharge           =     0.00   0.00   0.00 /yr
Median current of first direct stroke to line =       28.86   0.00   0.00 kA
---------------- End of Flashover Performance Analysis ----------------
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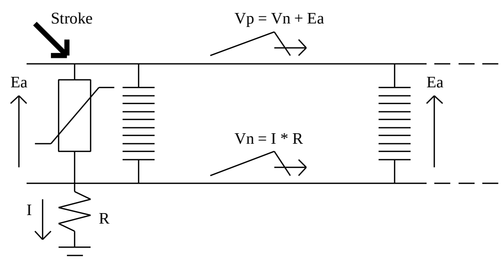
Sample Line Flashover Results

100 km, GFD=1, 9.1 first strokes to line/year
0.188 shielding failure flashovers in all cases

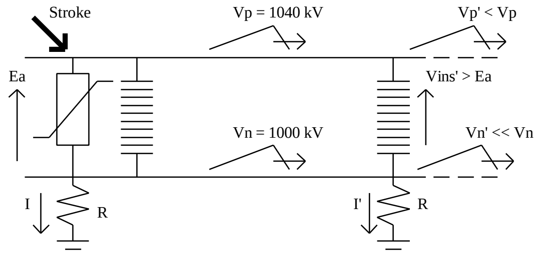
Arrester Spacing	Ground	Stroke to B 1-ϕ FO	2,3-ϕ FO	Excess Energy
None	50	8.910	0.000	0.000
Every 2	50	4.368	0.985	3.130
Every 1	50	0.000	1.969	5.311
None	10	8.910	0.000	0.000
Every 2	10	4.516	0.126	3.841
Every 1	10	0.000	0.373	6.907

Arresters at Every Ground



(Ground resistance makes no difference)

Grounds without Arresters



$V_{ins}' = E_a + V_n * [1 - (2R + Z_m) / (2R + Z_g)]$

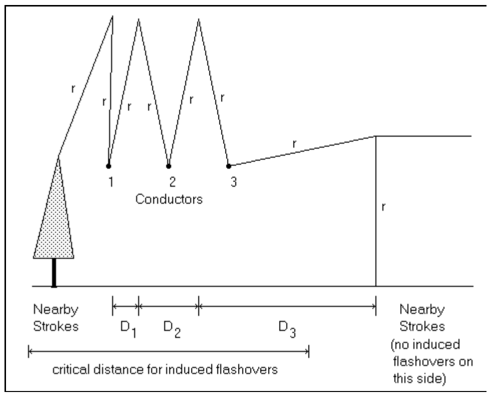
Ex.: E_a = 40 kV, Z_m = 179.82 Ω, Z_g = 428.48 Ω

R	**0**	**25**	**100**	**1000**	**inf**
V_{ins}'	620	560	436	142	40

Electrogeometric Model

- Roughly simulates final attachment process between lightning and objects on the ground (power lines, trees, masts, etc.)
- Estimate number of strokes to a line
- Which conductors are struck?
- Shielding from nearby houses and trees
  - Shielding Factor = fraction of direct strokes intercepted by nearby objects
  - How close can nearby strokes come?

EGM Determines both Stroke Collection and Shielding



Evolution of the EGM

- Strike Distance $r_c = 10 I^{0.65}$
- Dflash through version 4
  $$r_g = b r_c$$
  $$b = 0.9 \quad \text{(versions 4.x)}$$
  $$b = 22/h \quad \text{(versions 1-3)}$$
- Tflash in version 4
  $$r_g = b r_c$$
  $$b = \frac{3.6 + 1.7 \ln(43 - h)}{10}$$

