Studies on ELVES in AUGER

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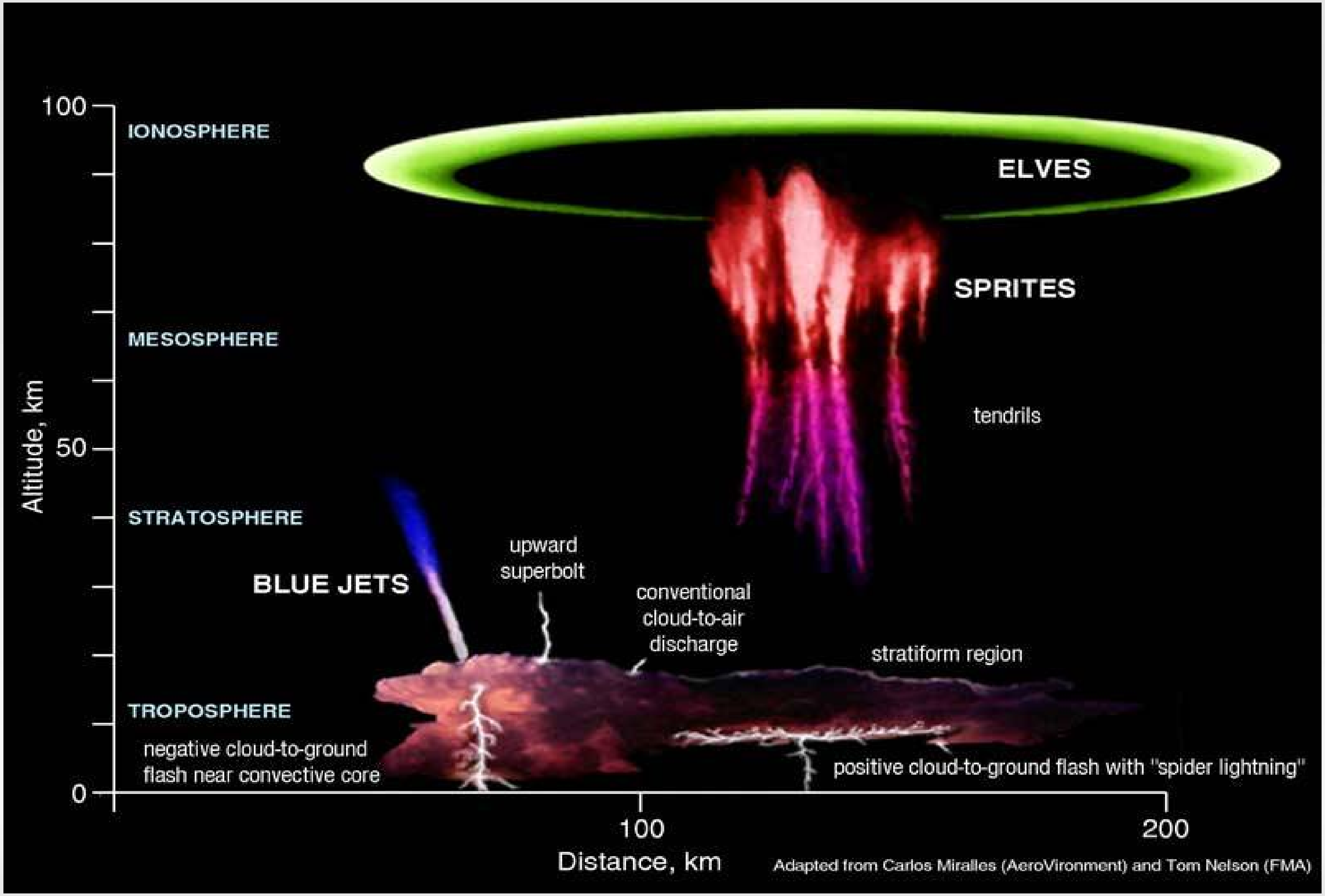
INFN TORINO



HiLite 2013 INFN Workshop , September 30th , 2013

Pierre Auger Observatory: a giant array

Malargüe,Mendoza, Argentina (35°28'S,69°20'W)

1600 tanks,1.5 km spacing, *1.4-1.5 km asl*

Detection of Cherenkov light from $\mu^{\pm}, e^{\pm}, \gamma$

3000 km^2 effective area

12 tons of H_2O per tank

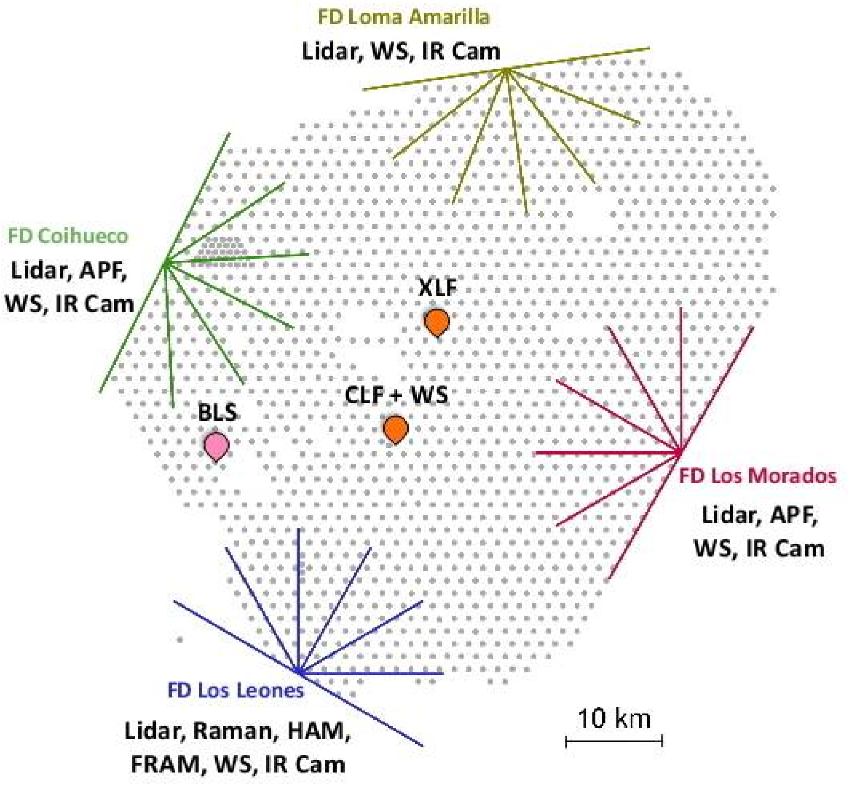
100% duty cycle

Angular resolution <1°

Threshold Energy: $10^{18.3}$ eV

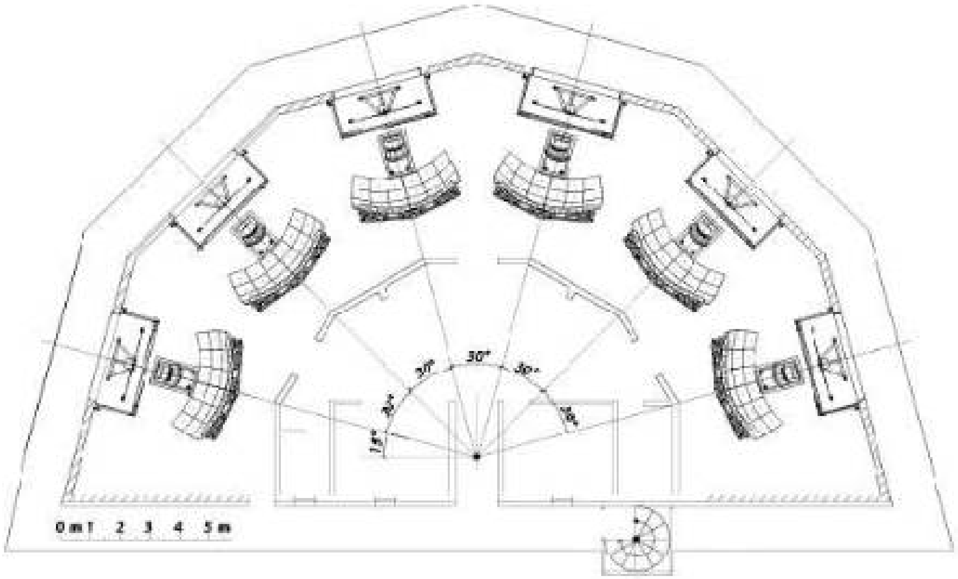
3 PMTs /tank

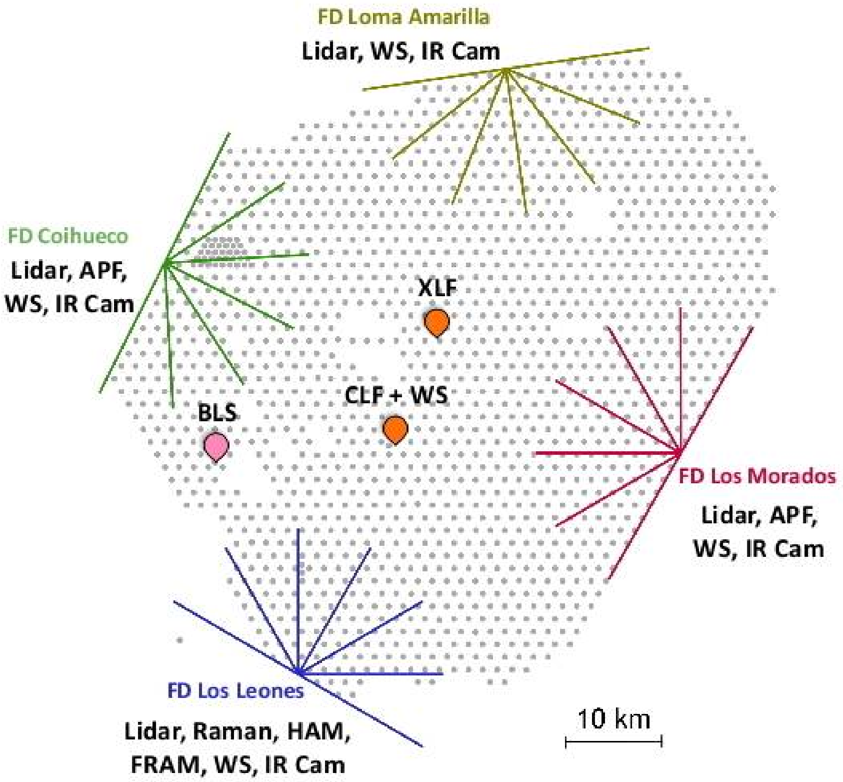
Complete since 2008



Fluorescence Detector

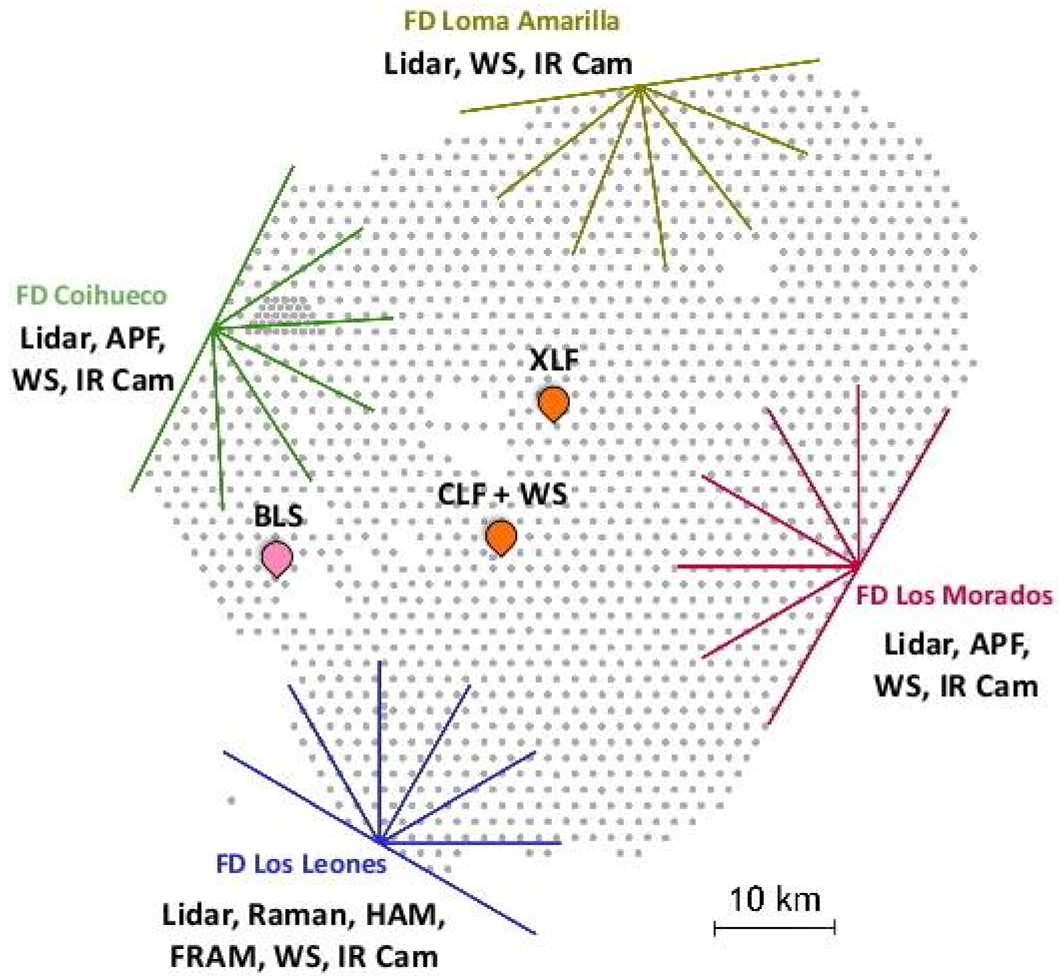
24 telescopes in 4 eyes
FD camera: 440 PMTs / telescope
Mirror area: 11m^2
Field of View: 6x30°x30° for each FD
Duty cycle ~12%
    (nights with <1/2 moon)
Angular resolution ~ 0.6°





Atmospheric Monitoring Systems

A 26.4 Giga Ton detector !

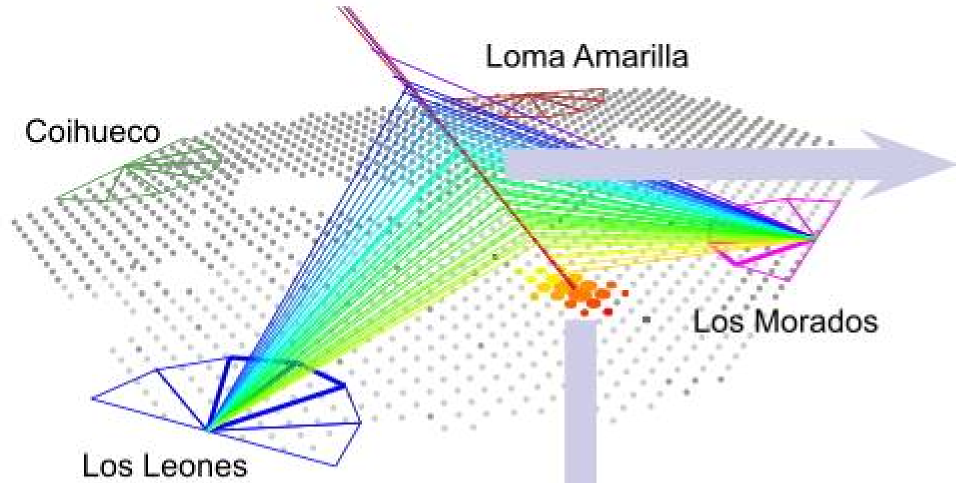


Molecular Measurements
- Weather Stations (WS)
- Radiosondes (launched from BLS)

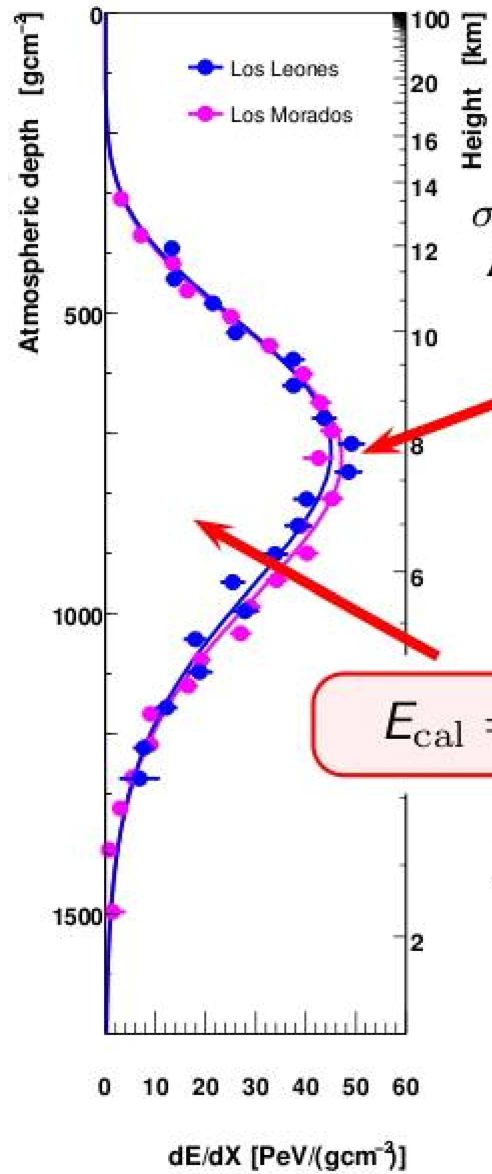
Aerosol Measurements
- Central Laser Facilities (CLF,XLF)
- LIDARs
- Aerosol Phase Function Monitor (APF)
- Horizontal Attenuation Monitor (HAM)
- Photometric Robotic Telescope (FRAM)

Cloud Measurements
- LIDARs
- IR Cloud Cameras

Hybrid Technique



FD : longitudinal profile



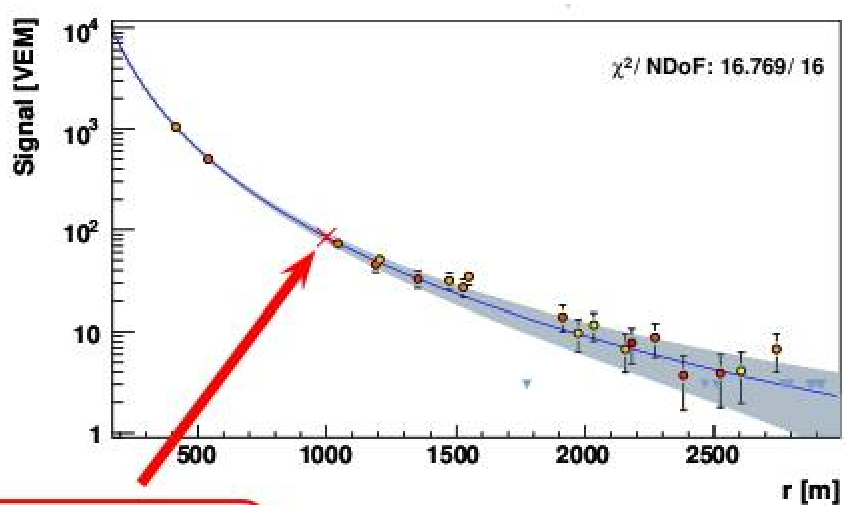
$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

$X_{\max}$

$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E / E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

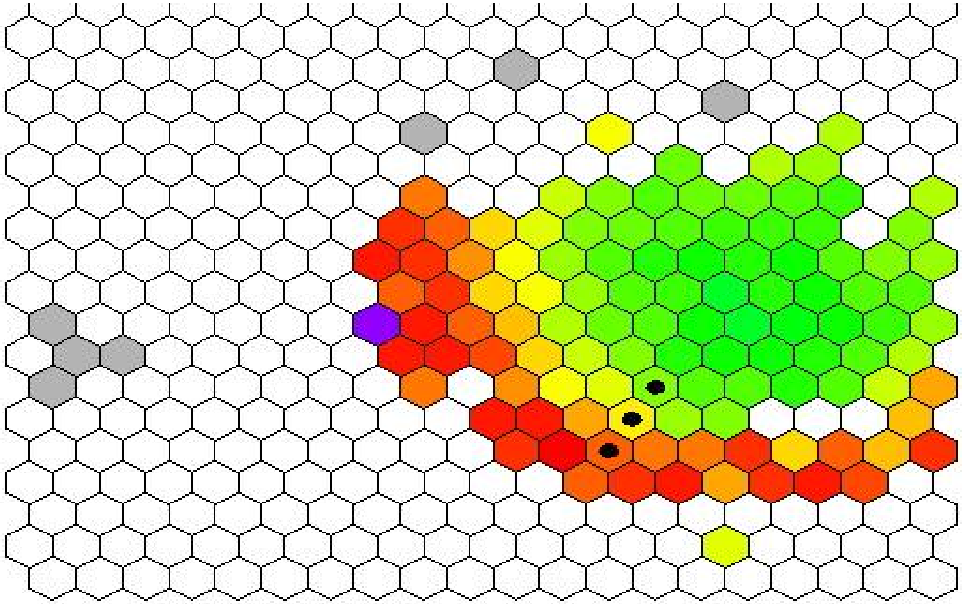
SD : lateral profile

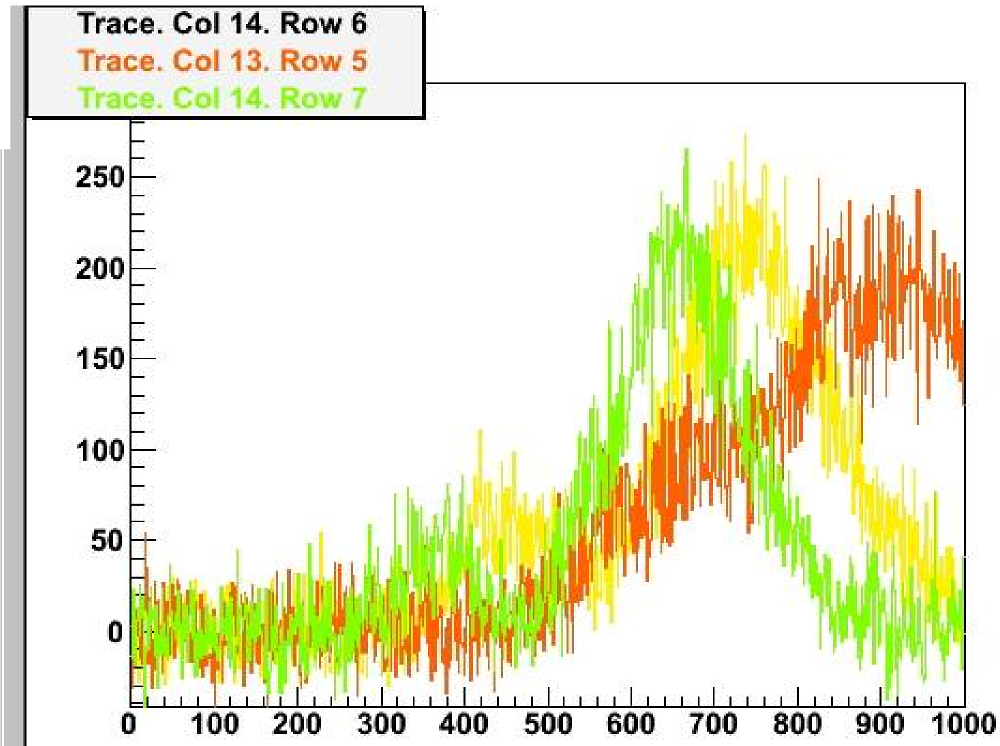


S_{1000}

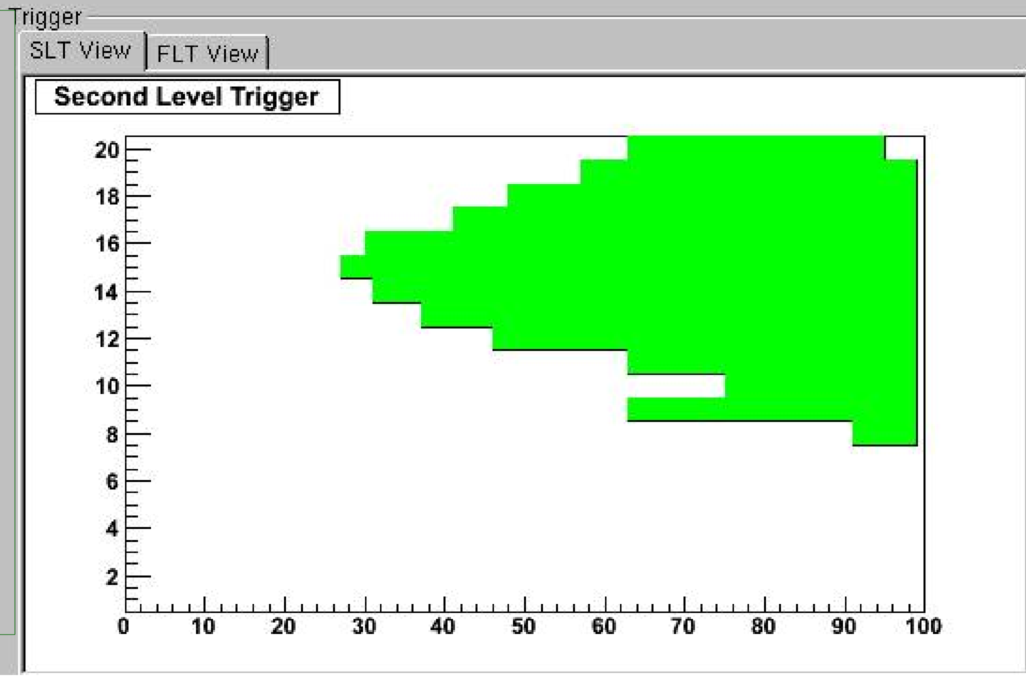
$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

