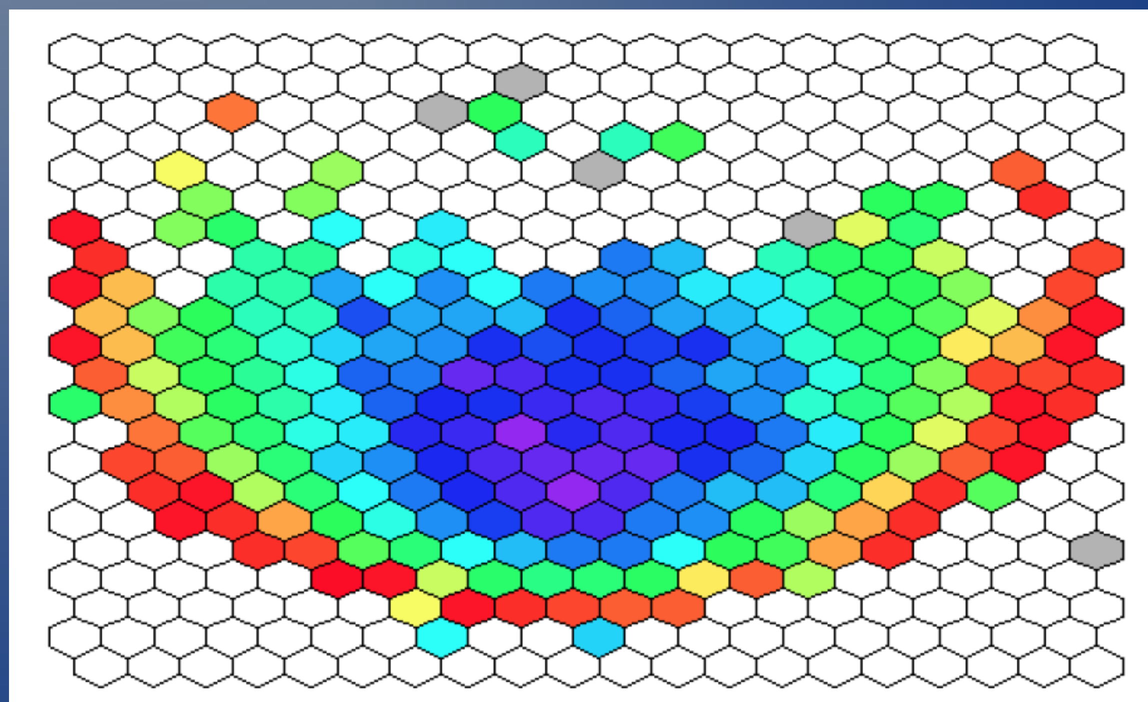
ELVES at the Pierre Auger Observatory

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

Roberto Mussa
INFN Torino



14th AGILE Workshop, ASI HQ

June 21st , 2016

Pierre Auger Observatory

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