Evolution of the EGM

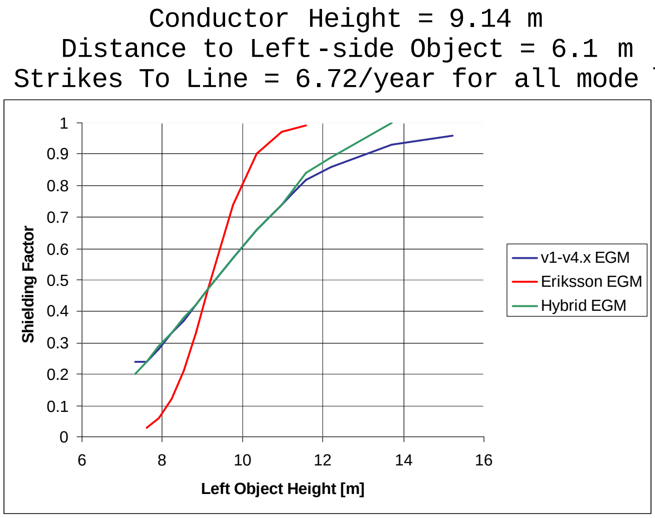
- Eriksson's stroke collection $r = 14h^{0.6}$

$$N_S = N_g \left(\frac{28h^{0.6} + b}{10} \right)$$

- DFlash in v5

$$r = 1.00 I^{0.74} h^{0.6}$$

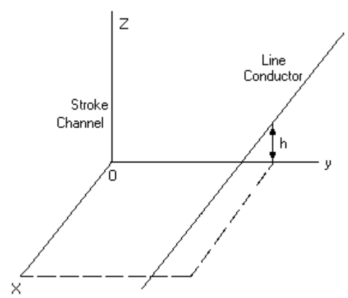
Effect of Strike Distance Change



Implications of the EGM

- Need to match shielding with stroke collection
- Median current of strokes to the line **increases with height**
- NLDN current distribution may become preferred data source, median to flat ground is in the 20's of kA
- A leader progression model (Rizk, Dellera and Garbagnati) might be better
- Could use a 3D model for nearby objects

Applying Rusck's Model



Maximum Voltage: $U_{max} = \frac{Z_0 I_0 h}{y}\left[1+\beta/\sqrt{2-\beta^2}\right]$

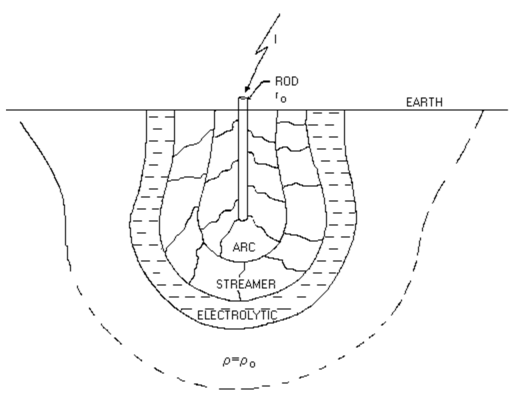
Voltage for 1-kA stroke, 1 foot away from a conductor 1 foot above ground: $V_{base} = Z_0\left[1+\beta/\sqrt{2-\beta^2}\right]$