LM6-800414142

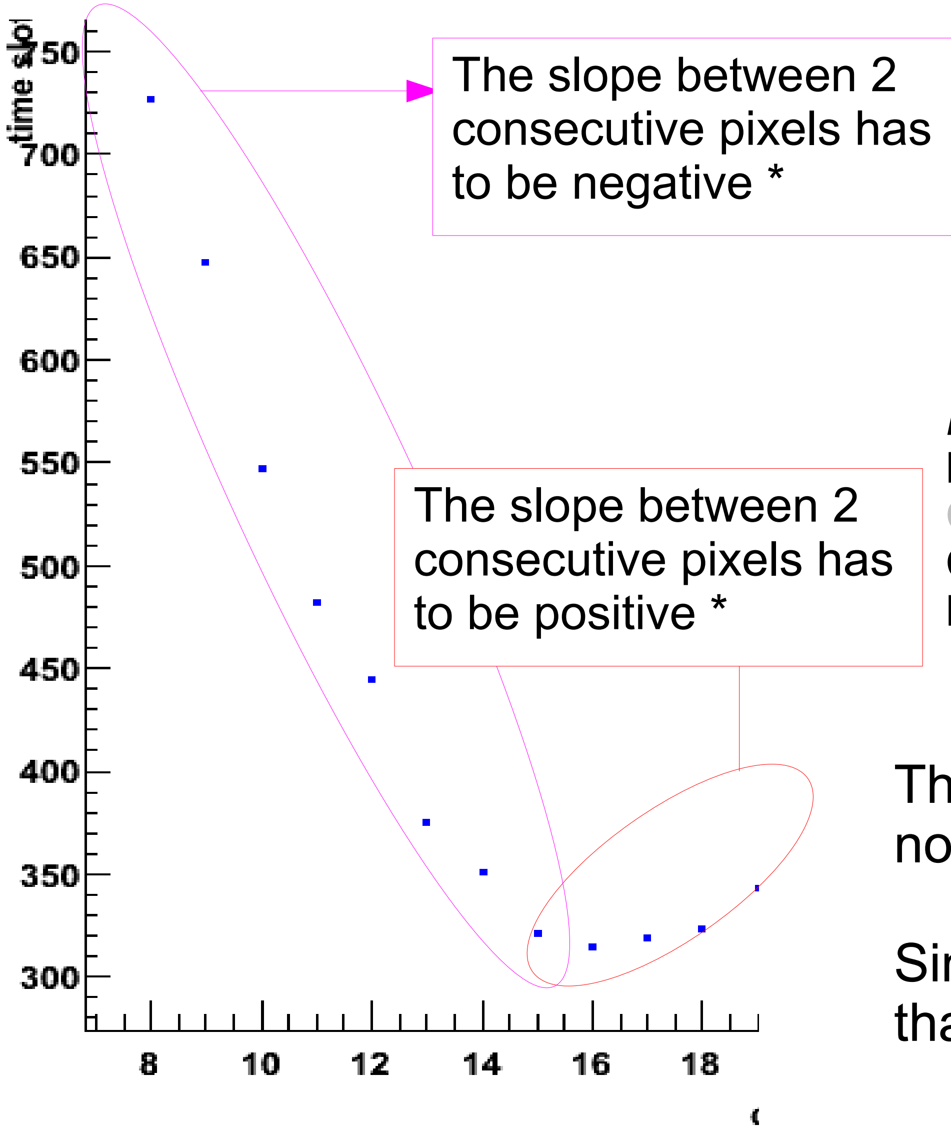




The first event was seen at Los Morados (LM) on 18/05/2005 01:15:29 GMT (GPS:800414142). It was a cloudy night, and only the FD sites of LM and Los Leones (LL) were operational.
LM6 saw this, followed by 6 other subtriggers.
(total length of the pulse: ~7msec)
LM5 (right of LM6) saw 7 subtriggers,
(starting 37.4 μsec later)
LL1 and LL2 did not see any activity.
No events in the SD as well.



Elves in AUGER:Selection criteria



We modified standard OffLine to select events with curved light fronts, inspired by one event seen during a shift in 2005.

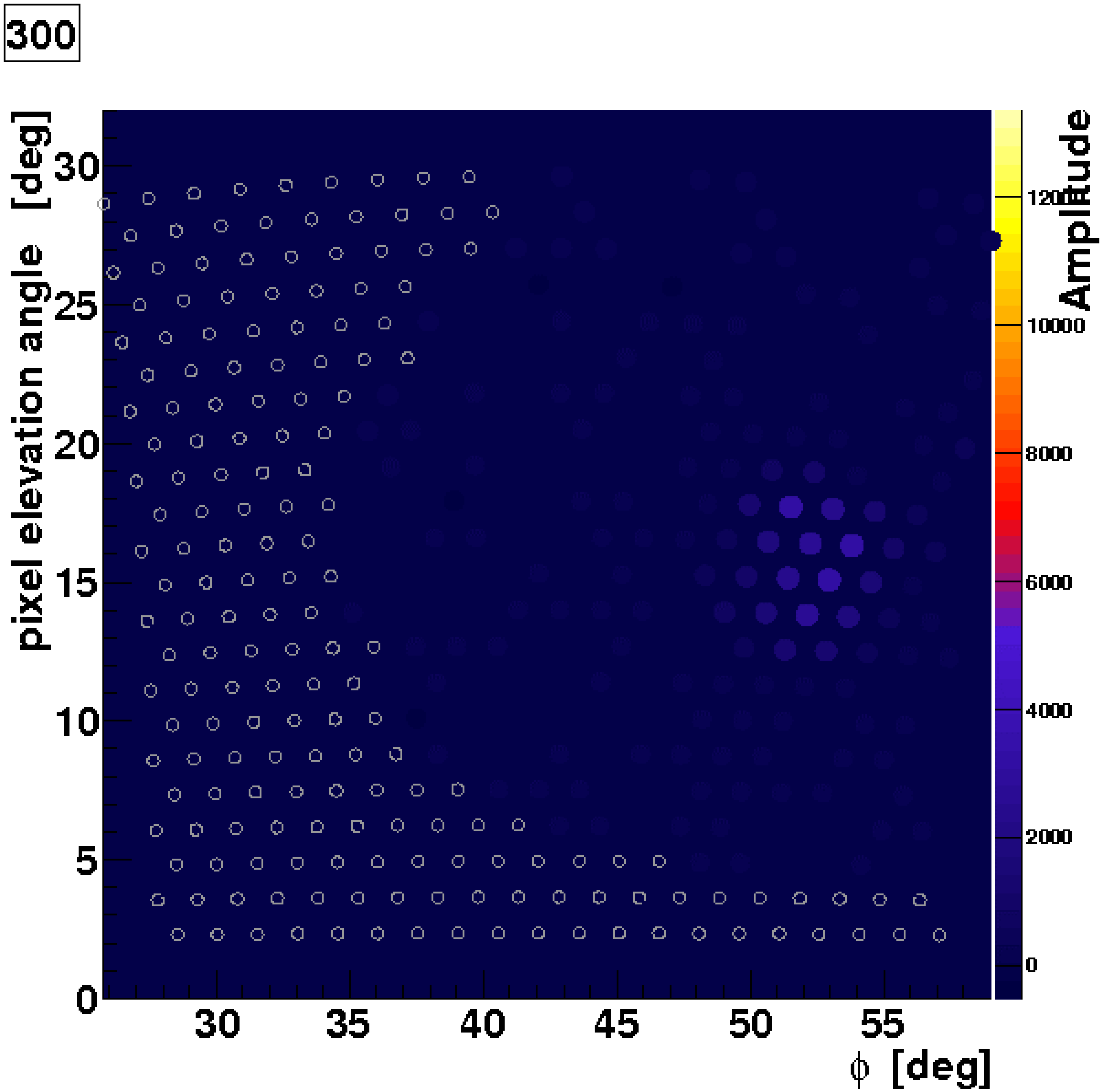
We found 4 events.

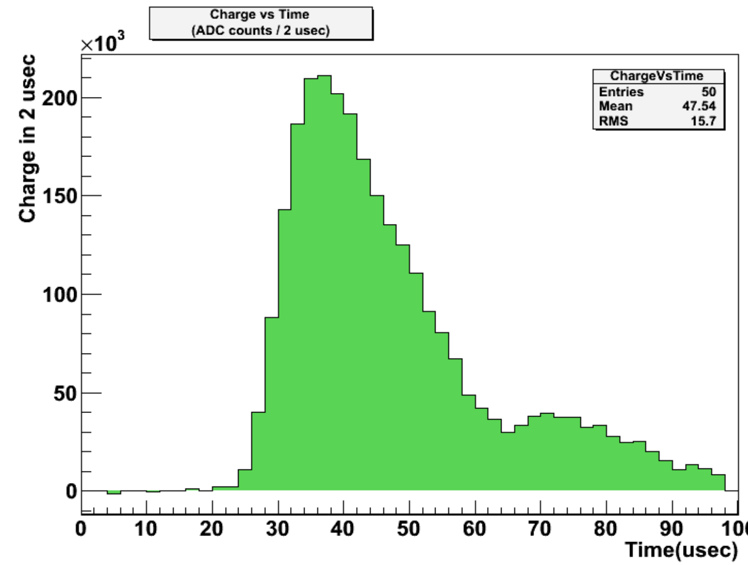
Bay	*GPS time*	*GMT*	*weather*
LM-6	800414142	18/05/2005 01:15:29	very cloudy
CO-5	855471392	14/02/2007 06:56:18	
CO-3	860806213	17/04/2007 00:49:59	clear sky
LL-1	861081389	20/04/2007 05:16:15	foggy

The two in 2007 are only 3 days apart; SD does not even see a rate increase during these events

Since Fall 2007 we reject them more effectively... thanks to an improved lightning filter