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

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

3000 km^2 effective area

12 tons of H_2O per detector

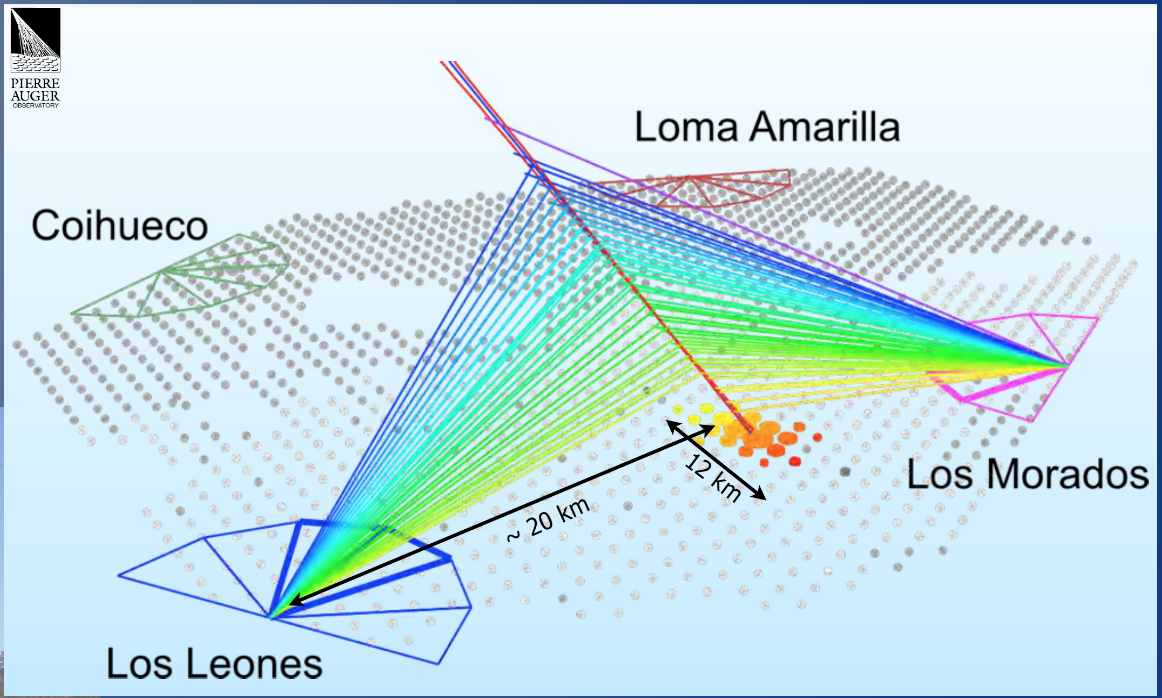
100% duty cycle

Angular resolution <1°