Critical distance for a nearby stroke: $y = \frac{V_{base}}{CFO} I_0 h$

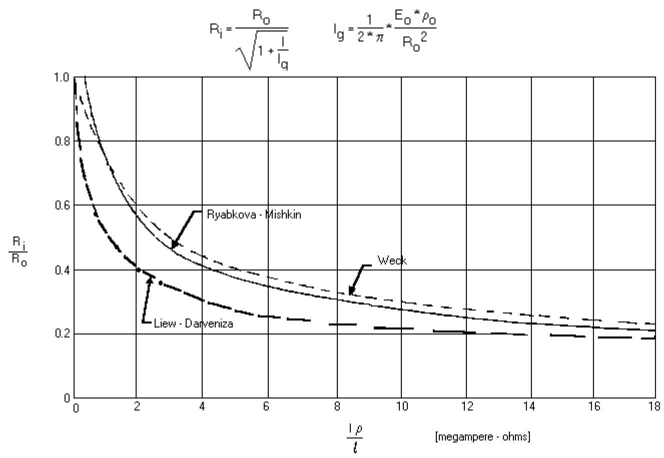
Implications of Induced Voltages

- Rusck model is widely criticized for simplicity
- Compensating errors in DFlash
  - Rusck model may be optimistic
  - steepness and insulation strength pessimistic
- At least 2 good travelling wave models exist, Anderson and Nucci et. al., but:
  - voltage between conductors less than voltage to ground
  - widely spaced arresters are effective
  - insulation above 300 kV CFO is effective

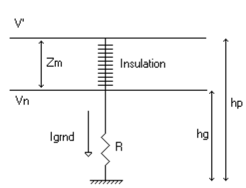
Soil Ionization Effects for Ground Rod



Weck’s Approximation



Effect of Pole Ground on the Induced Voltage



$V' = V \{1 - (h_g / h_p) [Z_m / (2R + Z_g)]\}$

$V_n = V (h_g / h_p) * [2R / (2R + Z_g)]$

$V_{ins} = V' - V_n$

$= V \{1 - (h_g / h_p) [(2R + Z_m) / (2R + Z_g)]\}$

Example: Induced Voltage with Pole Ground

$h_p = 30$ ft $h_n = 24$ ft $Z_g = 500\ \Omega$

$Z_m = 150\ \Omega$ $R = 50\ \Omega$ CFO = 300 kV

Suppose V = 300 kV from nearby stroke, on a conductor 30 ft above ground

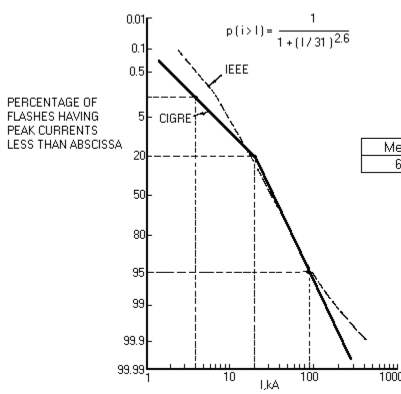
$V_{ins} = 300\ [1 - (24/30)] = 60$ kV at ungrounded poles