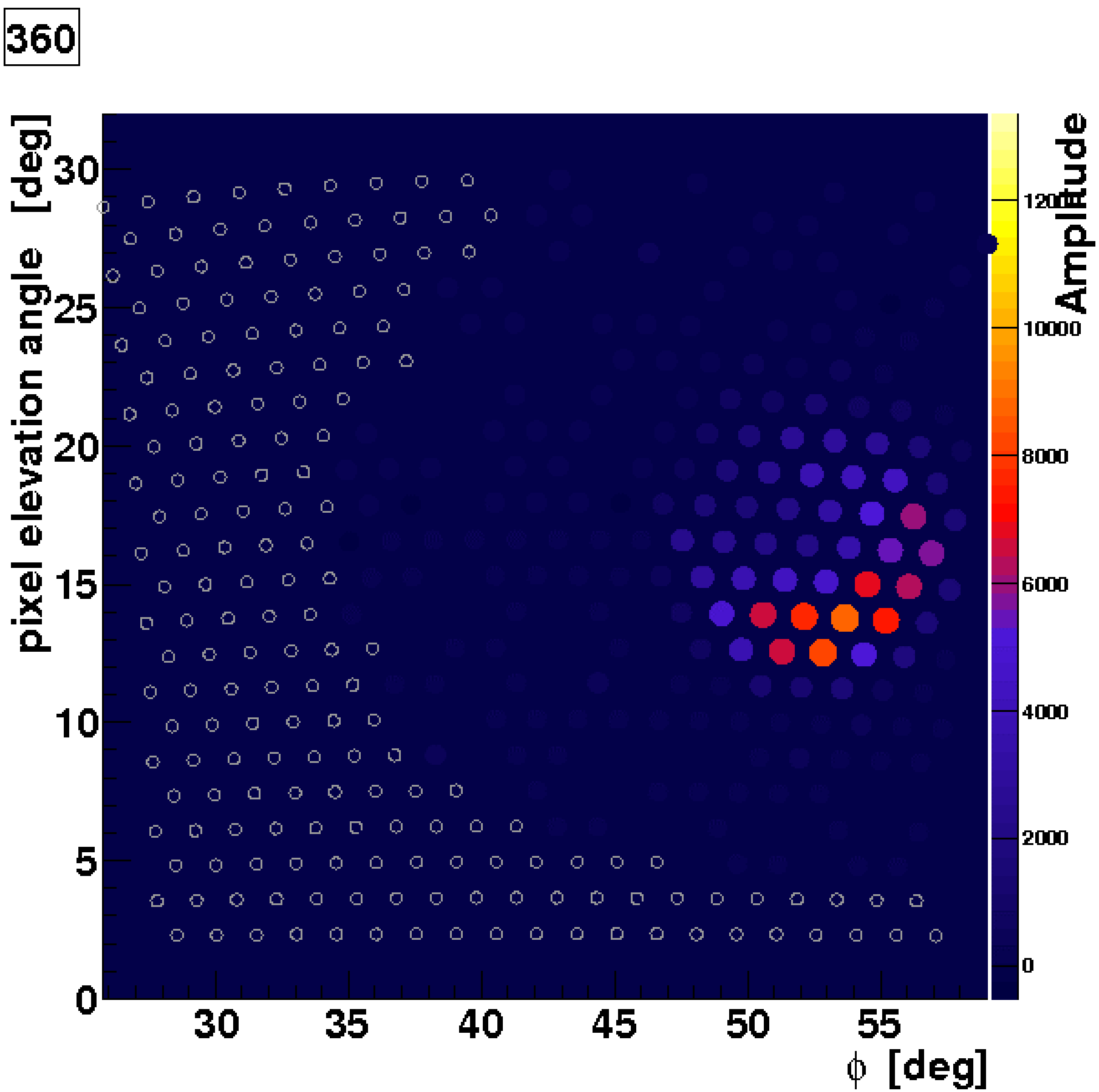
CO3-860806213

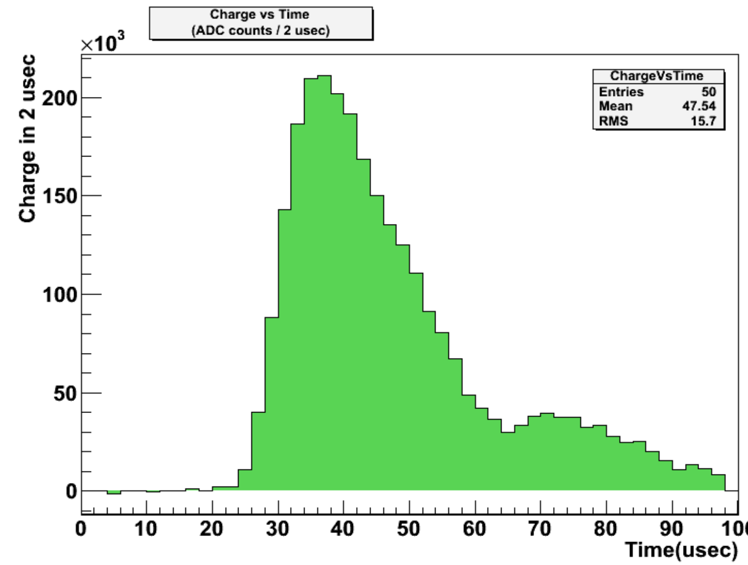




Charge at T=30us

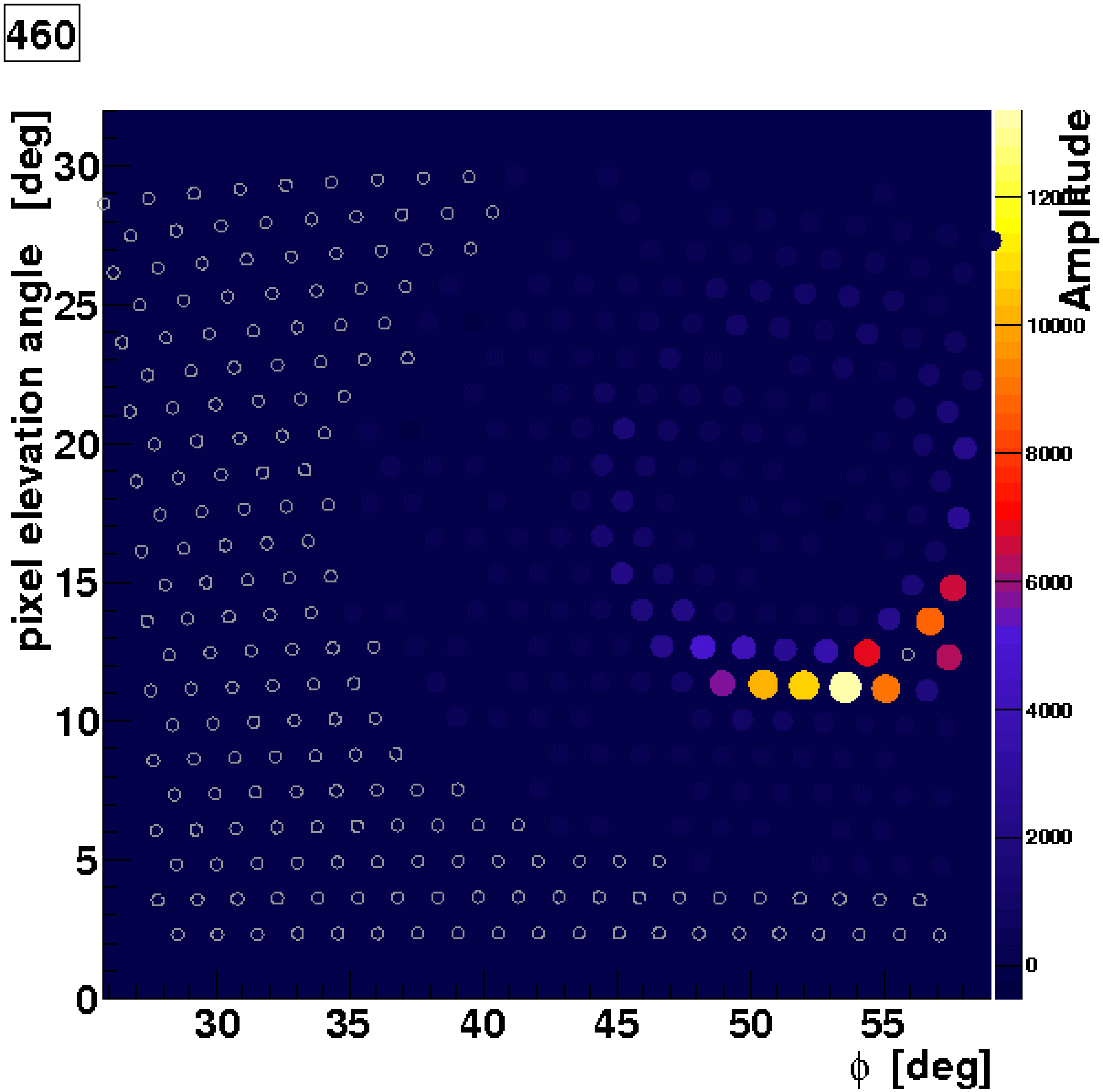
CO3-860806213

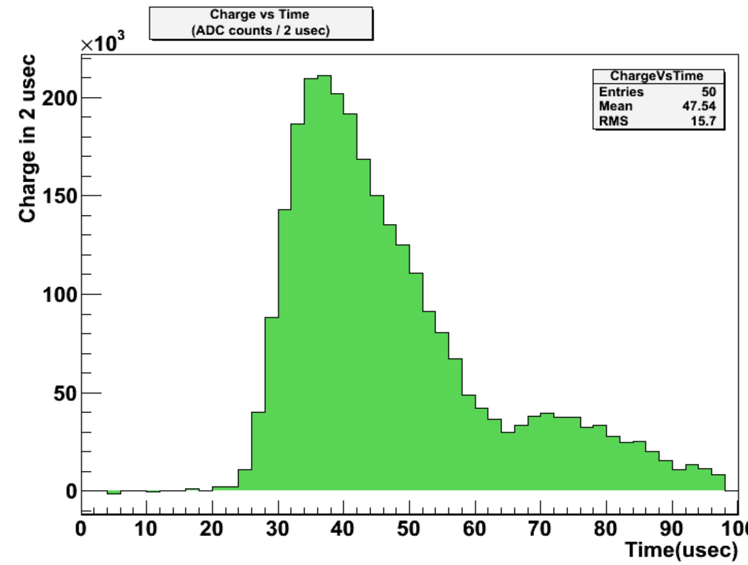




Charge at T=36us

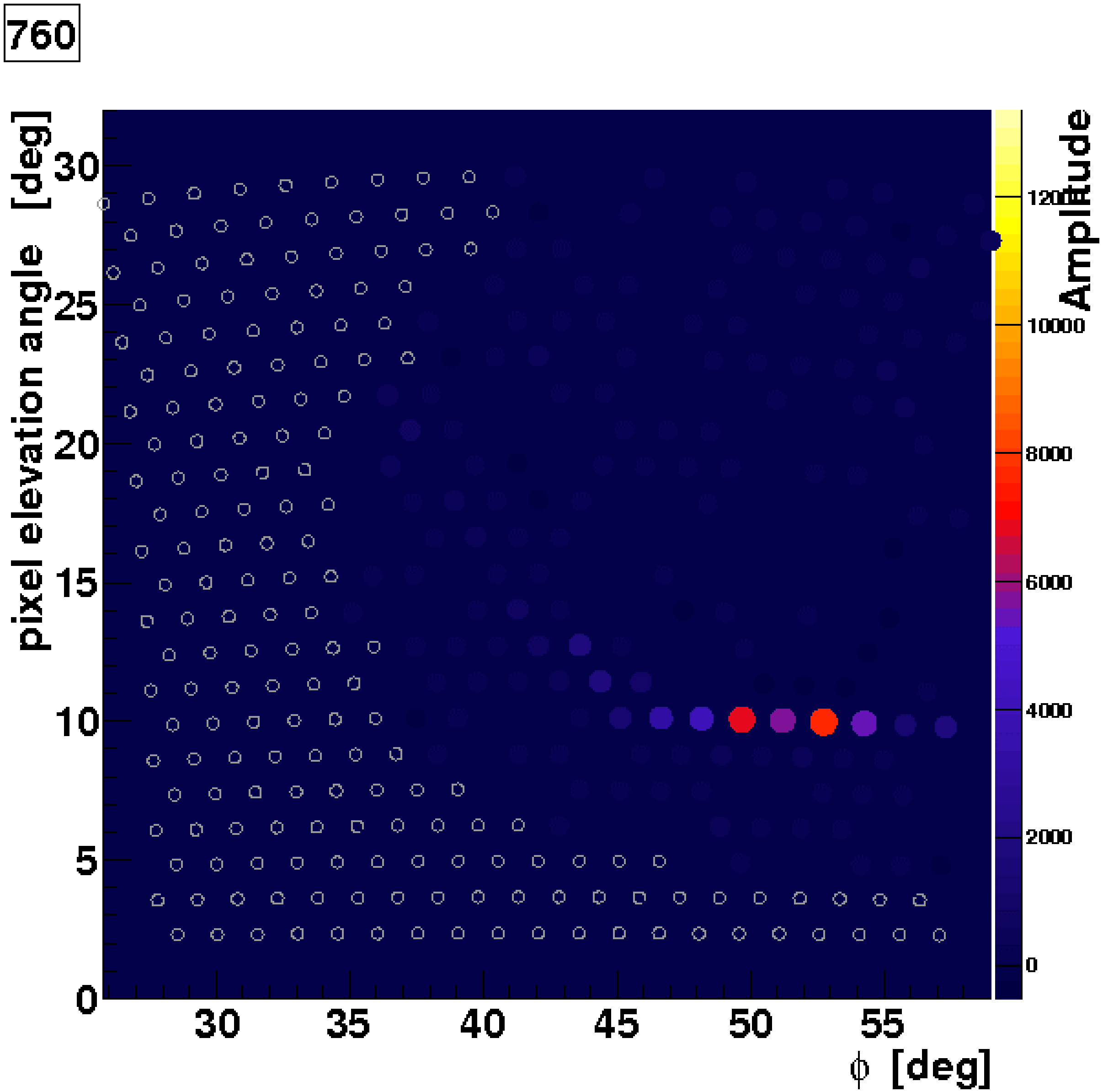
CO3-860806213

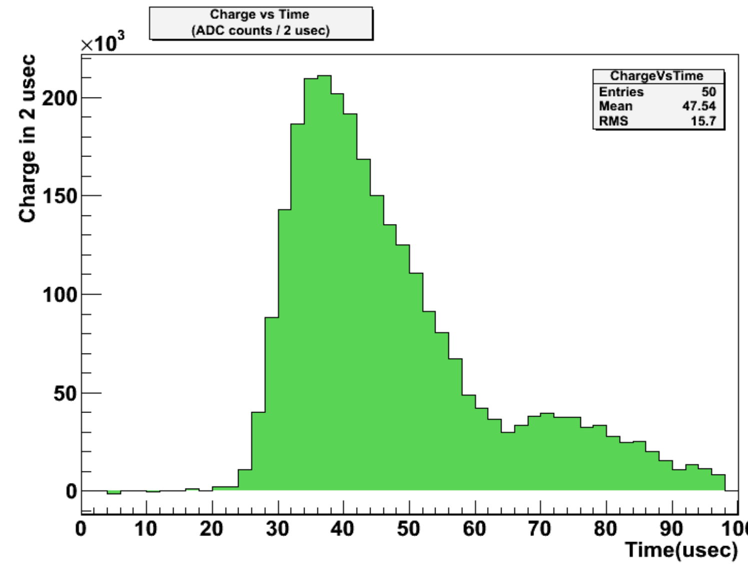




Charge at T=46us

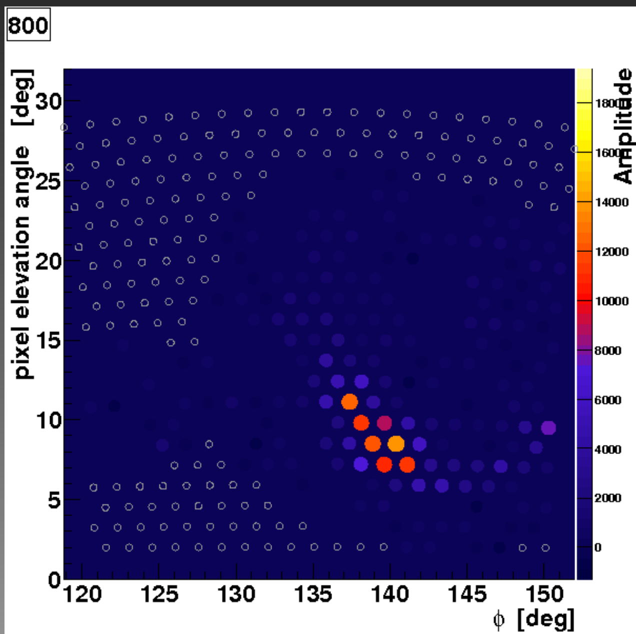
CO3-860806213



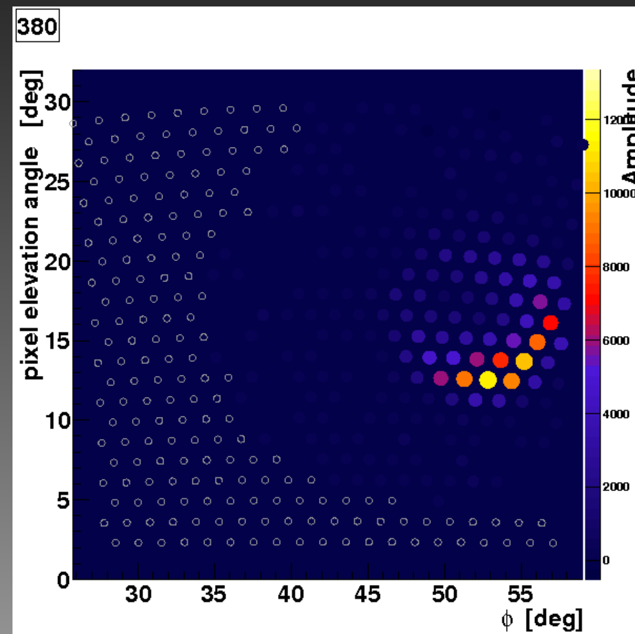


Charge at T=76us

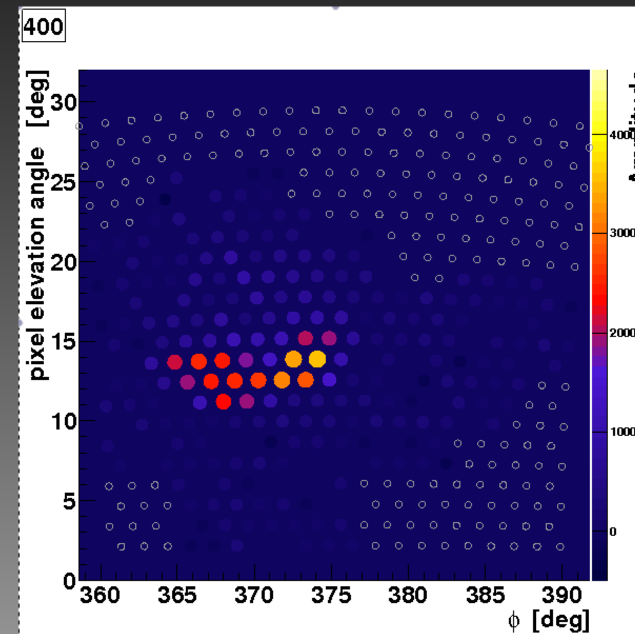
3 Cosmic Smiles in Auger data 2005-2009



LM6-800414142



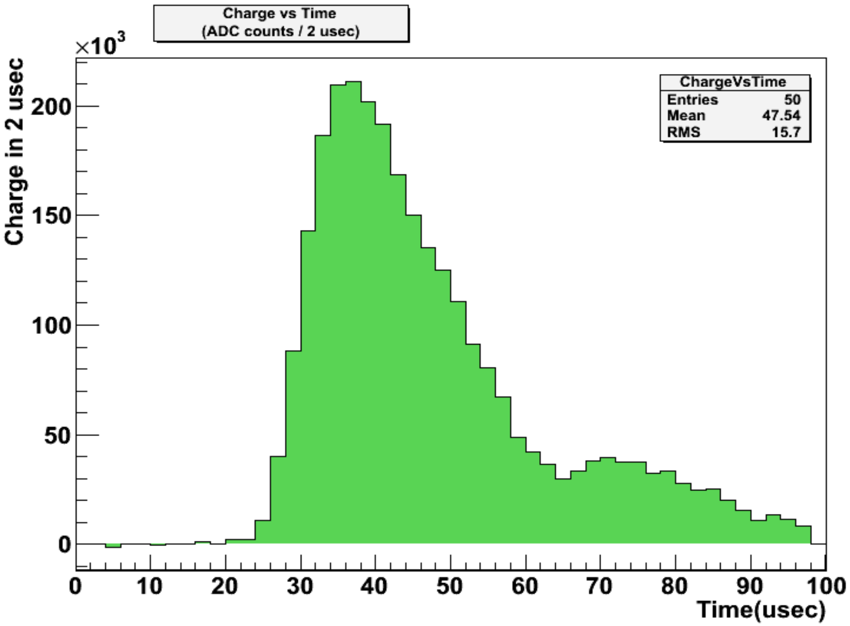
CO3-860806213



LL1-861081389

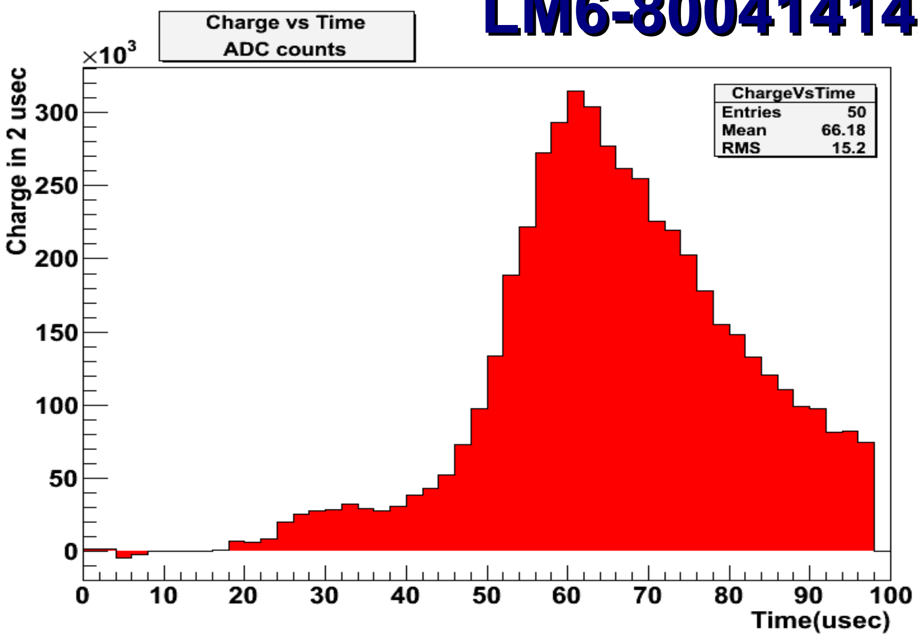
Total charge vs time

CO3-860806213

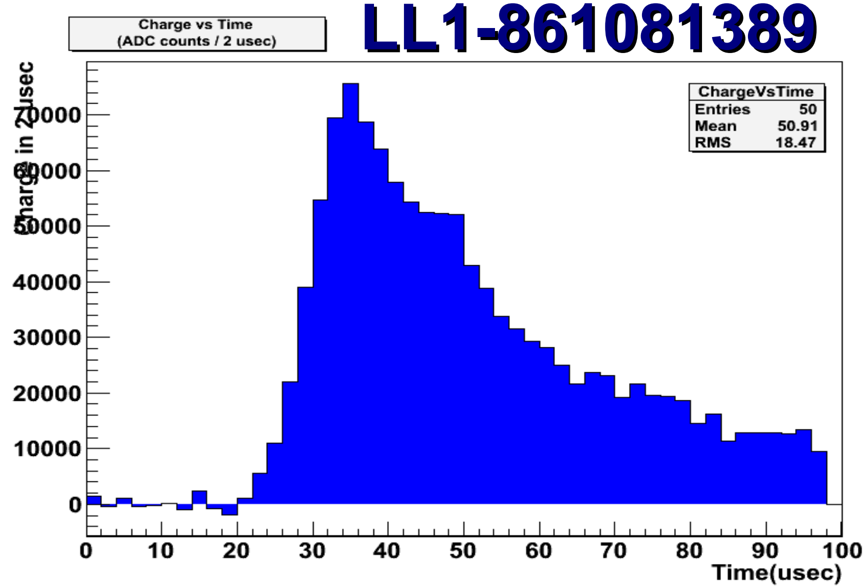


Time evolution of the light pulses quite similar for all 3 events, first one seems to come after a little shower: accidental?

LM6-800414142

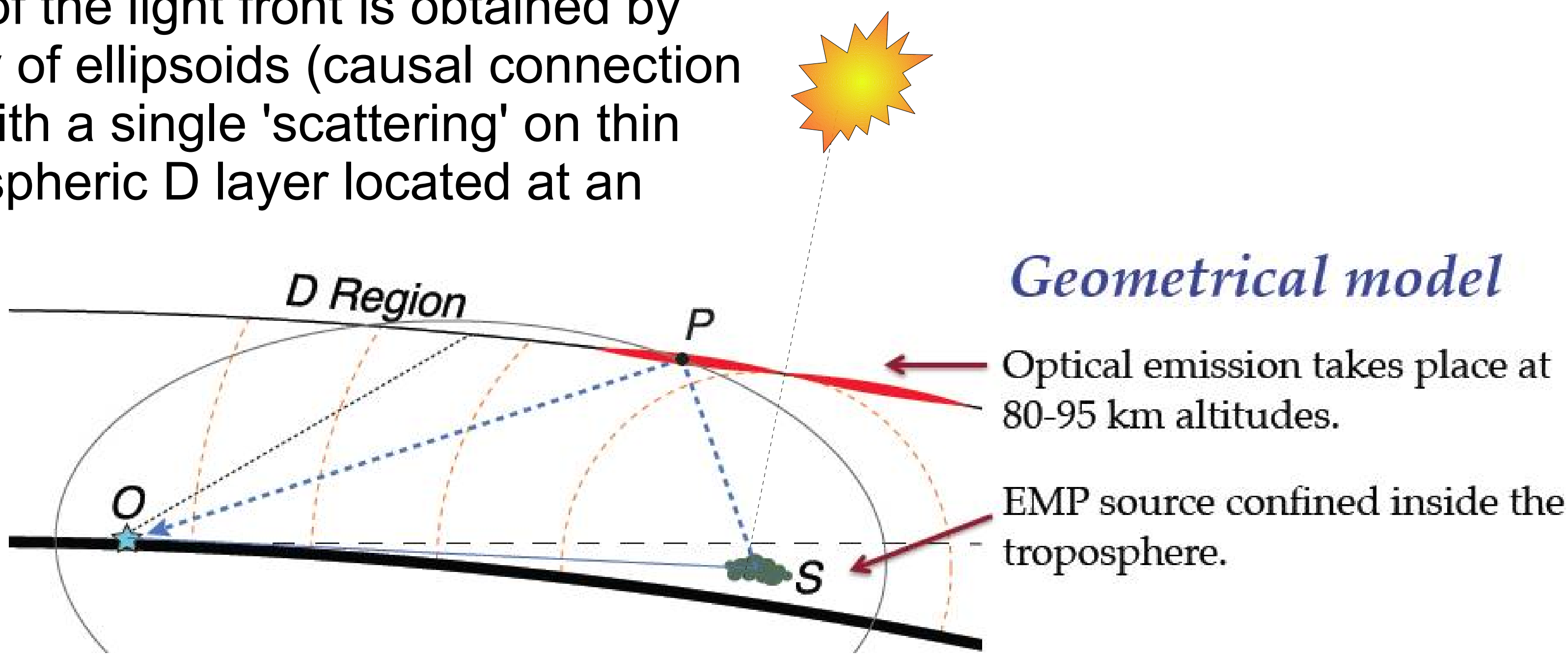


LL1-861081389

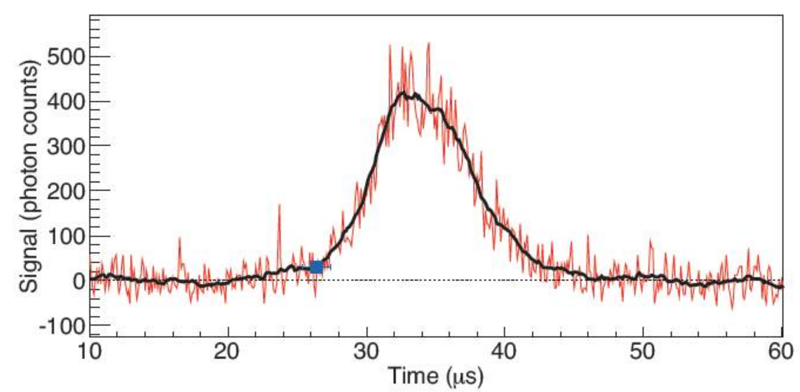


Time evolution of light front

The time evolution of the light front is obtained by intersecting a family of ellipsoids (causal connection between S and O with a single 'scattering' on thin layer) with the ionospheric D layer located at an altitude h_D.



For each pixel, the start time of the pulse is calculated after smoothing the 1000 bin trace with a running average on a 21 bins window. The threshold is set at 5σ above background.

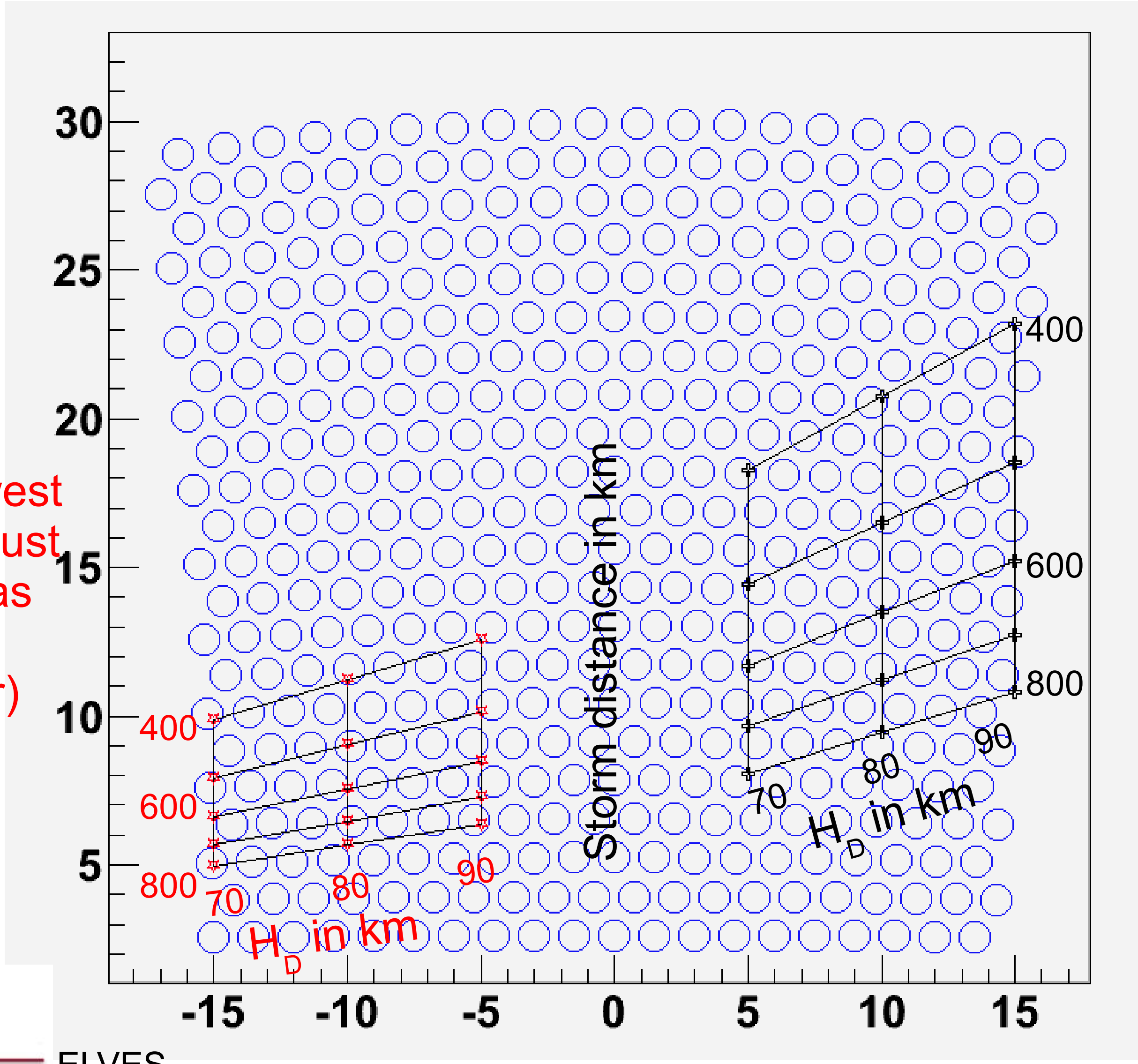


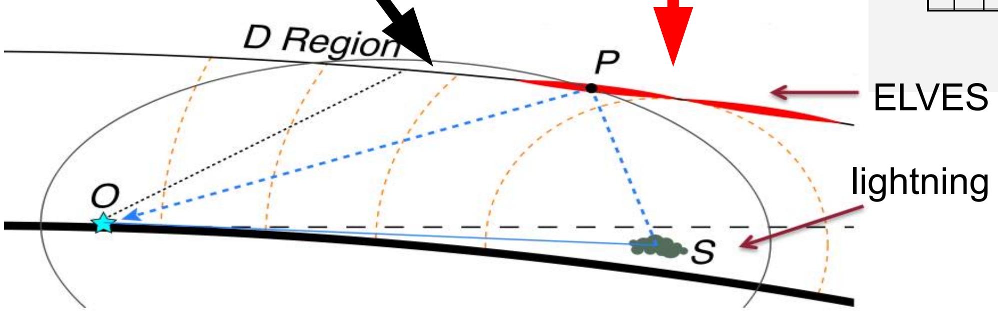
Caveat

The center of the elve does not coincide with the center of the light front as seen from a given observer !