Threshold Energy: $10^{18.3}$ eV

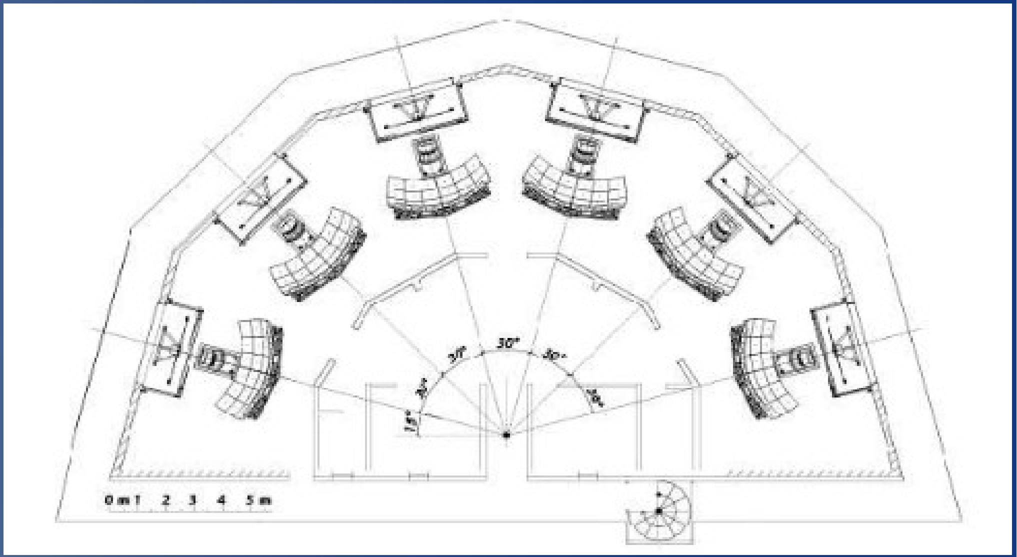
3 PMTs / SD detector unit

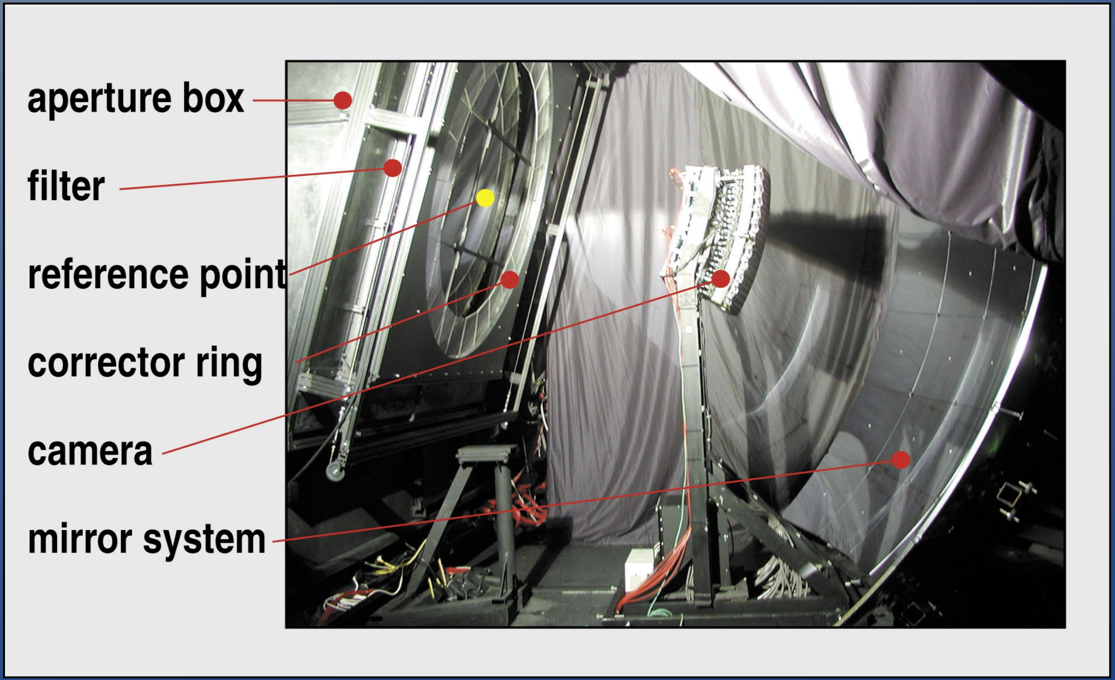
Complete since 2008

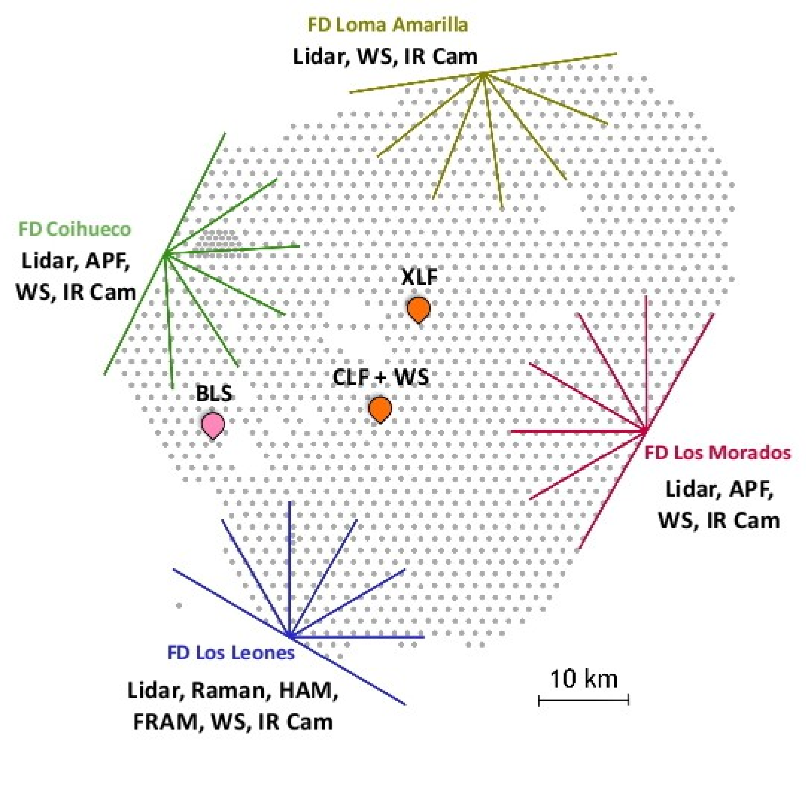


Fluorescence Detector

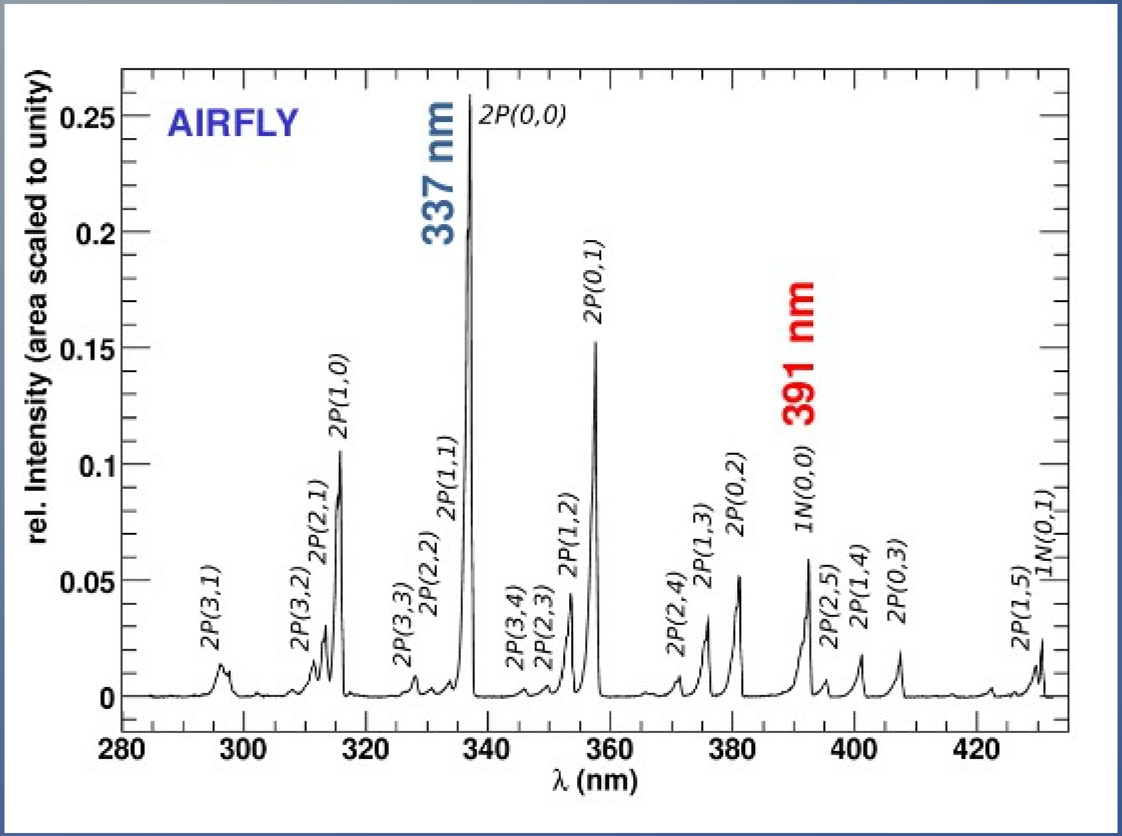
24 telescopes in 4 eyes
FD camera: 440 PMTs / telescope
Mirror area: $11 m^2$
Field of View: 6x30°x30° for each FD
UV filter: 300-420 nm
Buffering 1000 time bins, 100 ns each
A 10 Mfps camera !
Duty cycle ~12% (1/2 moon cycle)
Angular resolution ~ 0.6°