$V' = 300\ \{1 - (24/30) * [150/(2 * 50 + 500)]\} = 240$ kV

$V_n = 300\ (24/30) * [(2 * 50)/(2 * 50 + 500)] = 40$ kV

$V_{ins} = 240 - 40 = 200$ kV at grounded poles

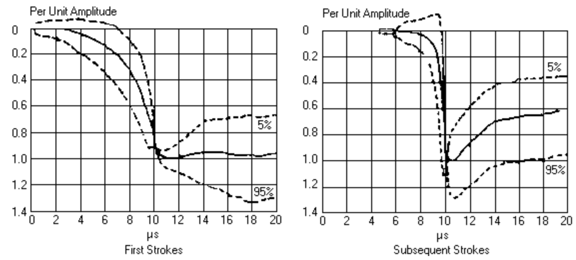
Crest Current Distributions



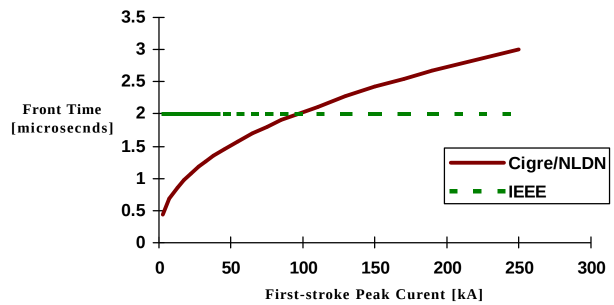
CIGRE First Stroke Current

I < 20 kA		I > 20 kA	
Median	Beta	Median	Beta
61.1	1.325	33.3	0.605

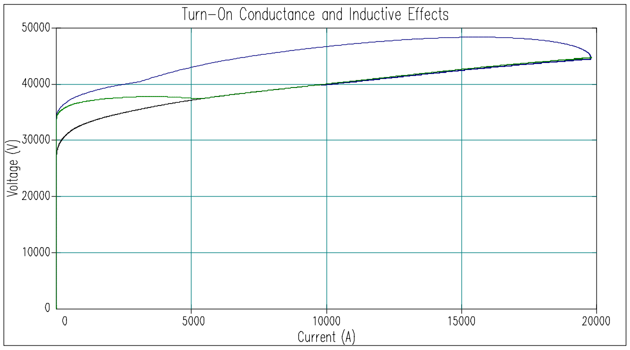
Front of Wave Distributions



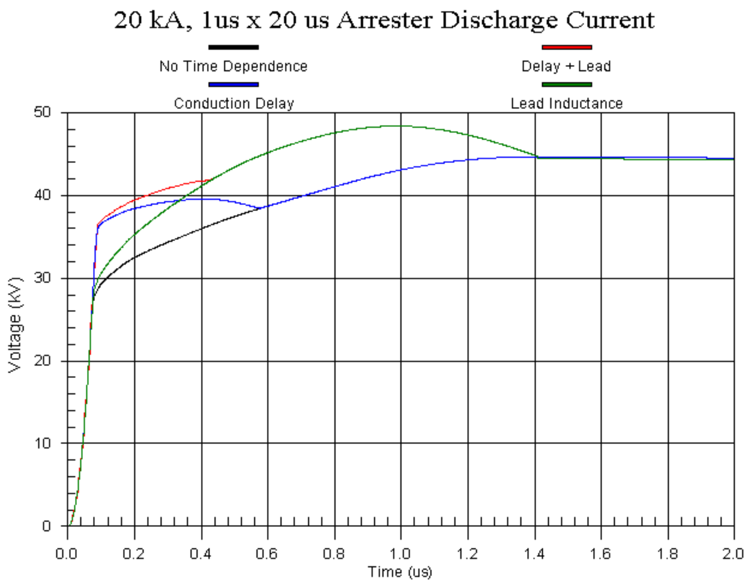
Stroke Front Time Options



Arrester VI Characteristics



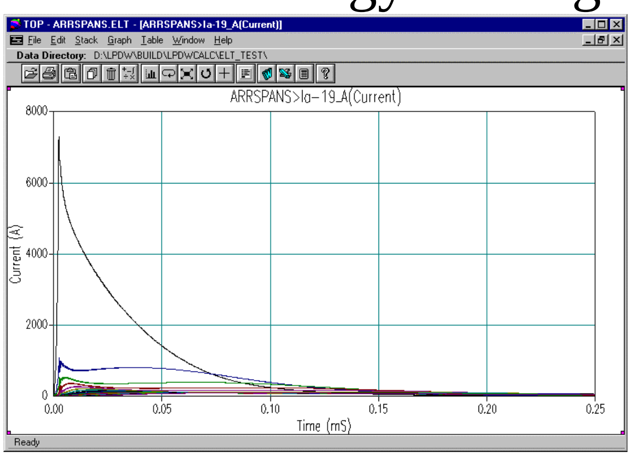
Arrbez Turn-On Conductance and Inductance Model, Uref = 0.051, L = 0.3 µH,
20 kA, 1x20 Discharge Current