Red stars:
Position of the lowest ionospheric point just above the storm, as seen from FD
(actual elve center)

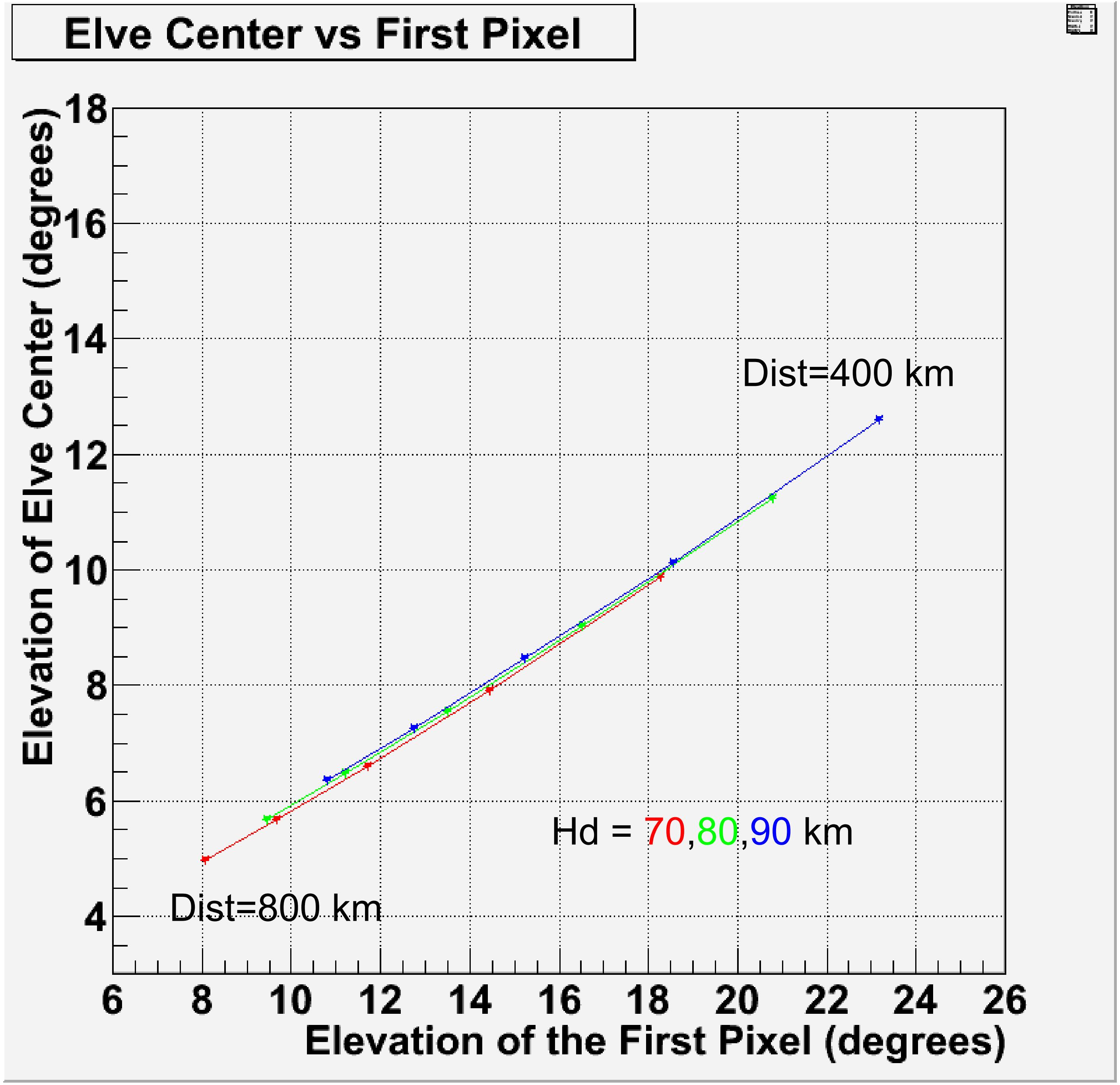
Black crosses:
Elve center from FD point of view





Caveat

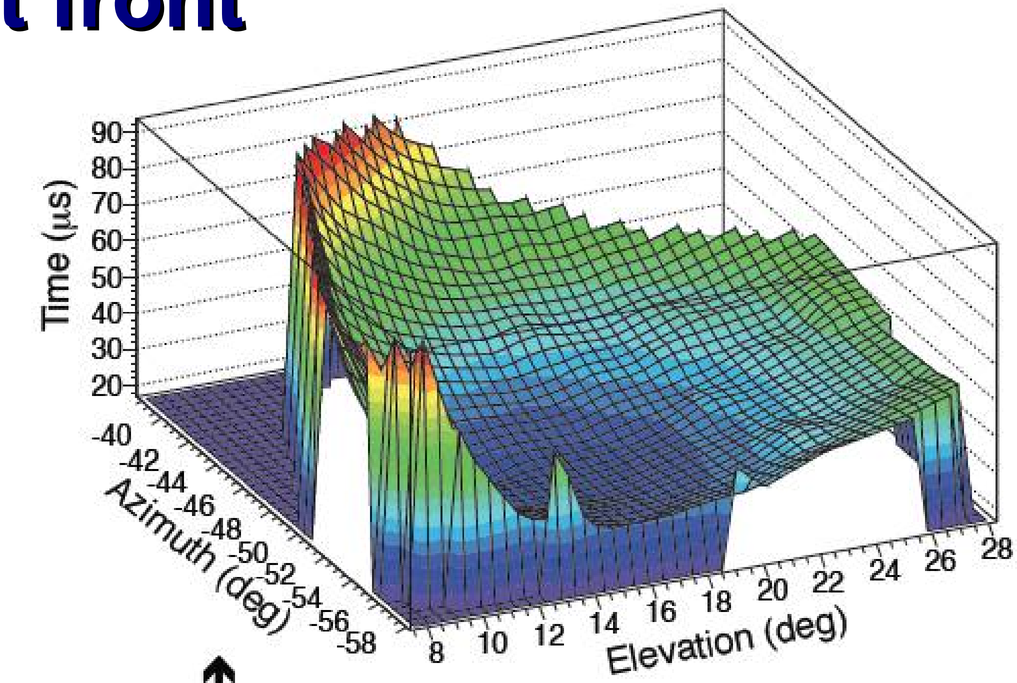
The center of the elve does not coincide with the center of the light front as seen from a given observer !



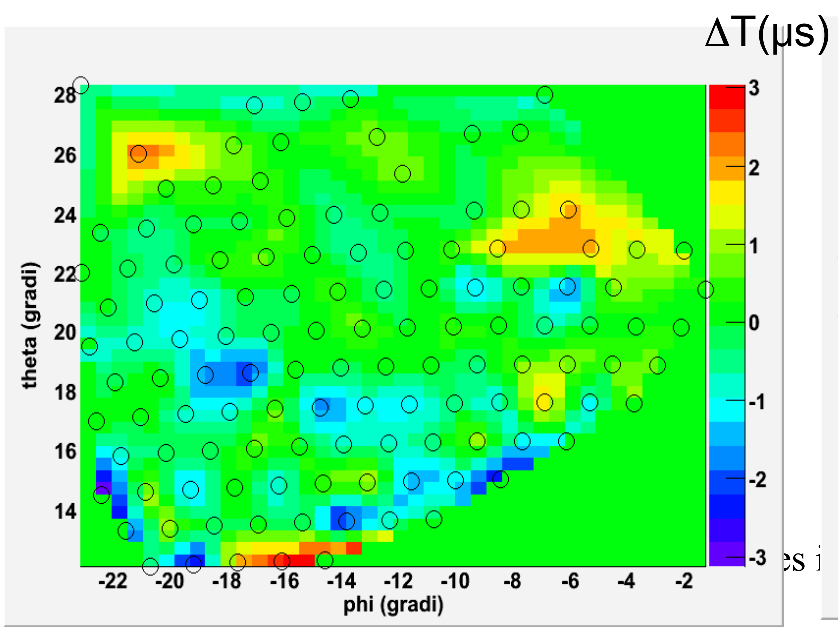
Time evolution of light front

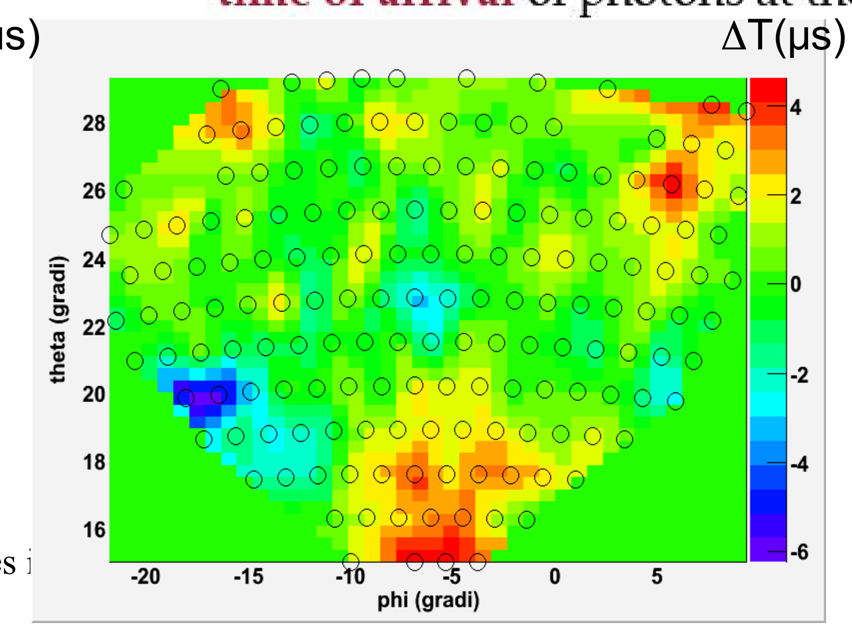
The light front $T_{obs}(\varepsilon,\varphi)$, shown on the right, is then fitted with the theoretical curve $F(\varepsilon,\varphi;\varphi_O,R_{OS},h_D)$
Pixel time resolution is obtained from standard shower analysis.

The distribution of residuals $\Delta T = T_{obs} - F$, in μs, is shown below, for two typical events.

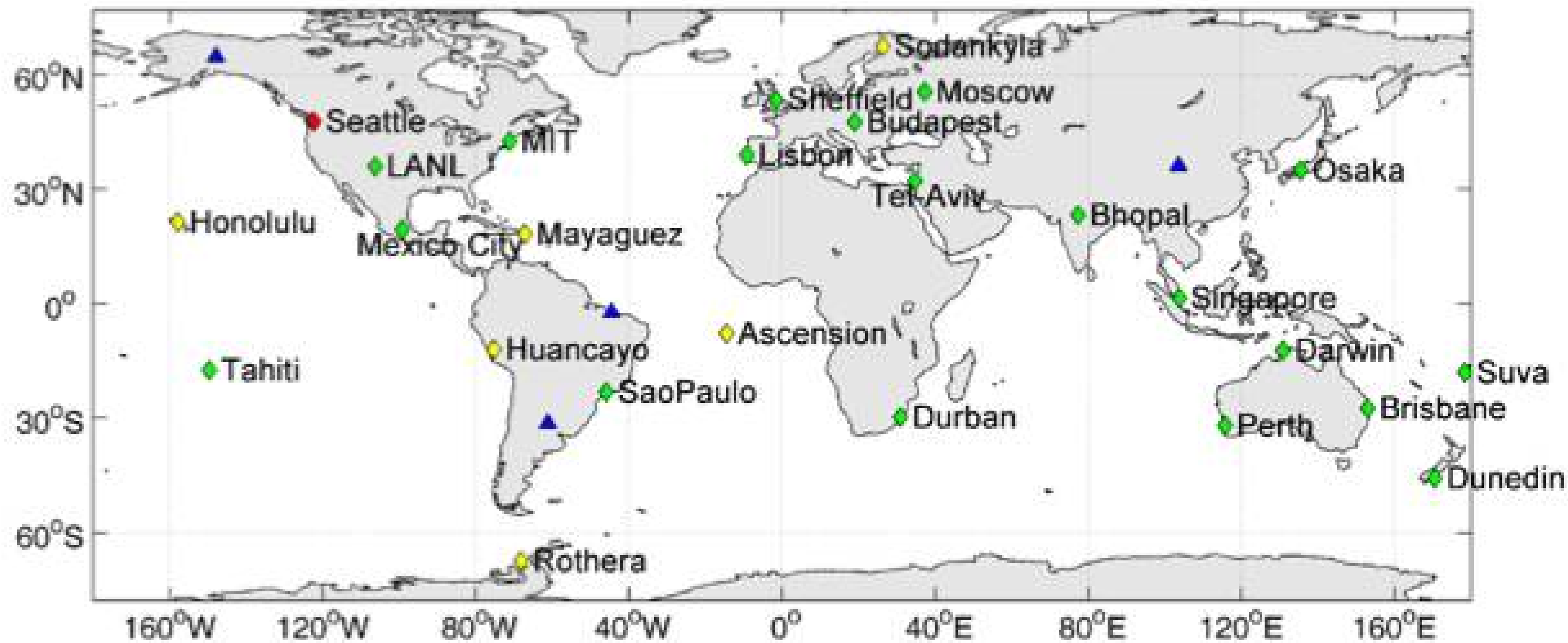


Interpolated *3D curve* representing the **time of arrival** of photons at the FD diaphragm.





Comparison with WWLLN data



25 stations around the world.
Global database available since 2004

Credit: Bob Holzworth University of Washington, Seattle WA

Low efficiency (10%) on average lightnings,
but probably >50% on elves sources.

WWLLN: thresholds

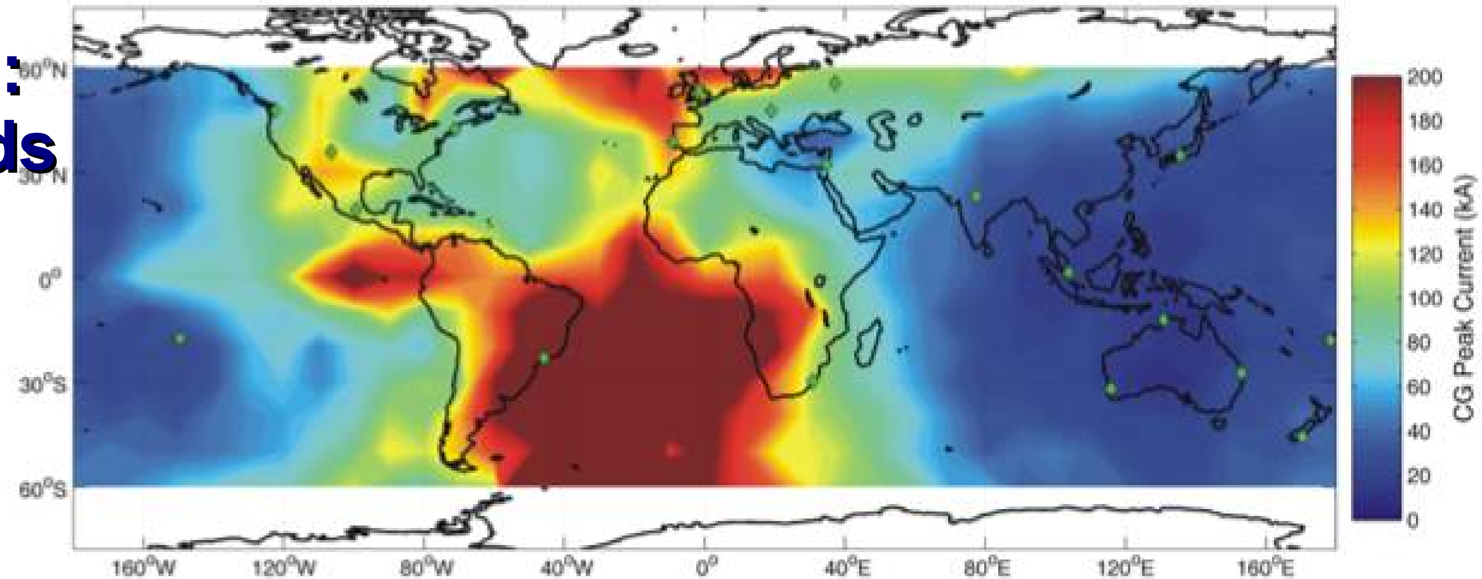


Fig. 11. Globally varying minimum CG return stroke peak current required for WWLLN detection. Modelling undertaken with the ionospheric conditions expected for 12:00 UT on 16 April 2005.

WWLLN: efficiency

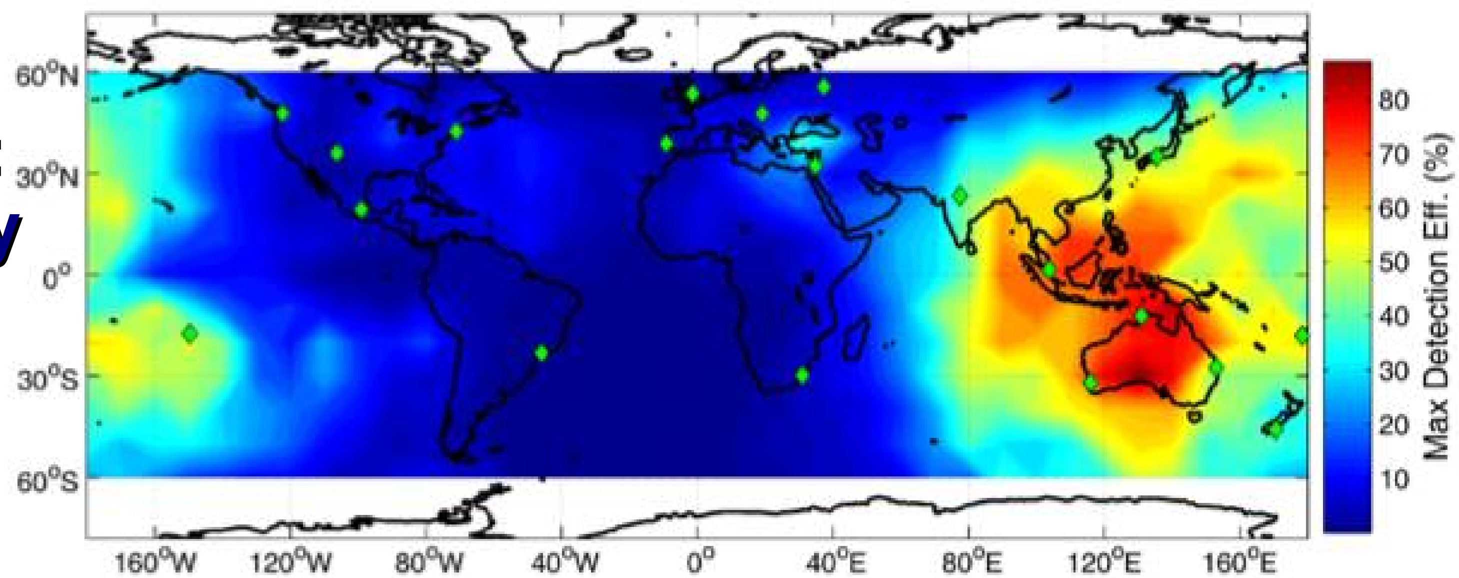


Fig. 12. Globally varying maximum WWLLN CG detection efficiency, on the basis of the mean triggering thresholds determined in Sect. 5.3 and assuming a "perfect" combination algorithm. Modelling undertaken with the ionospheric conditions expected for 12:00 UT on 16 April 2005.

WWLLN data vs 17/04/2007 event

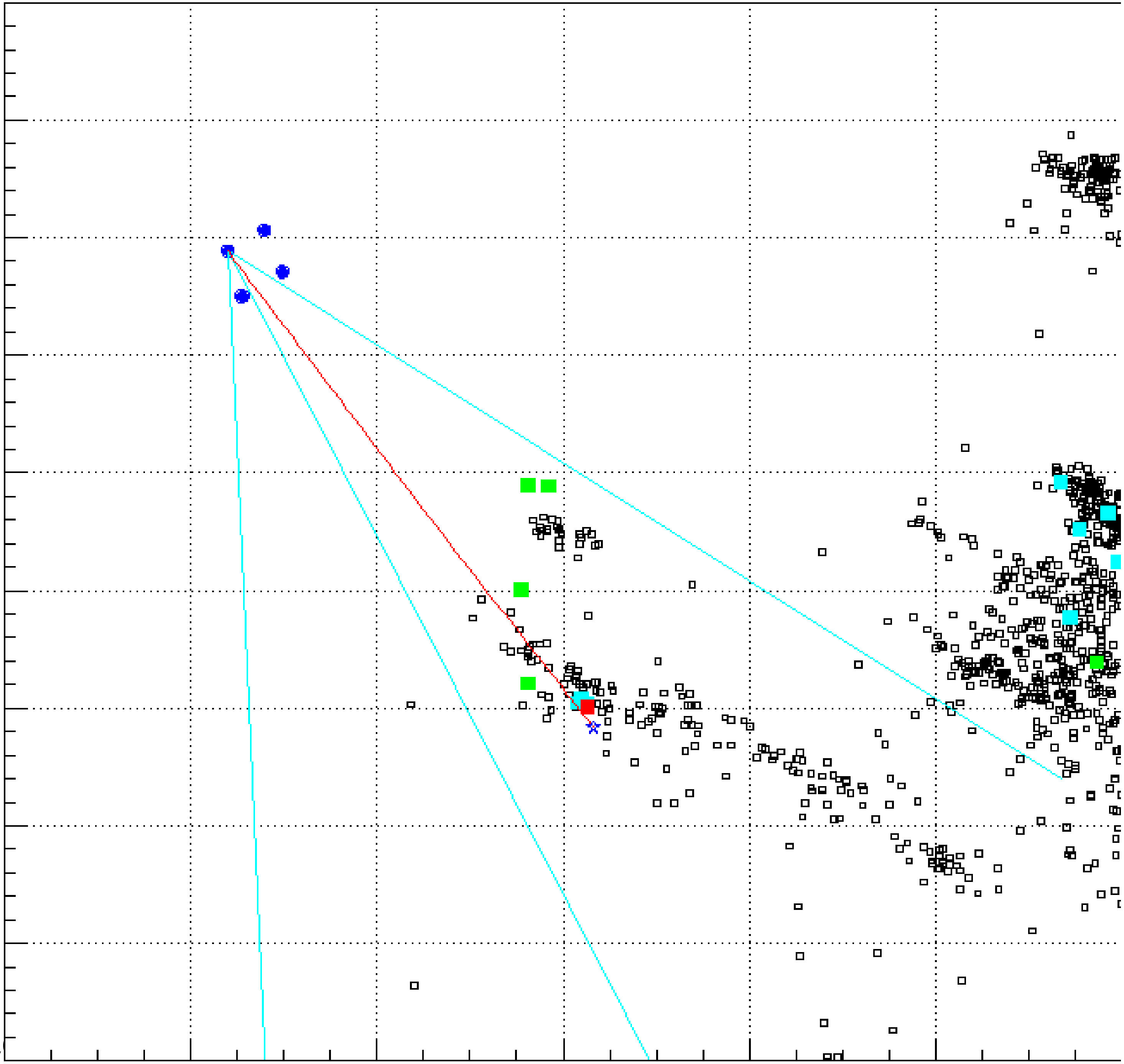
GPStime
860806213

GPSmicrotime
Lightning:
352376

FD trigger
354338:

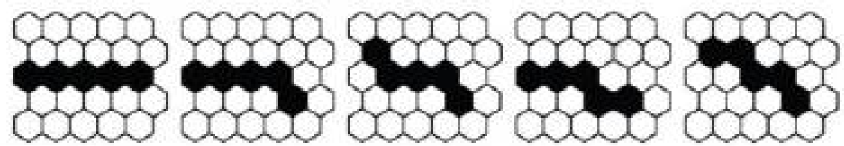
Time Diff
1962μsec

From Model
(Hairglow=90km;
Hcloud=10 km)
1980μsec



FD data selection criteria

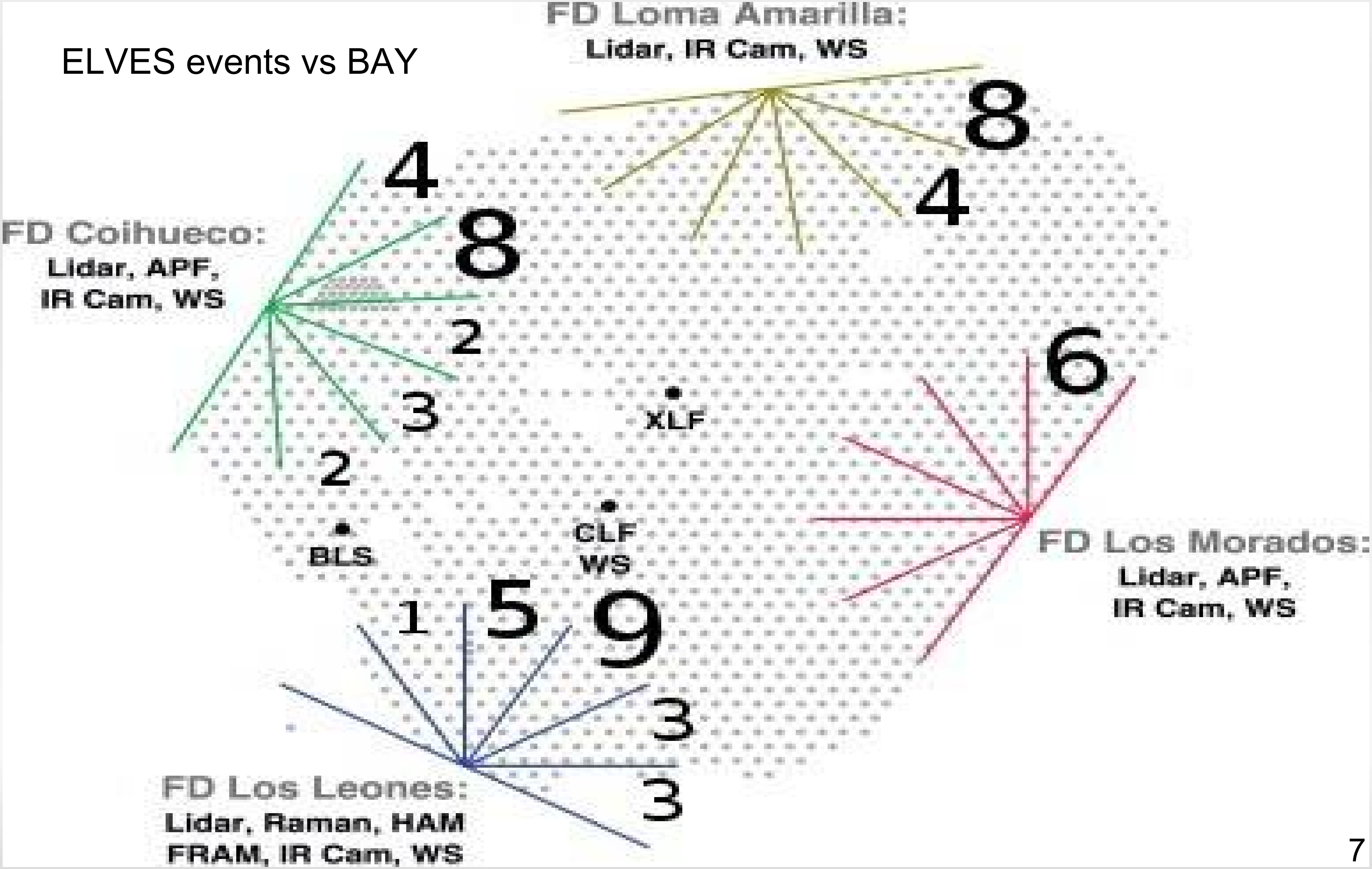
	type	purpose	event rate
First Level Trigger (FLT)	**HW**	Pixel threshold trigger	100 Hz / pixel
T1 ↓			
Second Level Trigger (SLT)	**HW**	Track shape identification	0.1-10 Hz / tel
T2 ↓			



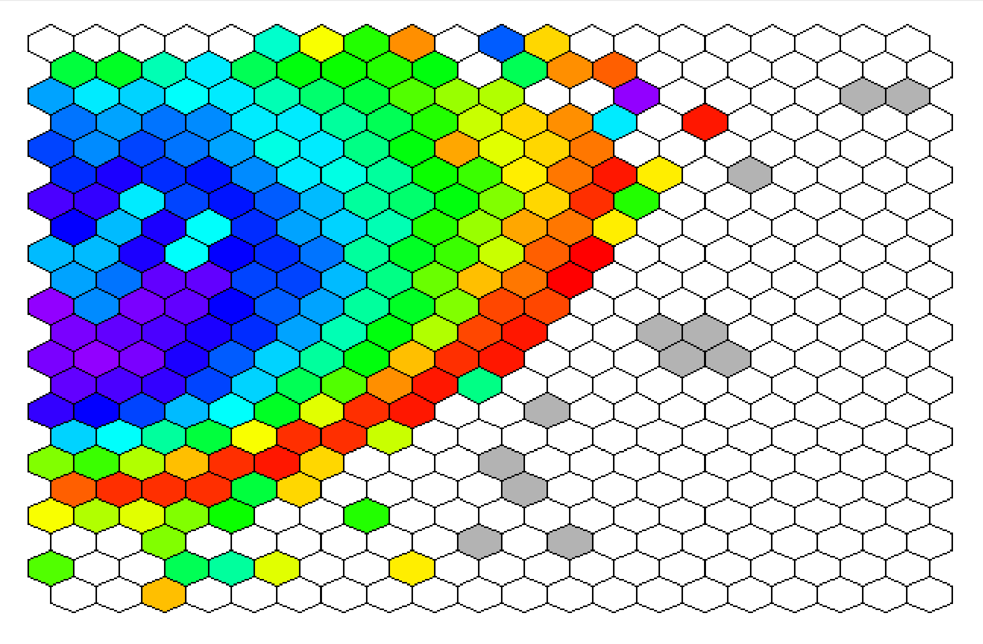
We decided to analize the fraction of events which pass the 2nd level of trigger, which is saved with prescaling factor 1/100 in a separate data stream (*minimum bias*) and is used for measuring efficiencies and testing new trigger algorithms.
All minimum bias data from 2008 to 2011 were analyzed.

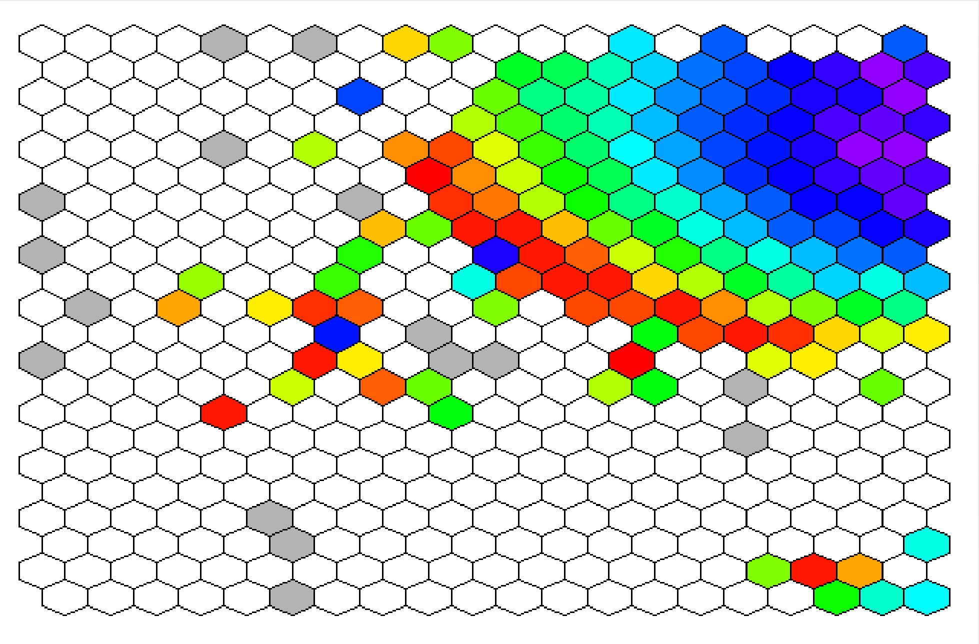
58 new events were found.

ELVES space distribution



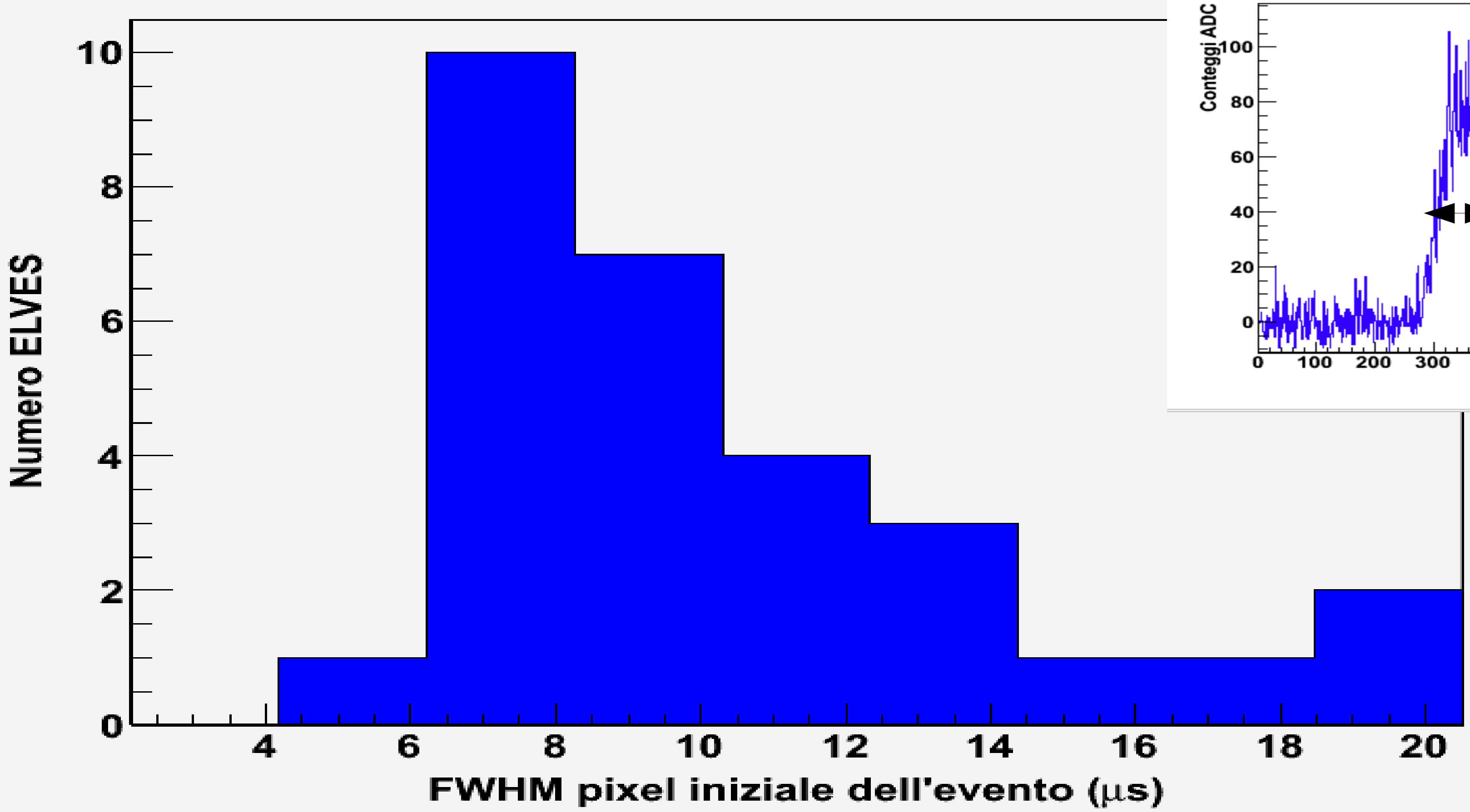
ELVES Topology

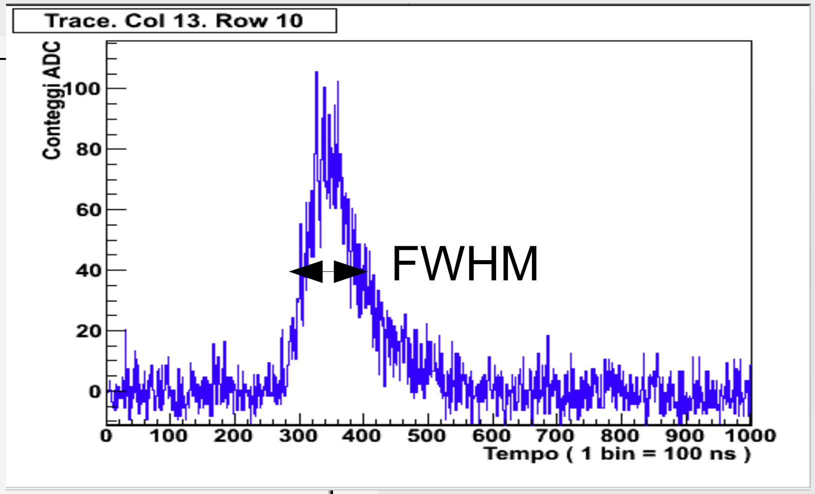




Site	Total ELVES	Centered ELVES	Lateral ELVES
Los Leones	21	8	13
Los Morados	6	0	6
Los Amarilla	12	6	6
Coihueco	19	6	13

FWHM of first pixel

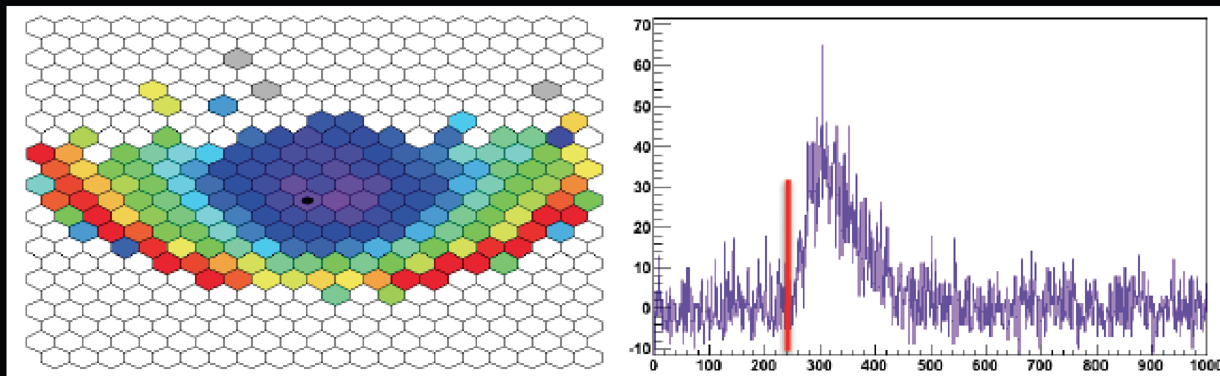




FWHM of the pulse in the first pixel related to either the size of the initial pulse , or the thickness of the light emitting layer. 6 -12 μs correspond to ~ 2-4 km.

ELVES Trigger

1. Find the FIRST PIXEL and define the PULSE START TIME



Pulse length must be > 25 bins

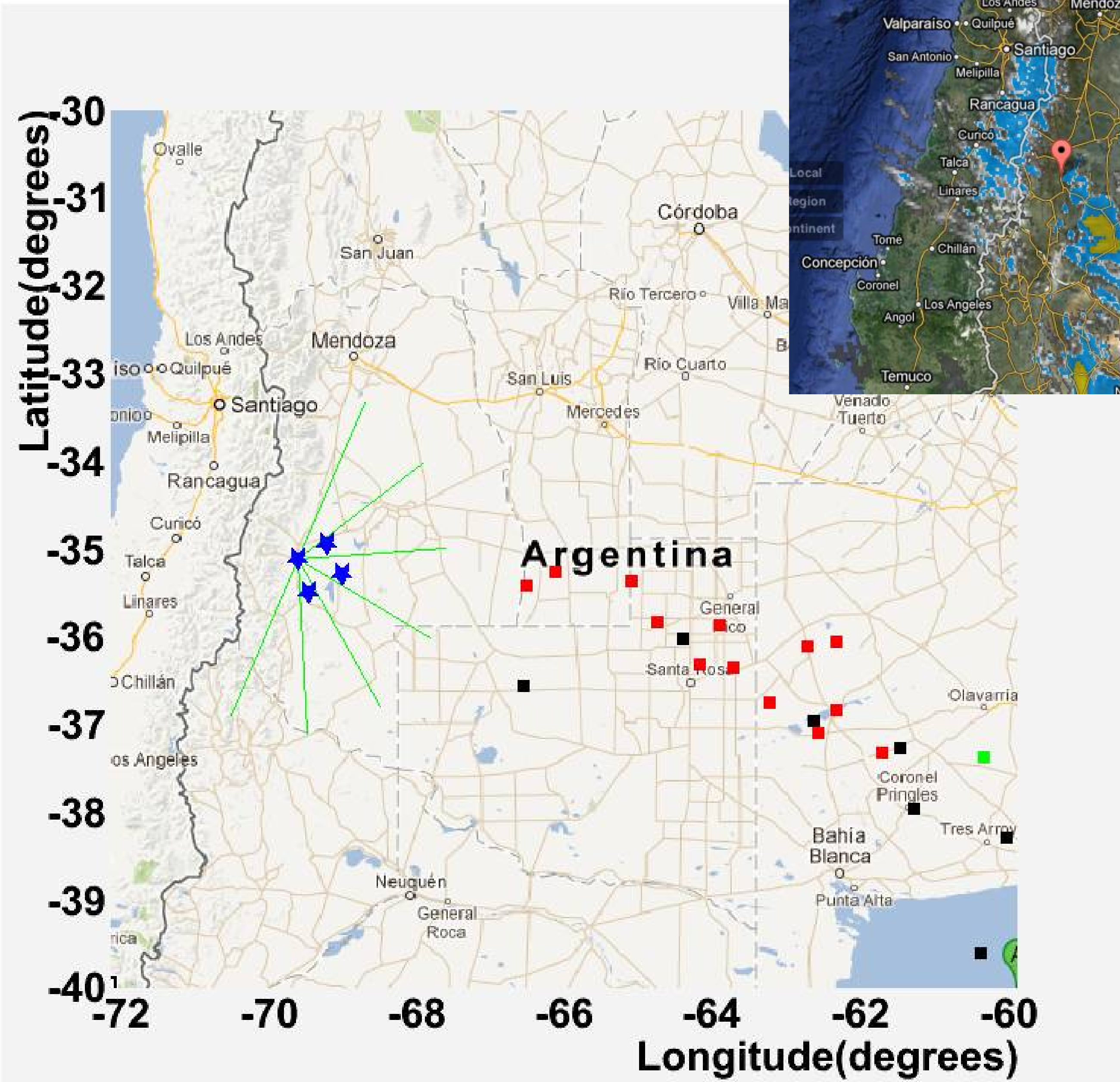
2. Quality cuts on start time

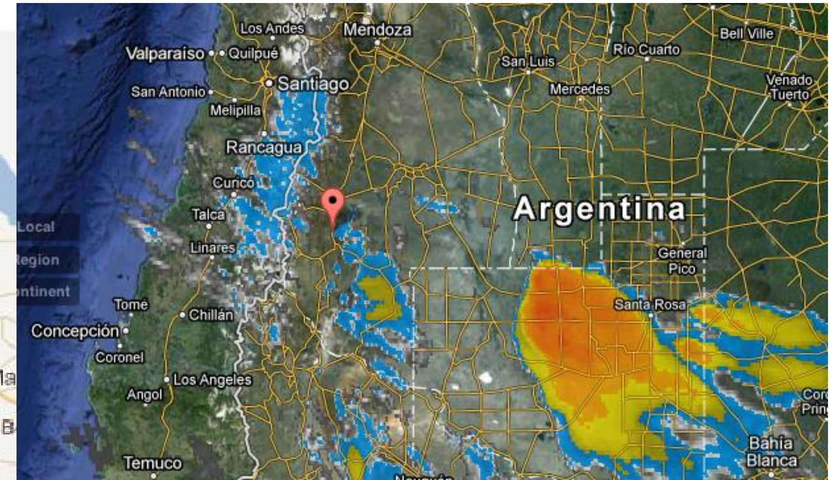
3. Check PIXELS on the same ROW
   - at least 3 pixels before ***OR*** 3 after the central one
   - **80%** of the pixels must show an increasing pulse time

4. Check PIXELS on the same COLUMN
   - at least 3 pixels before ***AND*** 3 after the central one
   - **80%** of the pixels must show an increasing pulse time

5. **Check signal amplitude**
   - **for each pixel measure average ADC counts before trigger**
   - **find signal peak**
   - ***at least ONE pixel with > 50 ADC counts***

First night of data taking on full site: March 9

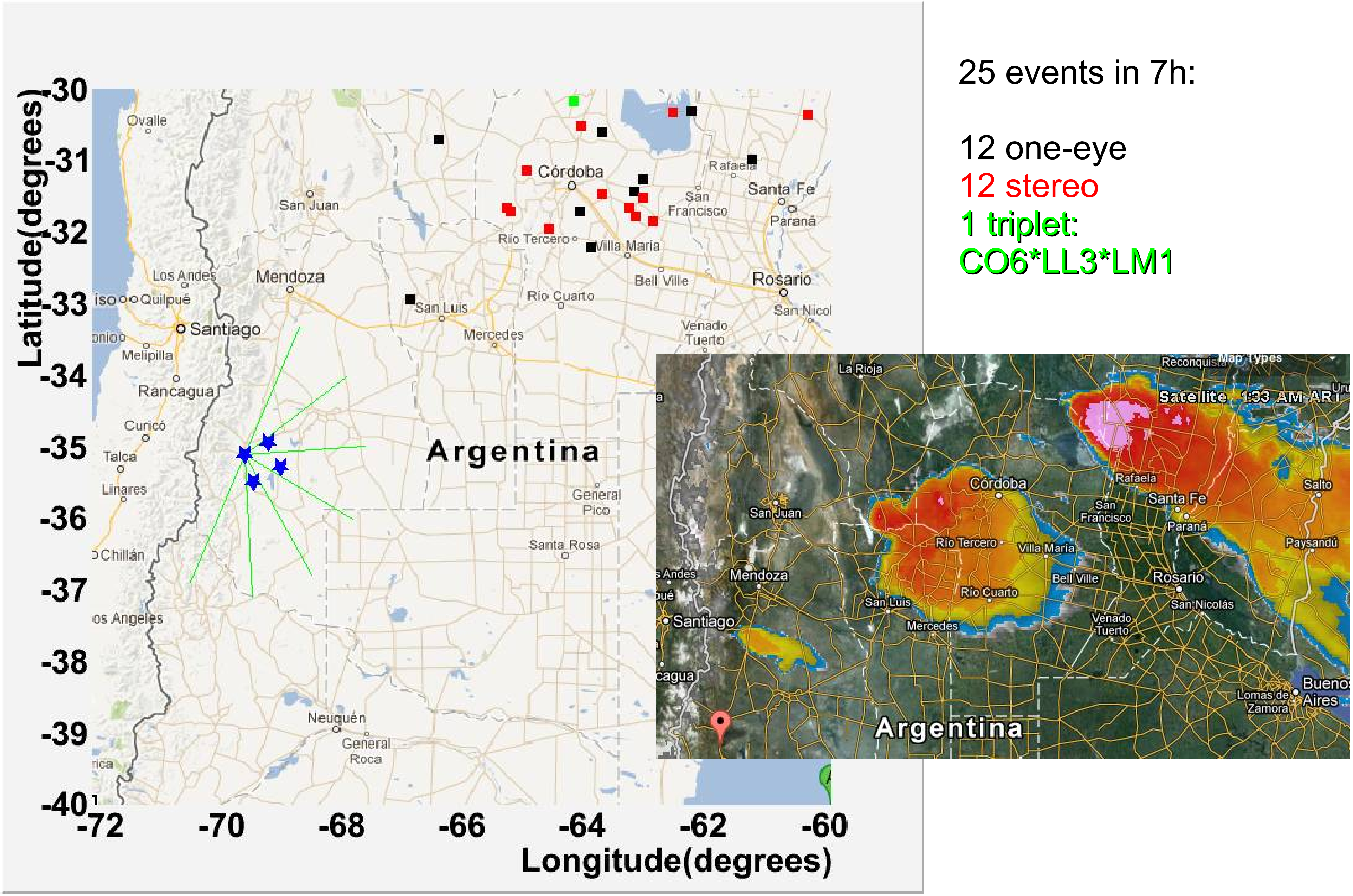




15 events in 3h30m:

7 one-eye
7 stereo
1 triplet:
LA6*LL1*CO4

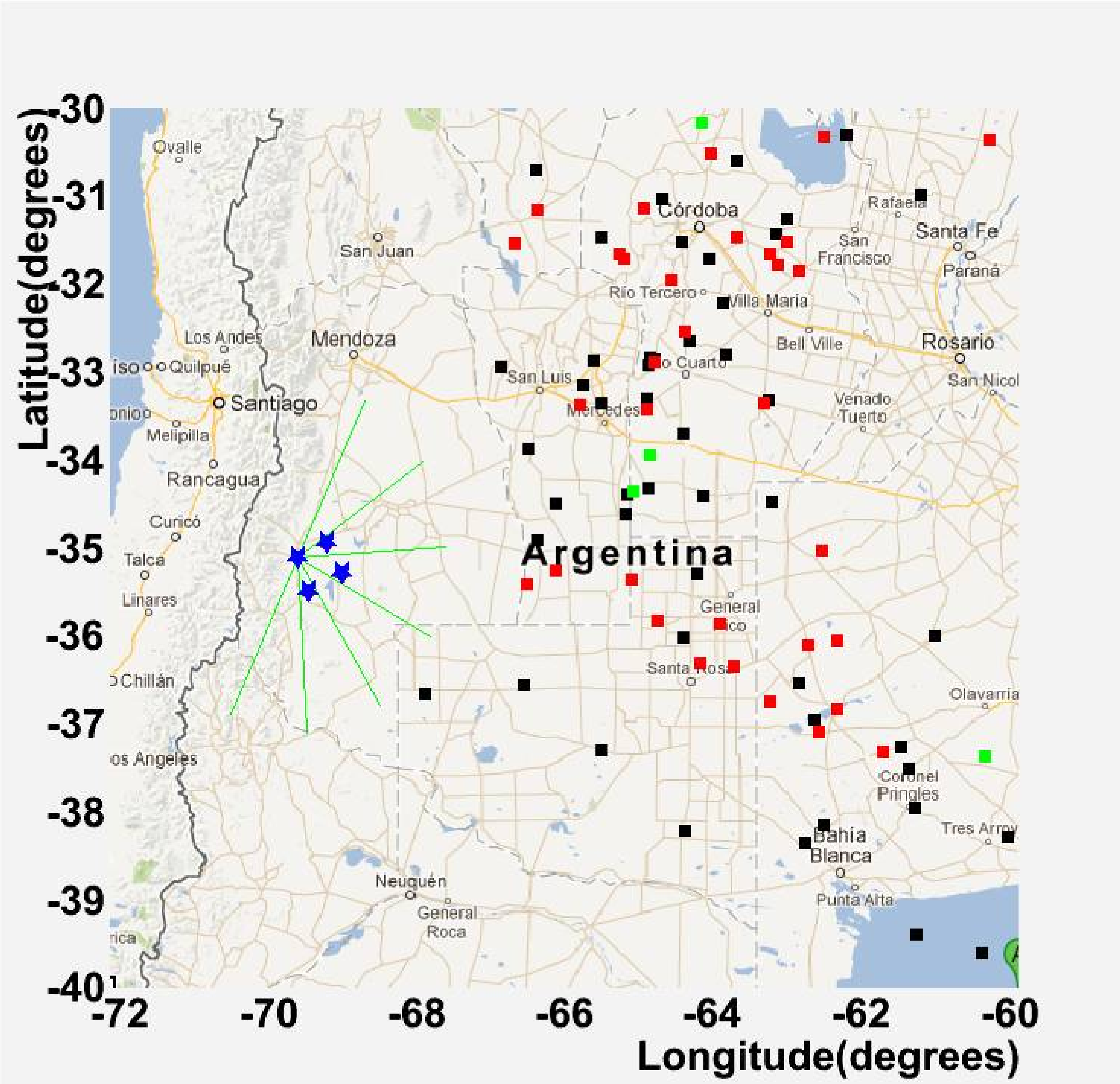
Second night of data taking on full site: March 10



25 events in 7h:

12 one-eye
12 stereo
1 triplet:
CO6*LL3*LM1

Summary of Elve Triggers: March+April

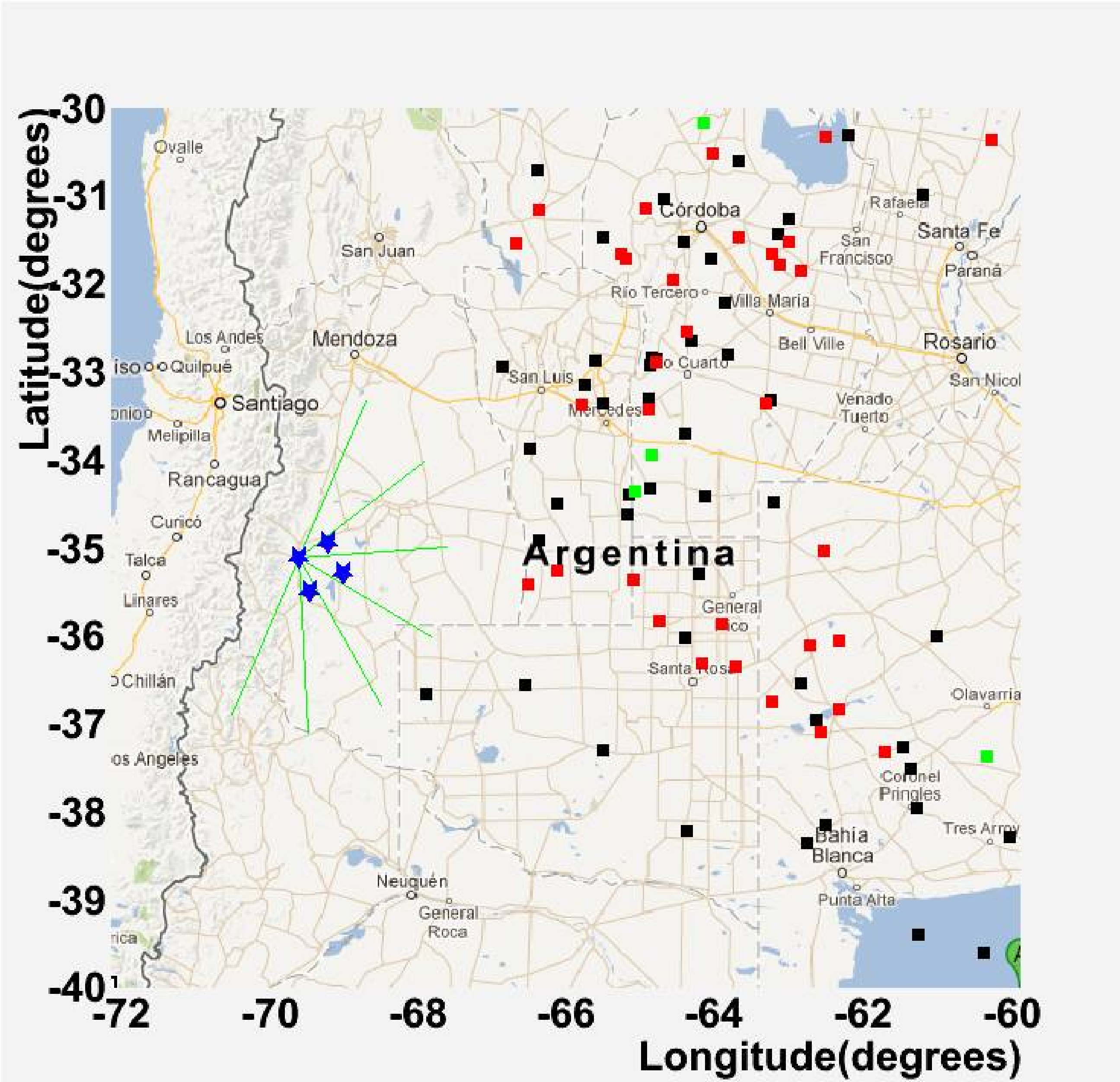


Day	Tot	Stereo	Triplet
7	1	0	0
9	15	7	1
10	25	12	1
12	10	2	0
13	19	3	0
15	1	0	0
21	3	2	0
Mar	74	26	2
6	2	0	0
10	4	0	0
11	18	4	1
12	1	0	0
13	2	0	0
Apr	25	4	1

We did not run in May 2013

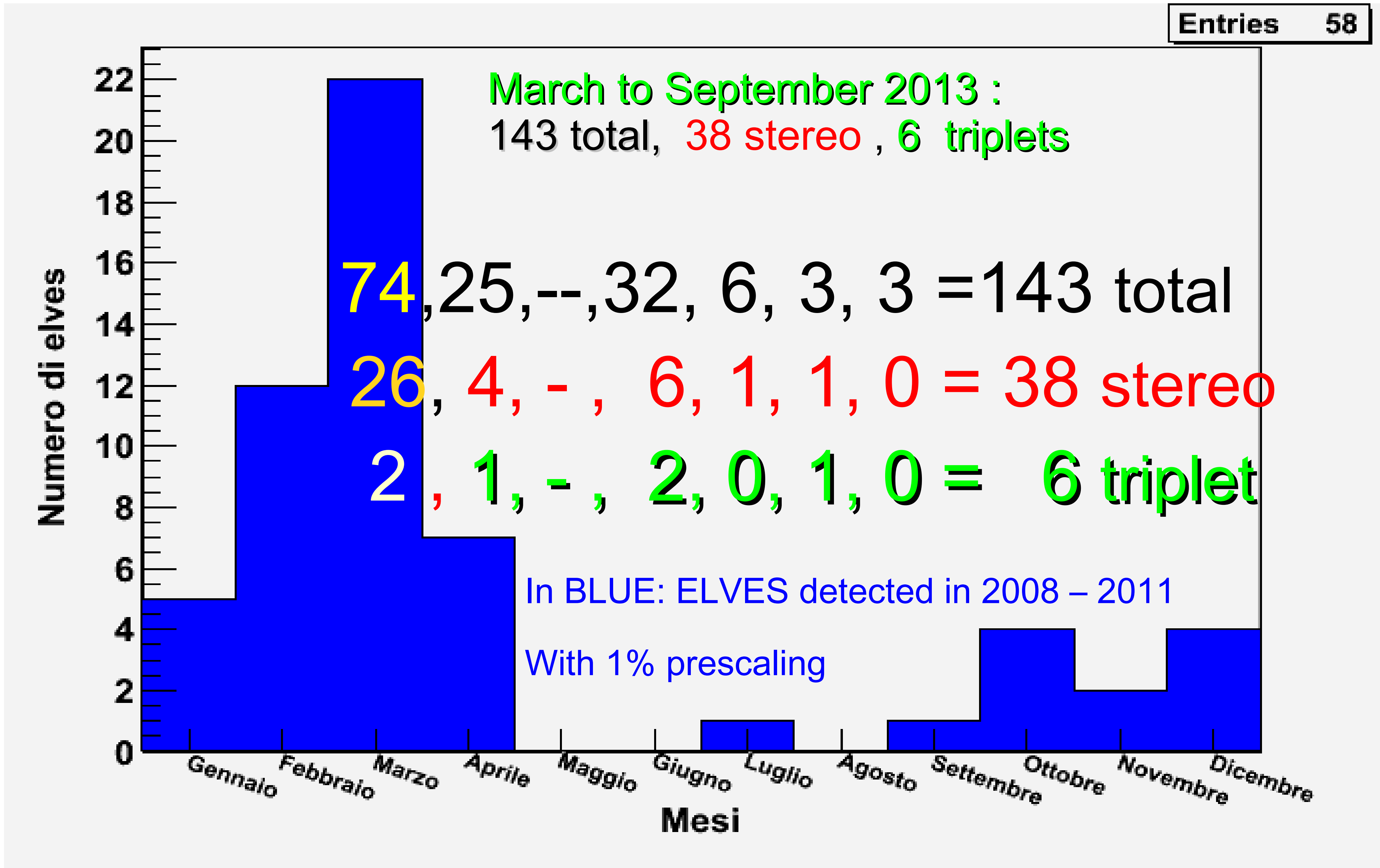
Total	99	30	3

Summary of Elve Triggers: June-September



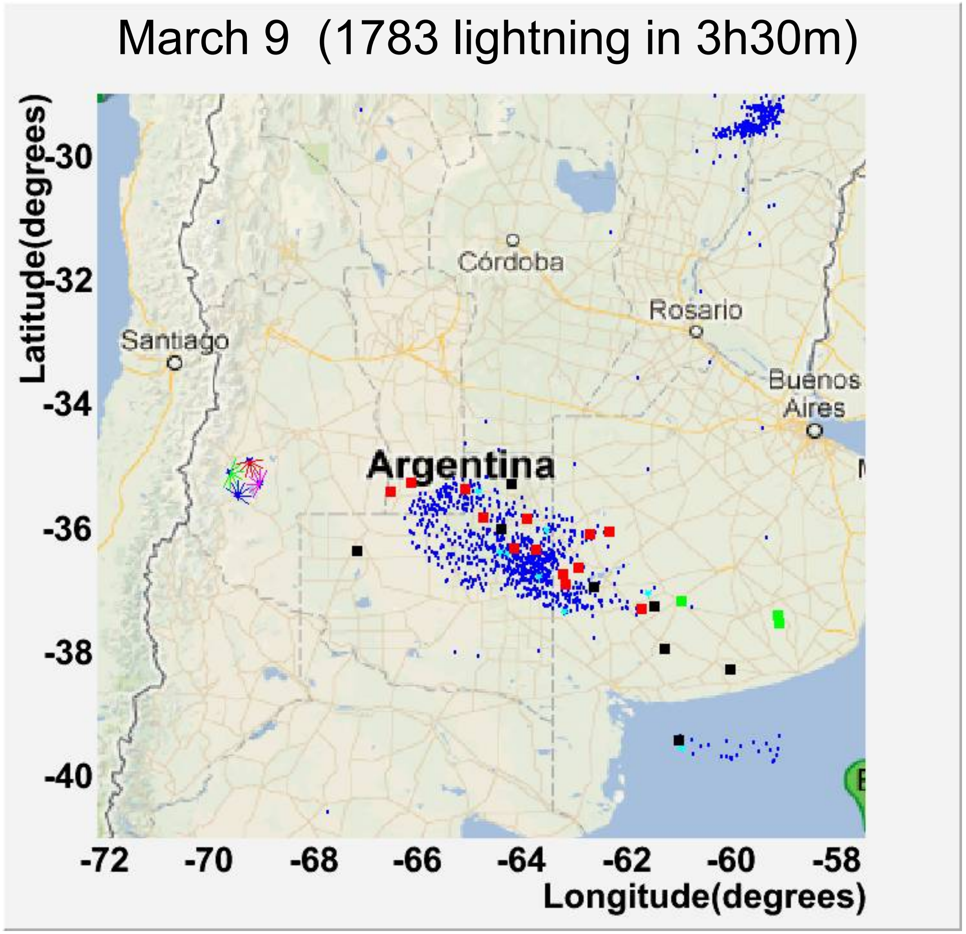
Day	Tot	Stereo	Triplet
9	28	6	2
14	4	0	0
Jun	32	6	2
13	3	0	0
31	3	1	0
Jul	6	1	0
5	2	1	1
8	1	0	0
Aug	3	1	1
9	3	0	0
Sep	3	0	0
Tot J-S:	44	8	3

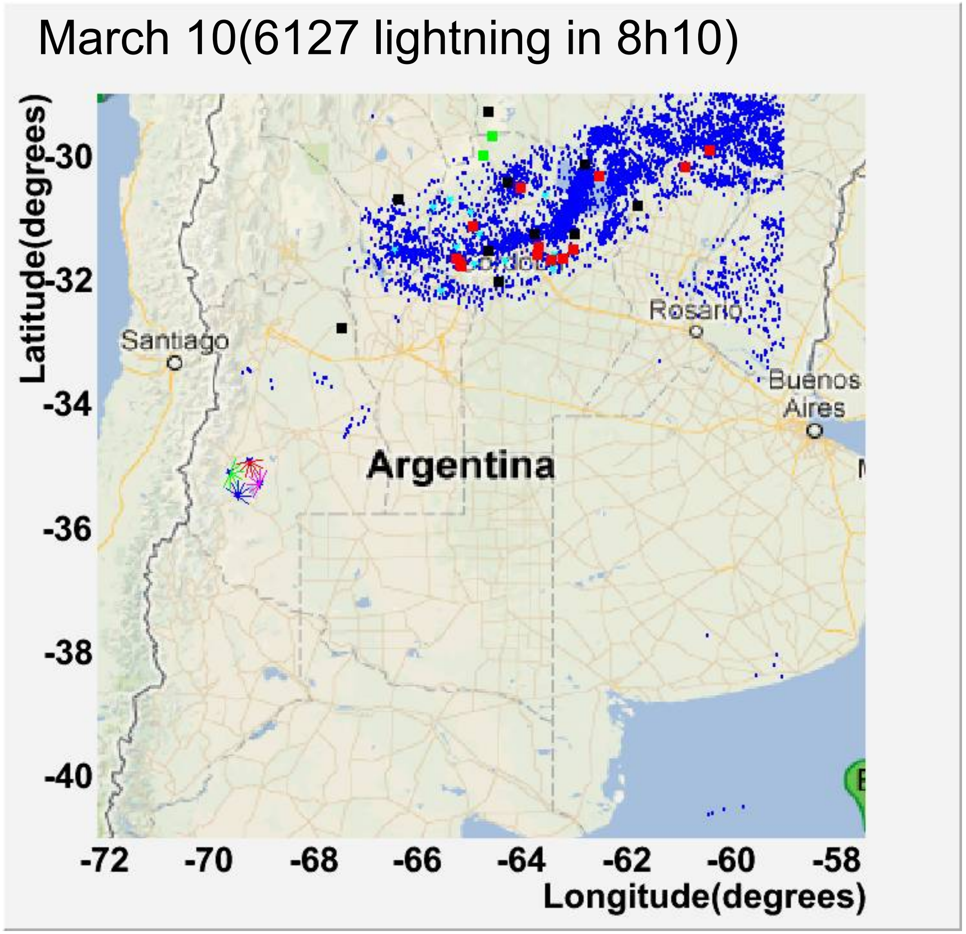
ELVES harvest: Mar-Sep 2013



Comparison with WWLLN data

(*Thanks to P.Gorham who sent us the WWLLN data for March 9,10; we'll get the full datasets sometime.*)

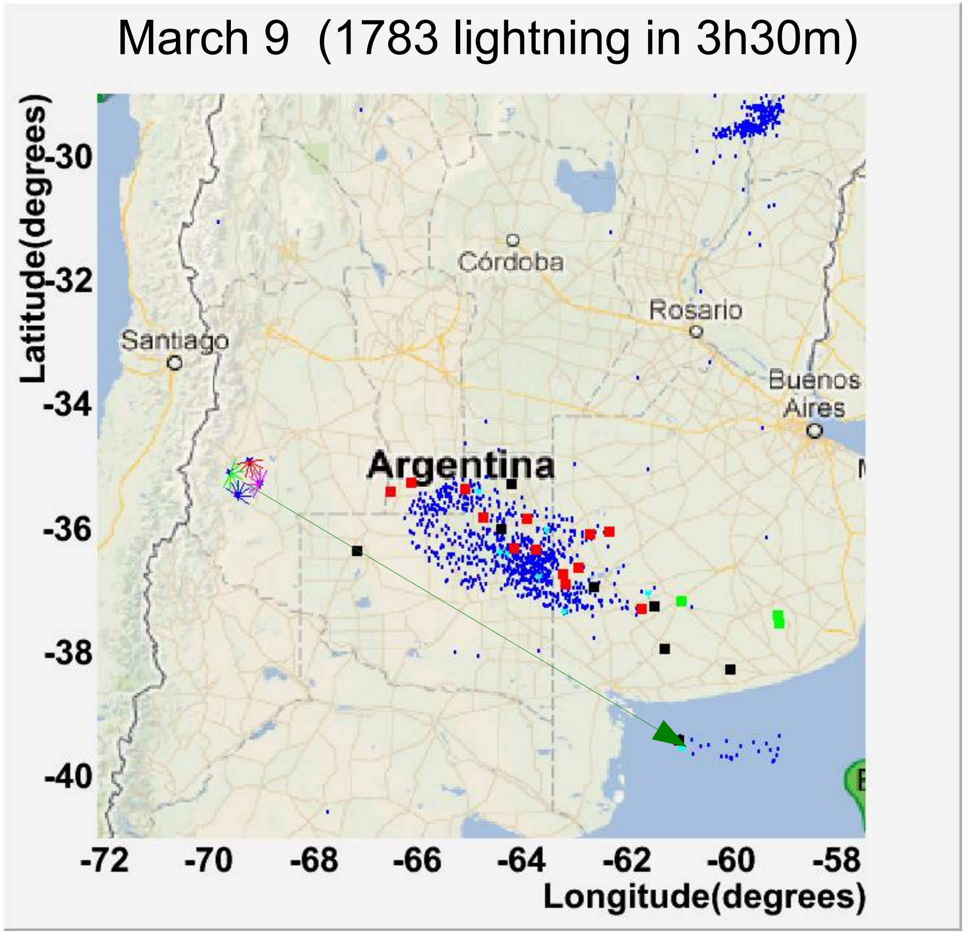


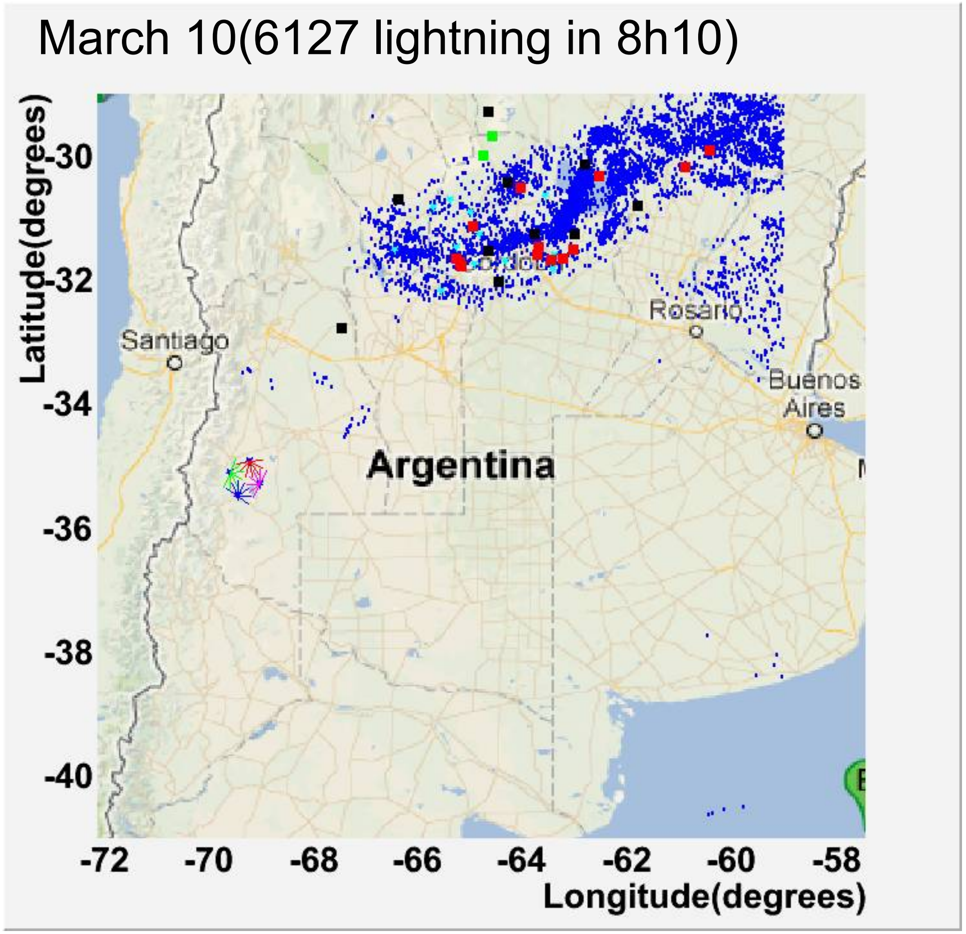


Matching condition: DeltaT<1 ms (corrected for front propagation)
Matches (☆): 2/7 mono, 5/7 stereo, 0/1 triplet

Comparison with lightning data

(*Thanks to P.Gorham who sent us the WWLLN data for March 9,10; we'll get the full datasets sometime.*)





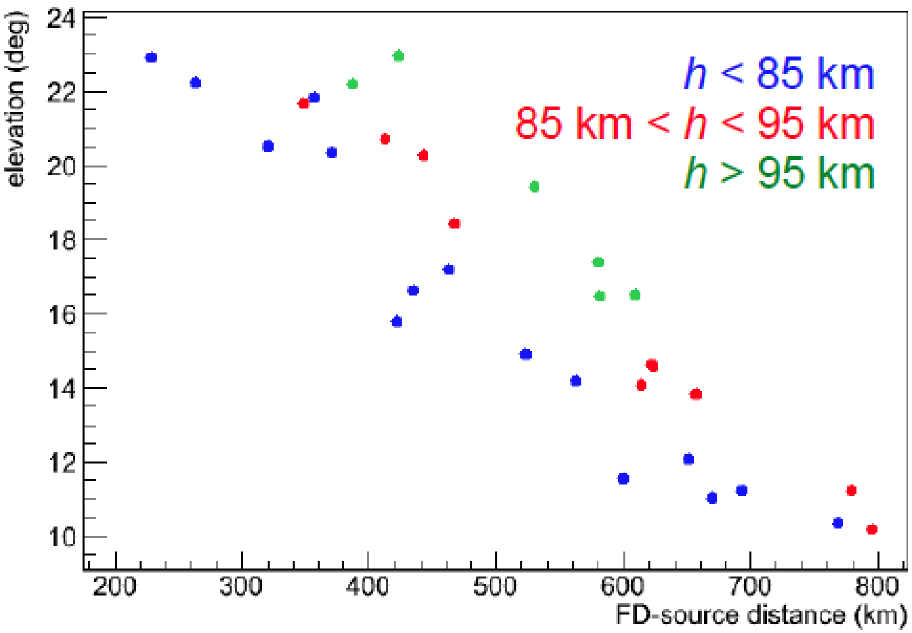
Most impressive match: GPS 1046828190, CO-3, 900 km away, on Atlantic Ocean: match with WWLLN within 15 km ! On this , we know the lightning strike current, 160 kA (*).