Stroke Tail Time

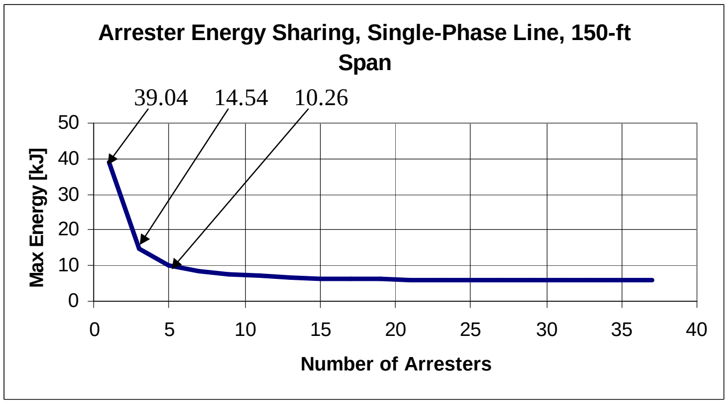
- Arrester energy approximation for an Exponential tail
  - Time Constant: $\tau = 1.44\ T_{50}$
  - Energy: $E = I\ V\ \tau$
  - Charge: $Q = I\ \tau$
- For median Q = 4.65 and I = 31.1, $\tau = 150$ μs, or $T_{50} = 104$ μs
- Berger's basic data was 77.5 μs

Arrester Energy Sharing

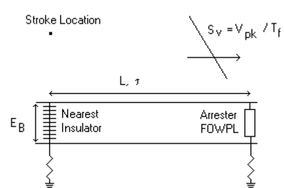


Arrester Discharge Currents with 37 Parallel Arresters

Arrester Energy Sharing



Effect of Arrester on Induced Voltage



CFO $= \text{FOWPL} + 2\ t\ S_v$

$= \text{FOWPL} + 2\ L\ V_{pk} / T_{front}\ c$

The "unprotected" induced voltage required to cause flashover is:
$V_{pk} = (\text{CFO} - \text{FOWPL}) * T_{front} * c / (2\ L)$

Example: Induced Voltage with Arresters and Grounds

FOWPL = 45 kV
T_{front} = 1 μsec
CFO = 300 kV

L = 150 ft/span
c = 984 ft/μsec
R = 50 Ω

Arr. Sep. L [ft]	V_{pk} for V_{ins} >= 300 kV
0	infinite
150	1255 kV
300	627 kV
infinite	450 kV
	(1500 kV for ungrounded)

IMPACT Sensors in the NLDN

- Combines magnetic direction finding with time-of-arrival
- Time of Arrival (TOA) modified to use absolute times from GPS clock, changes hyperbolas to range circles
- Improved hardware, calibration, adjustments, and algorithms
- The new NLDN is roughly half IMPACT, half TOA, and includes Canada

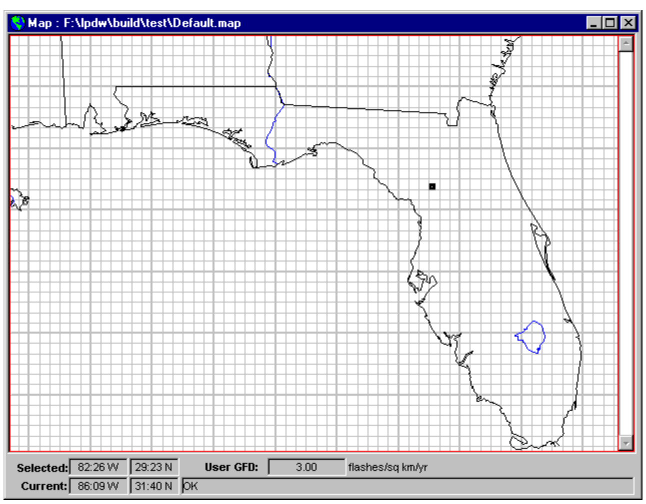
NLDN Performance Improvements

	50% Error Ellipse	Flash Detection
Year	**Semi-Major Axis**	**Efficiency**
1995	0.5-1.0 km	80-90%
1992-94	2-4 km	65-80%
1989-91	4-8 km	70%

Some interesting observations

- Peak current distribution seems to vary with location
- Many subsequent strokes have higher peak currents than the first stroke

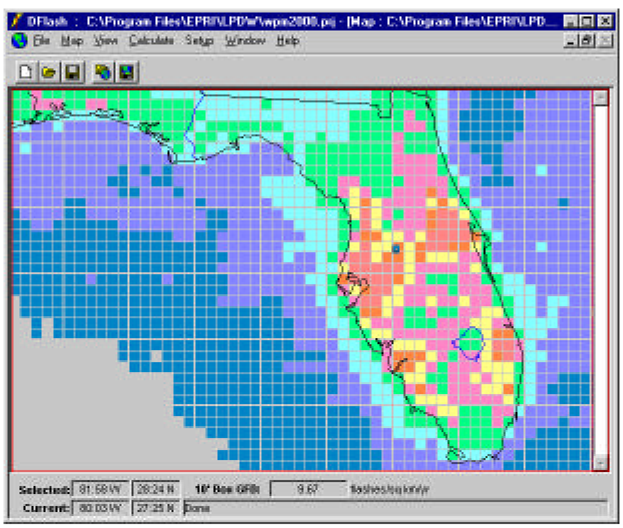
LPDW Grid System for Flash Data



Small Boxes

- 10 minutes on a side
- About 16 x 16 km at the equator
- Cumulative flash counts for positive and negative polarity
- Use for local ground flash density (GFD)
- Line Sections and Towers are located in small boxes

GFD from NLDN



Large Boxes

- 1 degree (60 minutes) on a side
- About 100 km x 100 km at the equator
- Cumulative GFD statistics
  - Mean annual GFD
  - Standard deviation of annual GFD
- Histogram of first-stroke peak currents
- Histogram of stroke multiplicity, for positive and negative polarity

Lightning Parameter Options

- IEEE: 31-kA median, 2-μsec front
- Cigre: 31-kA median, 1.28-μsec median front that depends on current
- NLDN: median peak depends on the Large Box, Cigre fronts

In Dflash:

- All: tail time = 77.5 μsec
- All: 12.3-kA median subsequent stroke, but multiplicity varies

Effect of Lightning Environment

Arresters Every Pole, 50-Ω grounds

Option	First Strokes to Line	Median of First Strokes to Line [kA]	Shielding Failure FO	Top-Phase Flashover
Cigre	11.24	44.63	0.130	4.717
IEEE	11.09	42.33	0.128	4.392
NLDN	9.10	31.98	0.188	1.969

Caveats for NLDN Data

- There are 10 years available for use with LPDW Version 4.1, 1988-1997, but the first few years did not cover the entire U. S. (48 states)
- Before 1995, the ground flash detection efficiency ranges from 40% to 70%, depending on geographic location
- Calibration of peak current magnitudes is very approximate
- Many ground flashes have multiple attachment points
- Actual "Ground Strike" density could be up to 2-3x raw GFD from NLDN, depending on year and location

Fault Analysis and Lightning Location System (FALLS)

- First release in 1995
- GIS-based (MapInfo)
- Uses NLDN flash or stroke data with time-correlated power system events
- Small-area GFD and stroke parameter maps
- Asset exposure and reliability analysis
  - difference between "hot lightning areas" and "hot flashover areas"
- Solaris/Sybase server, Solaris or NT client

TFlash Features

- Complete modeling of the line, tower-by-tower
- Ground rods, radial and continuous counterpoise with impulse resistance
- Transmission line surge arresters
- Shielding from nearby objects
- Transmission line surge arresters
- Corona effects
- Tower surge impedance

Improvements for Version 6

- Map based on commercial GIS
- Improve archived NLDN data, with stroke current distributions in the 10-minute boxes
- Internationalization, allow other sources of lightning data
- Pole model options (underbuild, H-frame)
- More access to modeling options

Future Work

- Revised/redone electrogeometric model
- Better characterize the arrester energy discharge capability
- CFO added from fiberglass guy insulators (needs laboratory testing)
- Time-domain simulation of induced voltages