(*) from GLD360 network, courtesy of Stanford VLF Group

Elves: Mono vs Stereo reconstruction

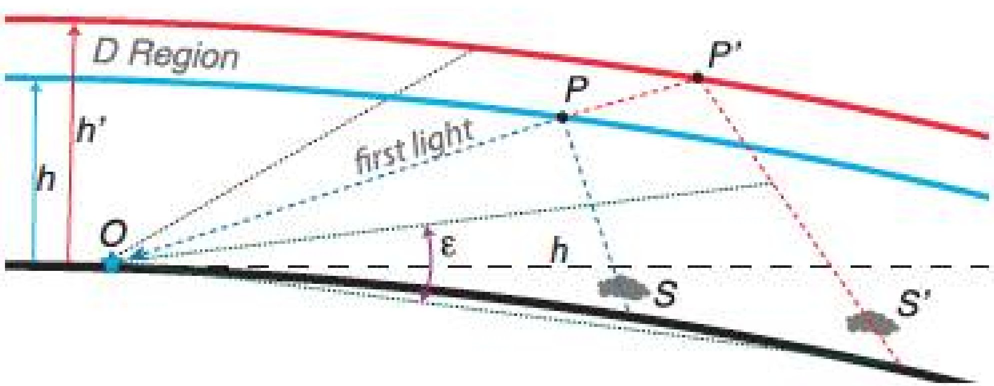
In MONO reconstruction, the calculated distance is strongly correlated to the D layer height h.

Two ways to better measure h:
- use an independent information on lightning position (e.g.:WWLLN data)
- use triangulation of STEREO events, to determine distance using only azimuth angles.



STEREO reconstruction procedure:
- Calculate Lat,Long of the elve candidate (accounting for earth curvature) using **only azimuth** of elve center (first triggered pixel);

- Use Elevation angle of elve center to calculate the height of the D layer, by varying distance and elevation ε of the hypotethical source



Stereo reconstruction : example

Event GPStime=1046828421

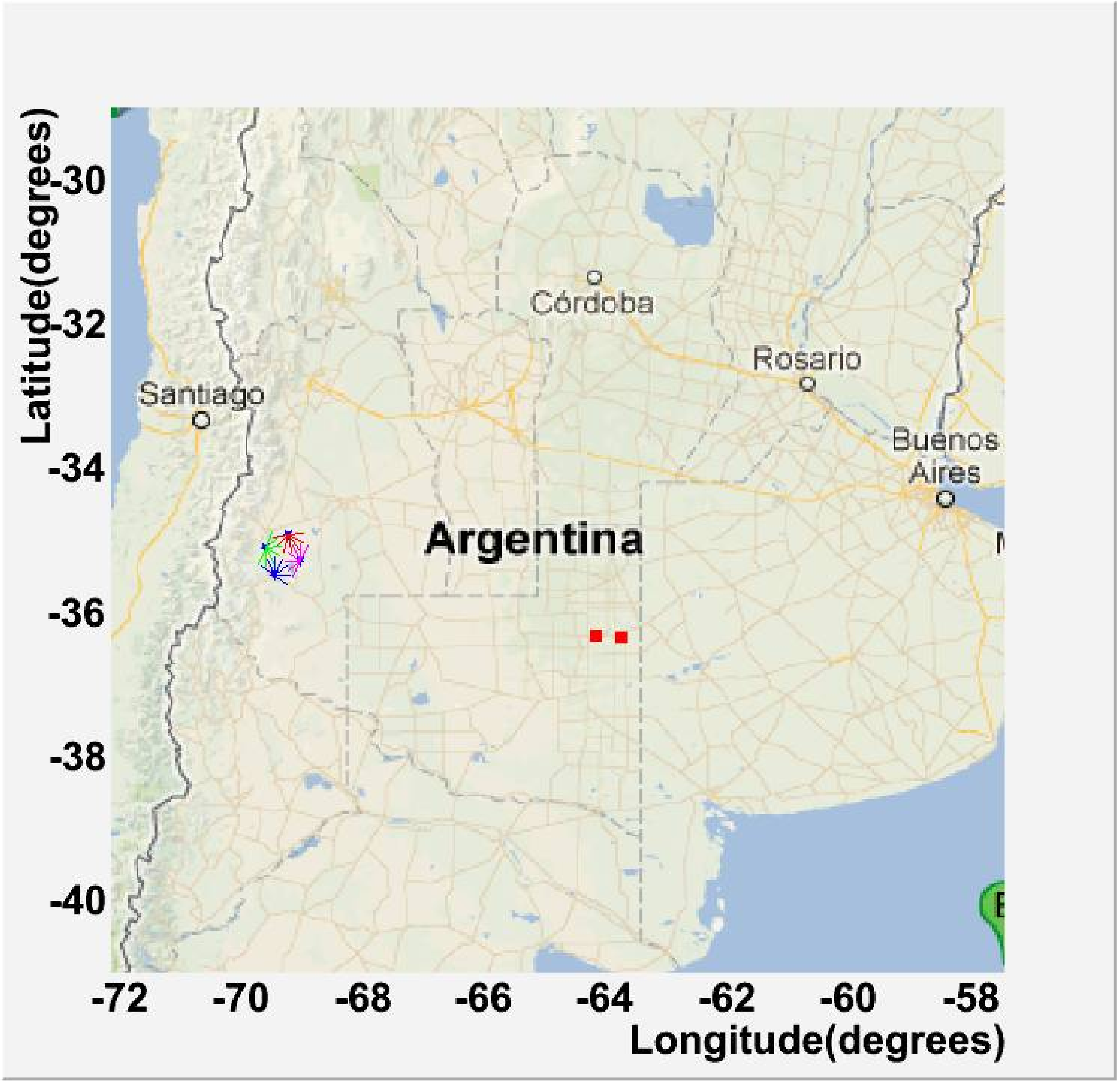
■ Mono reconstructions

Time of Lightning:

LA-6: 937221-1700 = 935521

LL-1: 937231-1853 = 935378

	Lat	Long	h,km
LA-6:	-36.33	-64.15	84
LL-1:	-36.36	-63.72	90



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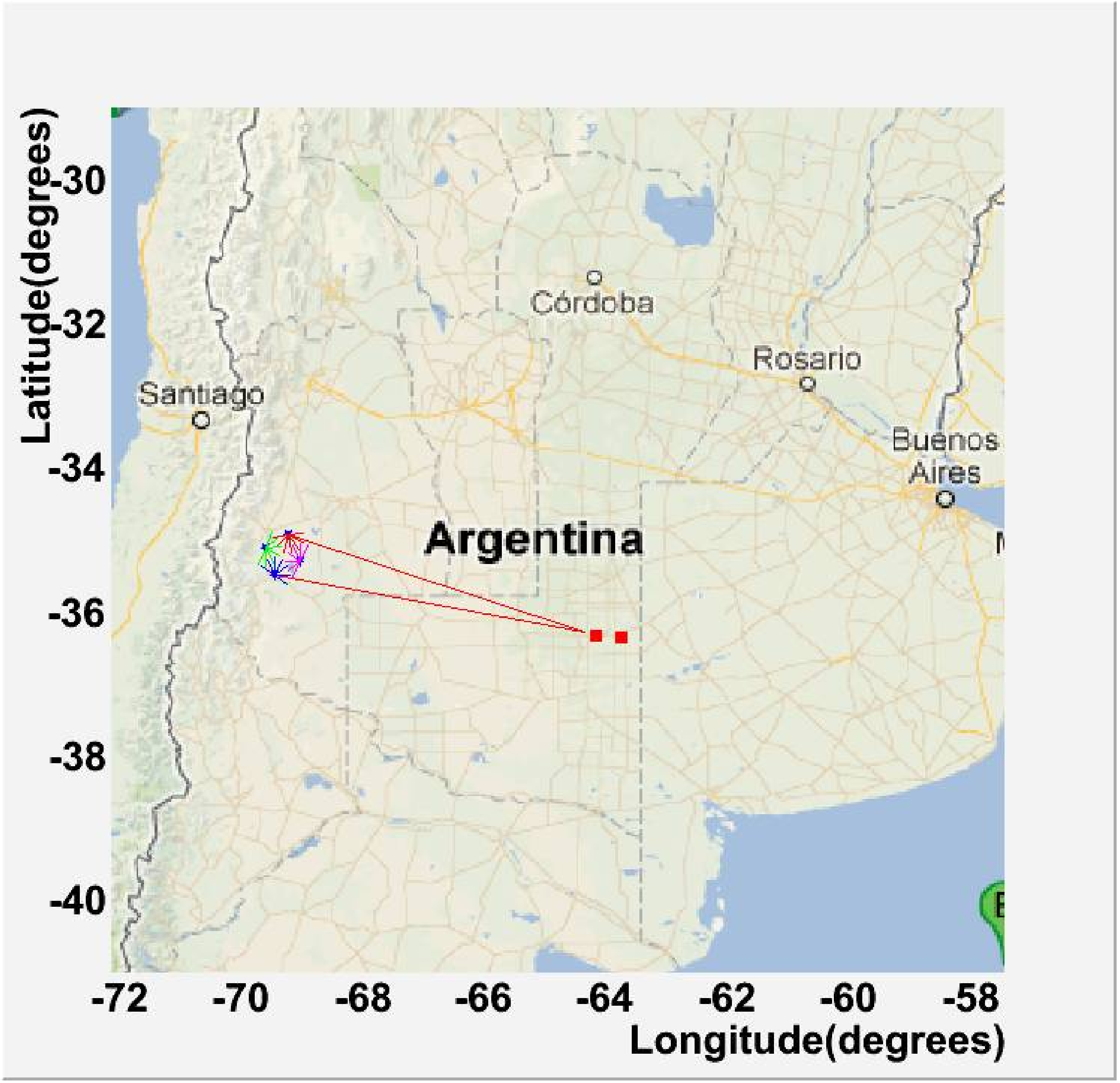
> Stereo reconstruction

Microtime:

LA-6: 937221-1639 = 935582

LL-1: 937231-1654 = 935577

	Lat	Long	h,km
LA-6:	-36.29	-64.34	75
LL-1:	-36.29	-64.34	77



Stereo reconstruction: example

Event GPStime=1046828421

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<u>WWLLN:</u>

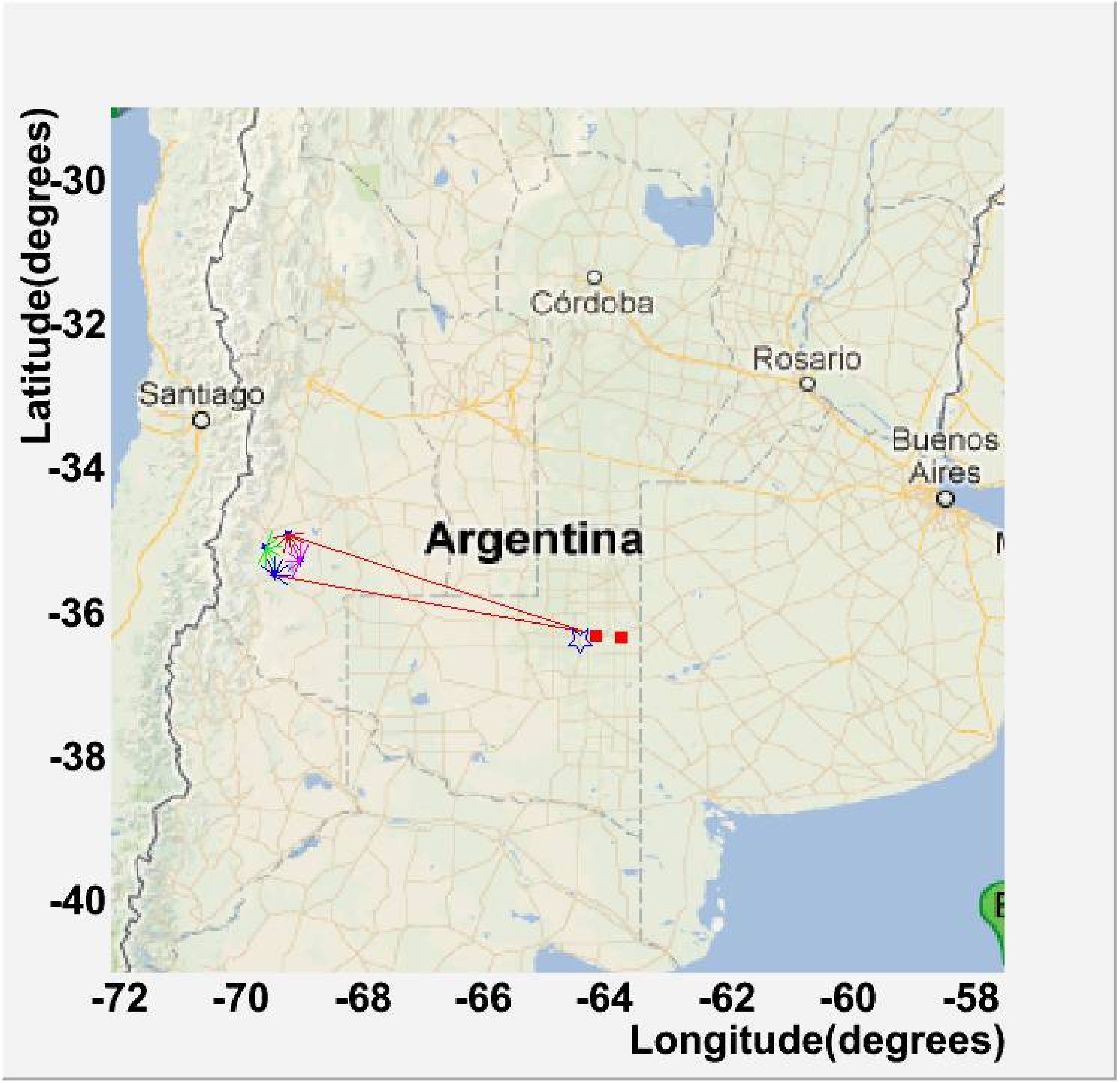
☆ lightning in time

GPSutime: 935492

LA-6:ΔT=+90 us

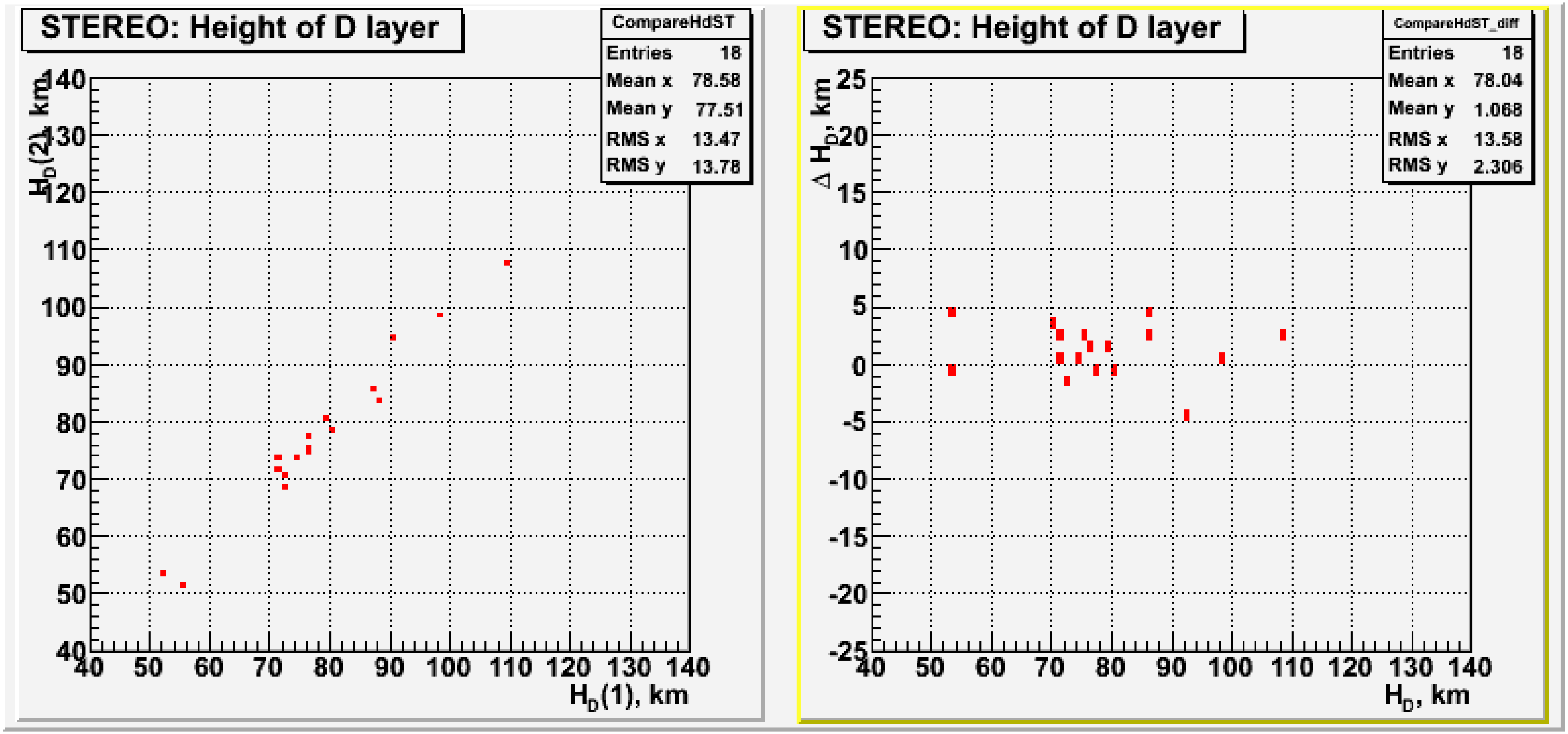
LL-1: ΔT=+85 us

Earth Distance: 15 km

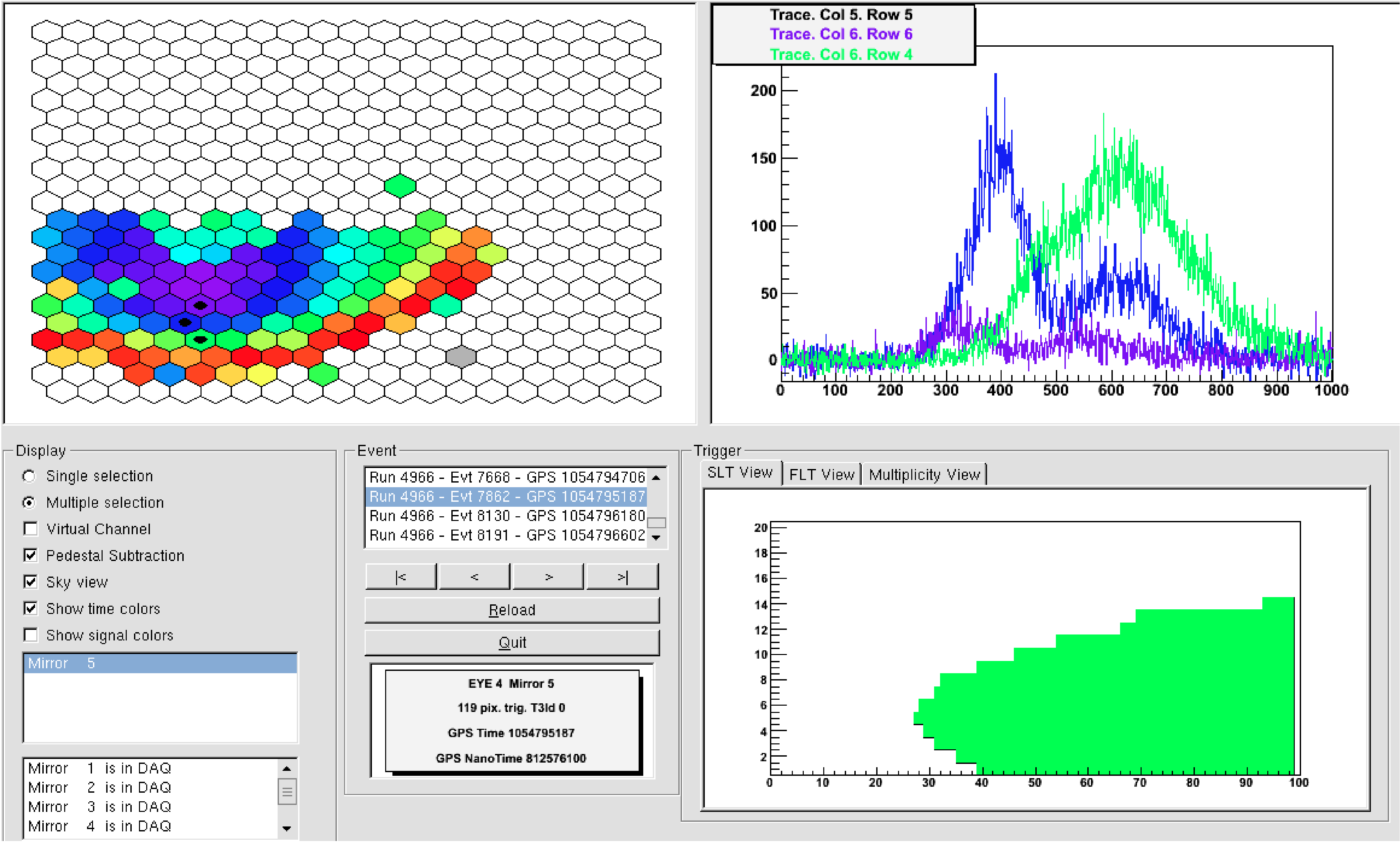


Stereo reconstruction: Hd calculation

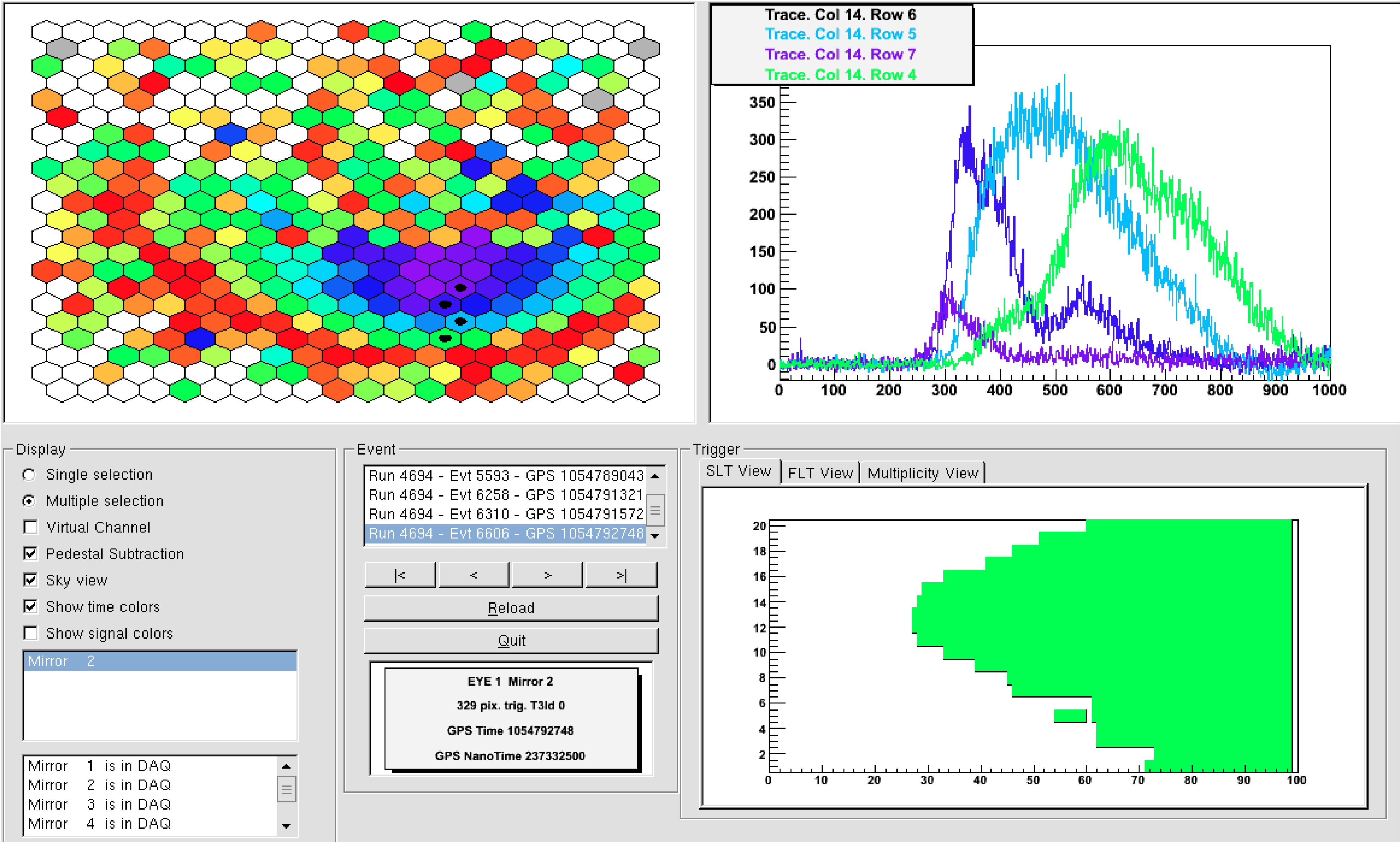
Using STEREO events we can determine the light emitting layer altitude with resolution of 2 to 3 km , and study its variation across the night, or as function of the lightning density



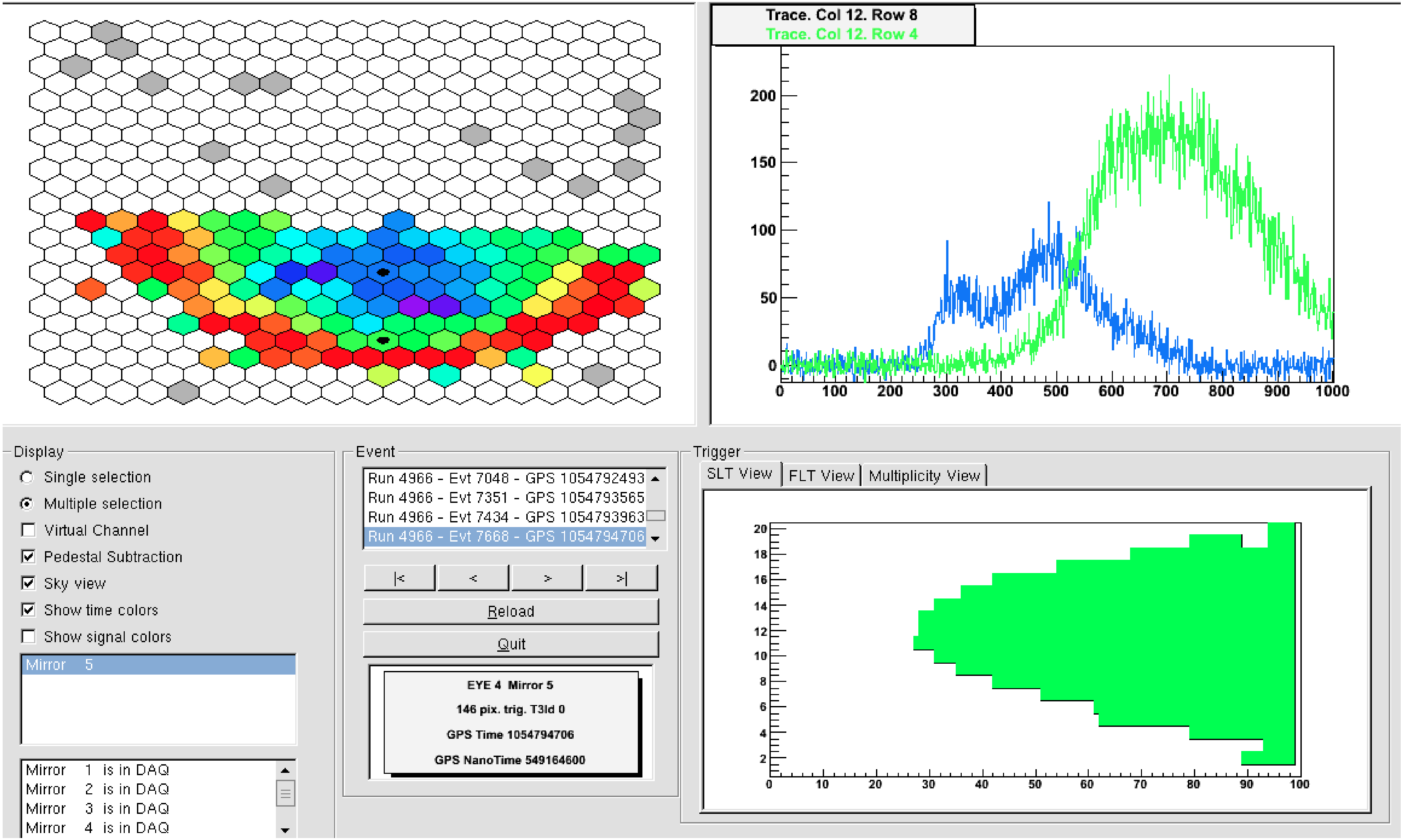
Double ELVES



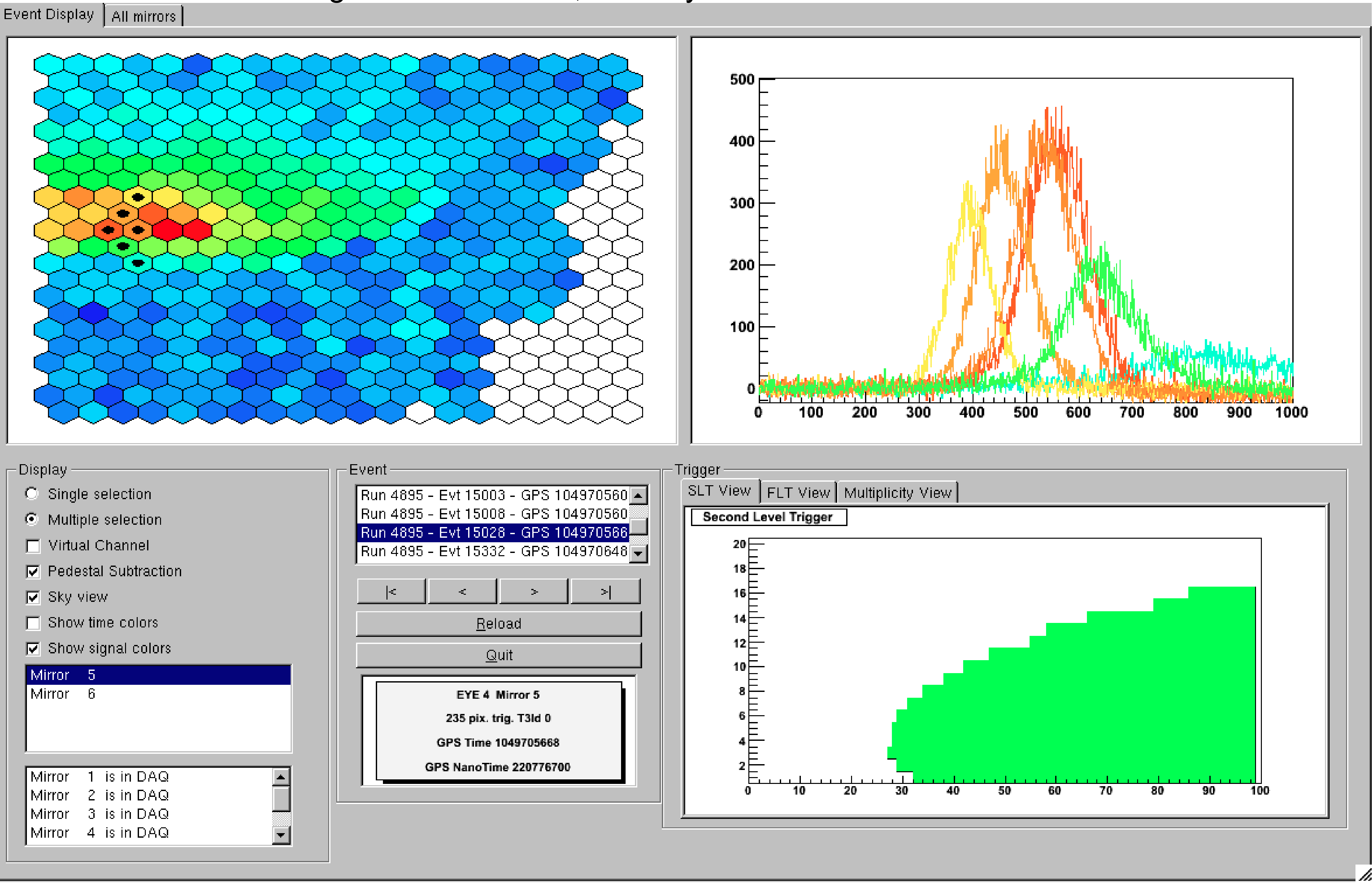
Double ELVES



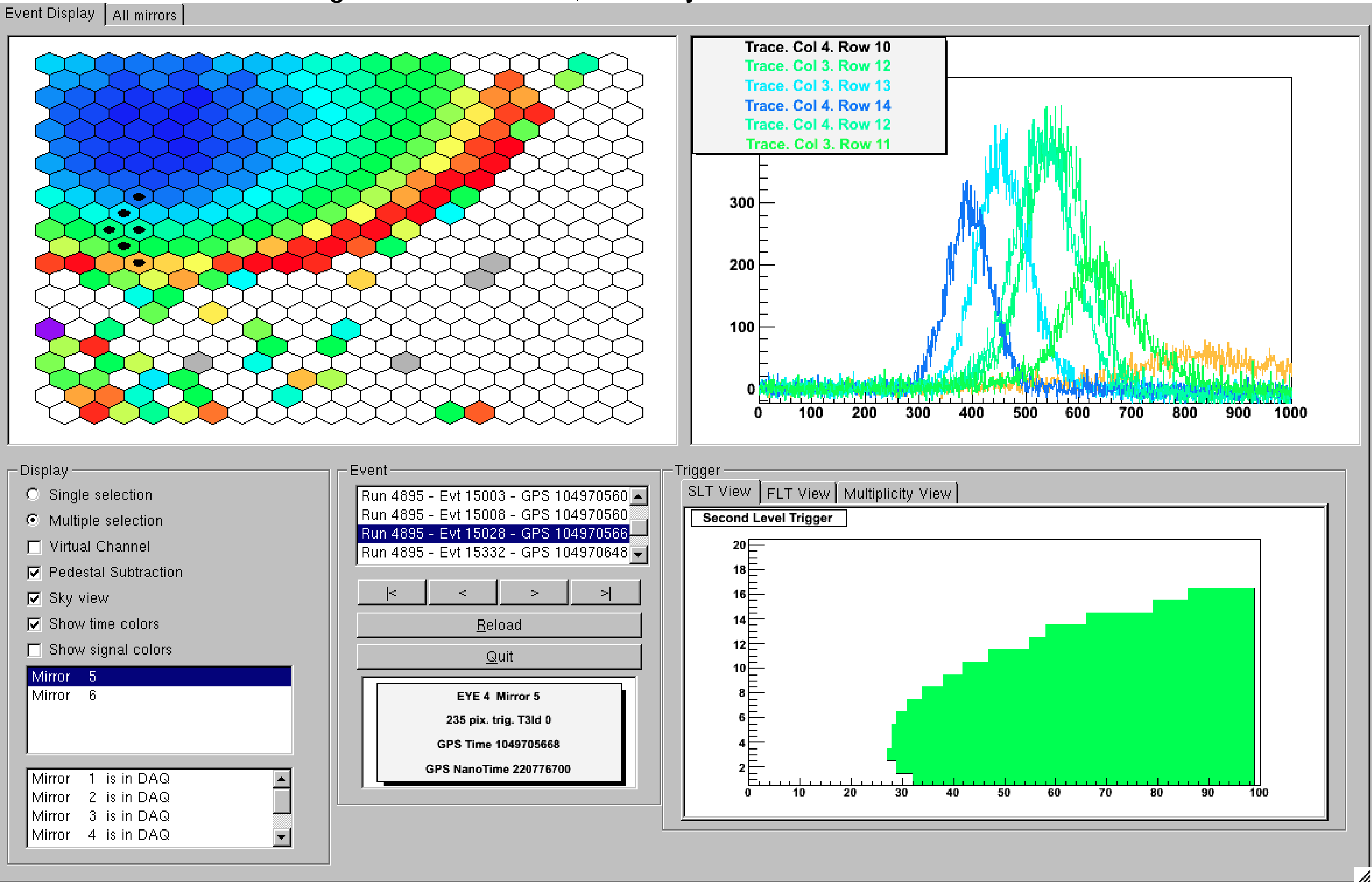
Double ELVES



ELVE candidate event at GPS 1049705668, CO-5 , signal colors
Stereo event occuring at 8:54:12 UTC , seen by Coihueco 5&6 and LosLeones 3



ELVE candidate event at GPS 1049705668, CO-5 , time colors
Stereo event occuring at 8:54:12 UTC , seen by Coihueco 5&6 and LosLeones 3



ELVE candidate event at GPS 1049705668, CO-5 , time colors
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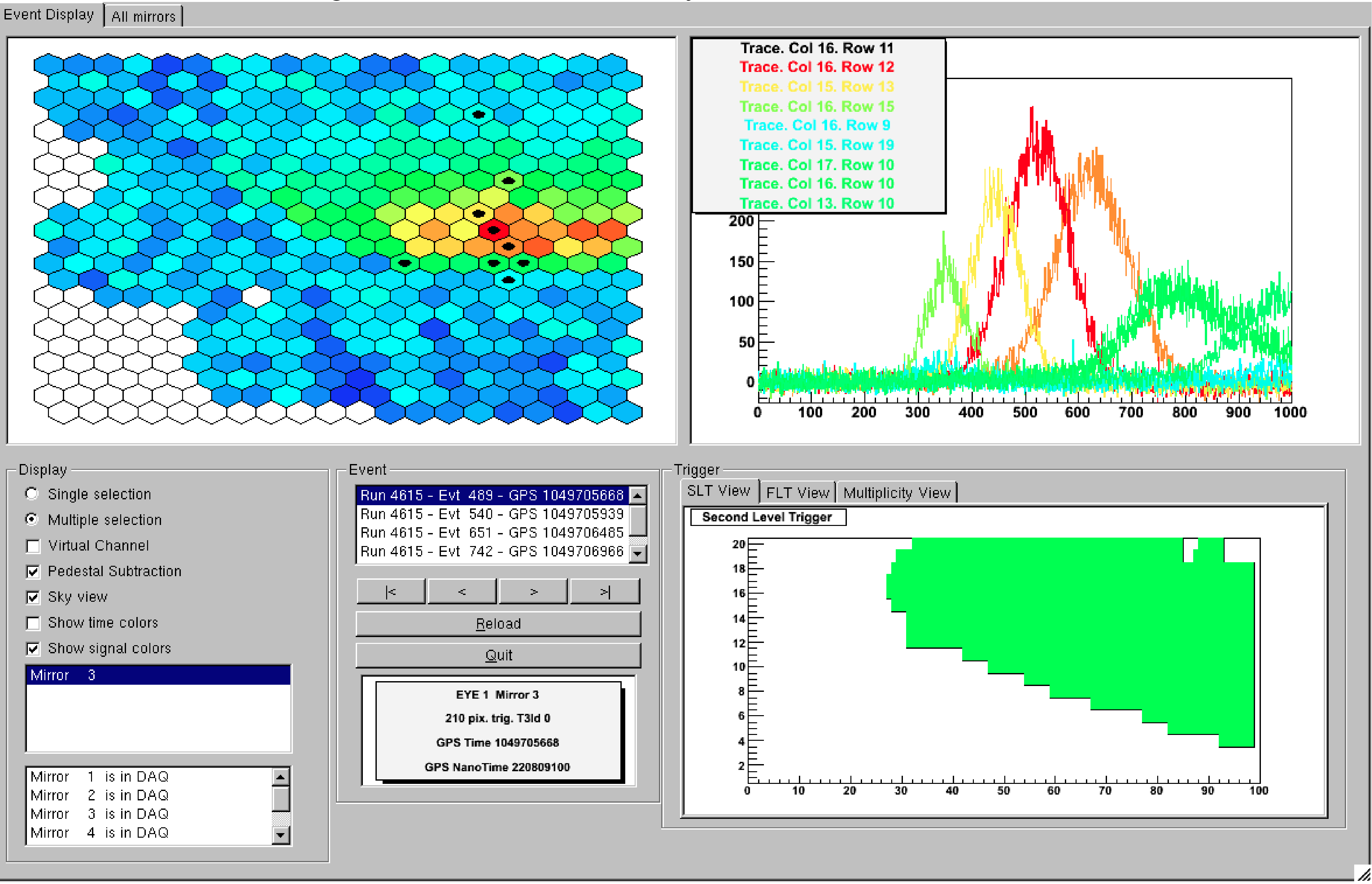

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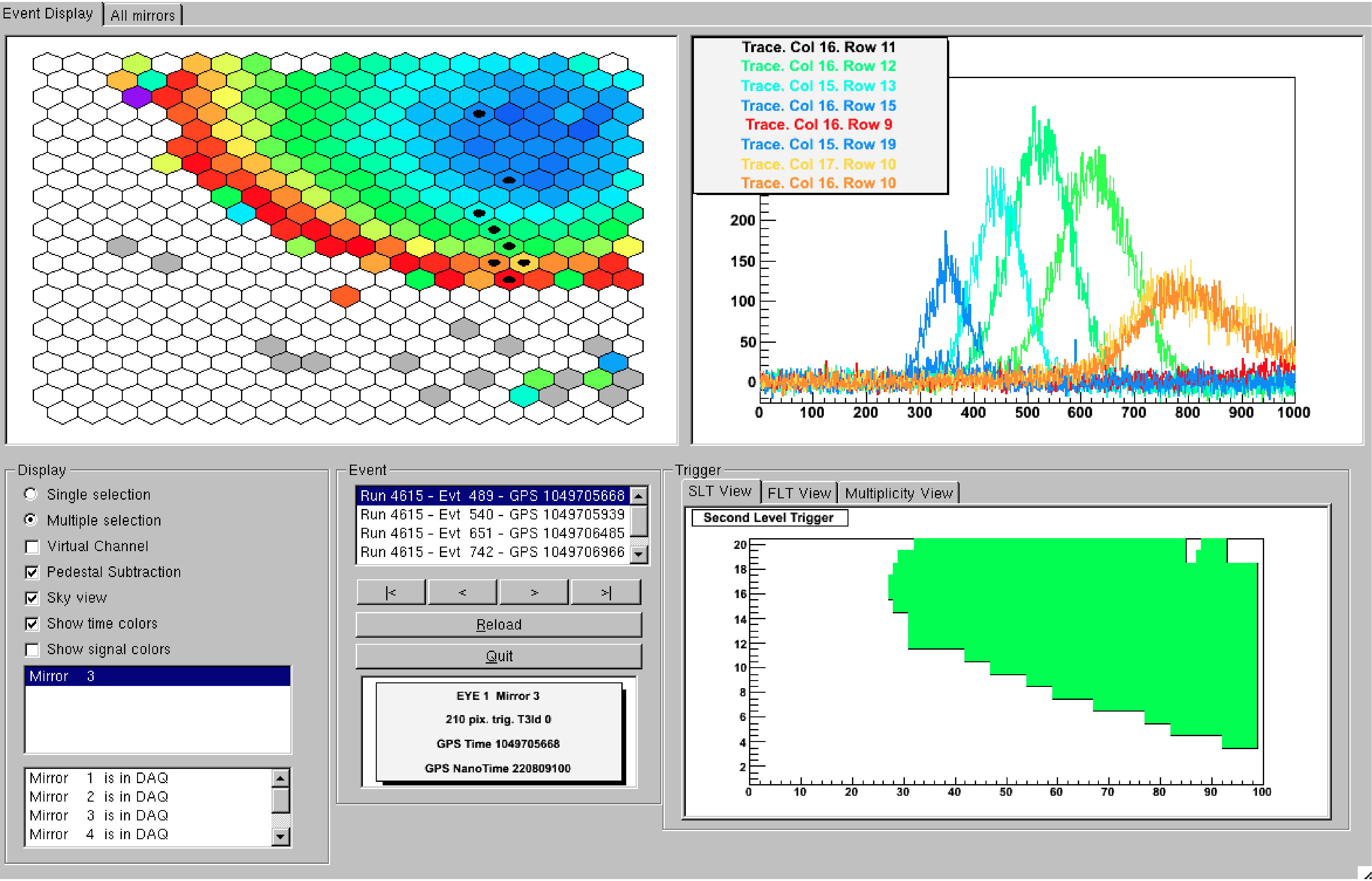

Wrapping it up ....

In 6 months we accumulated 143 events, 25% stereo

Stereo reconstruction improves Hd and lightning distance calculation, but something seems inconsistent

Correlation with WWLLN: 25-30% of the candidates match

To do list : open questions

- Space and Time Resolution
- Elve detection efficiency: how to compute it
- Missing side bays is OK, the central is NOT
(DAQ chokes when sprites follow the elve?)
- Analog signal analysis: collaboration w/ Stanford VLF group
- Reading the following 0.1 ms to fully see the central dip in the ELVES.

ELVES in South Atlantic Anomaly

The South Atlantic Anomaly is the region where the lowermost part of Van Allen belts is closest to the earth surface. The extension of this area depends on solar cycle, and may reach the Observatory. We may be uniquely placed to study ELVES in the proximity of the South Atlantic Anomaly.