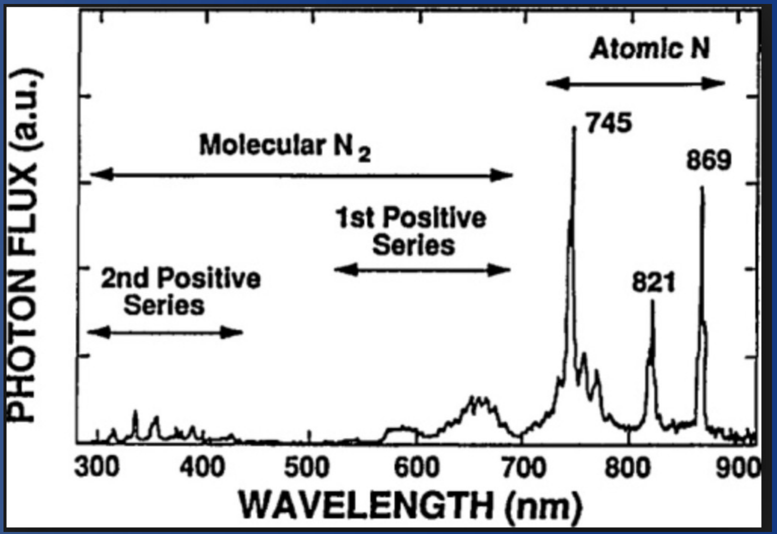


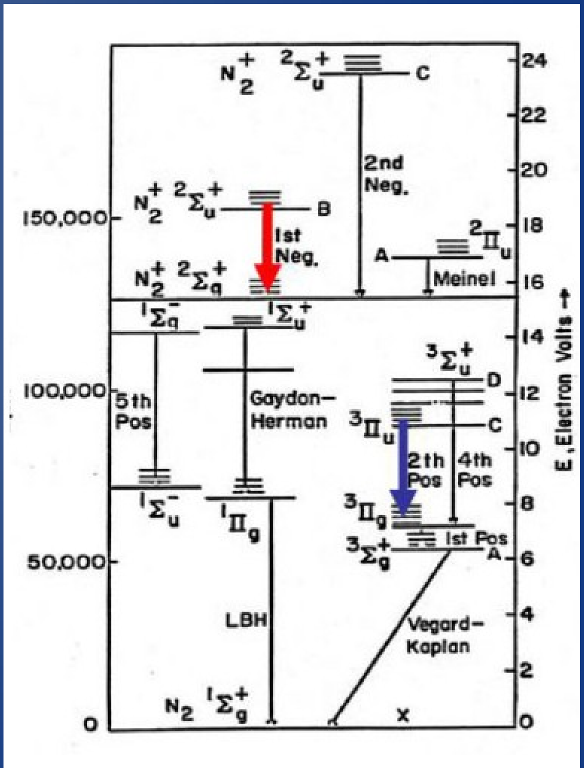


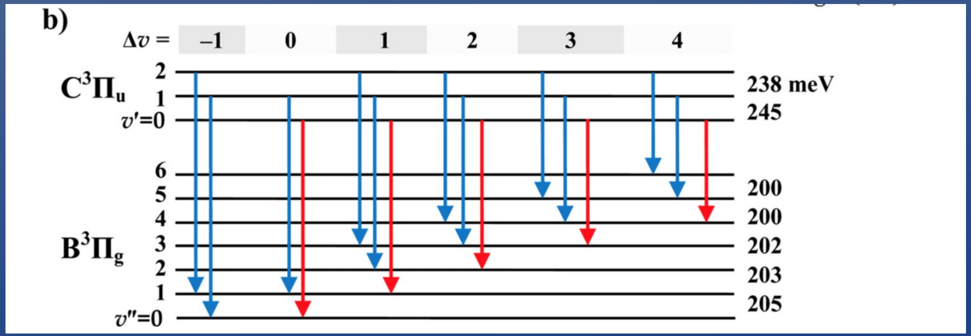


Fluorescence Light
Emission spectrum





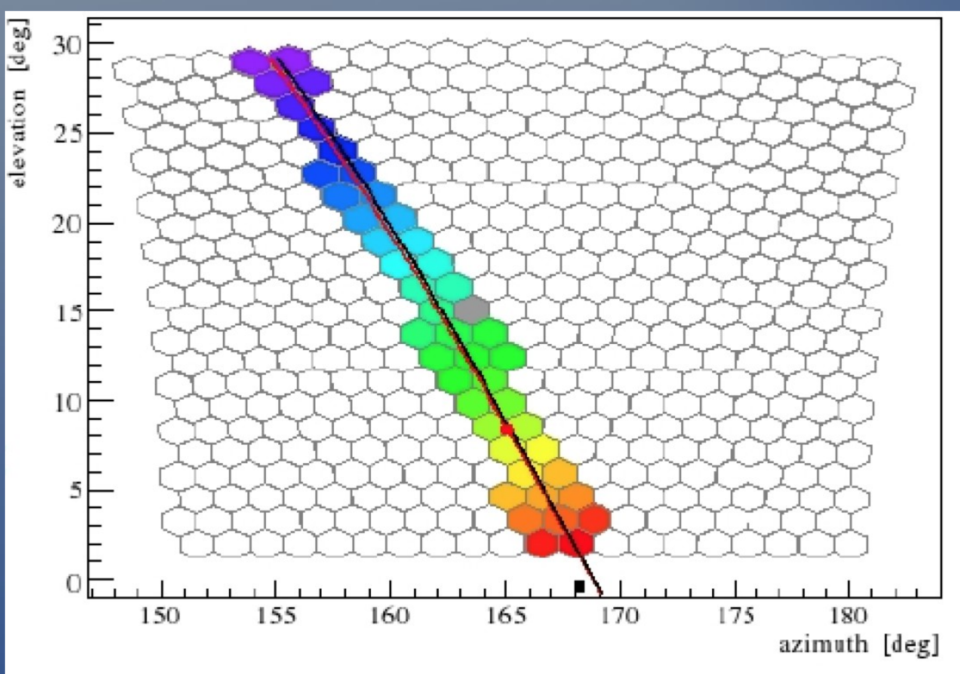




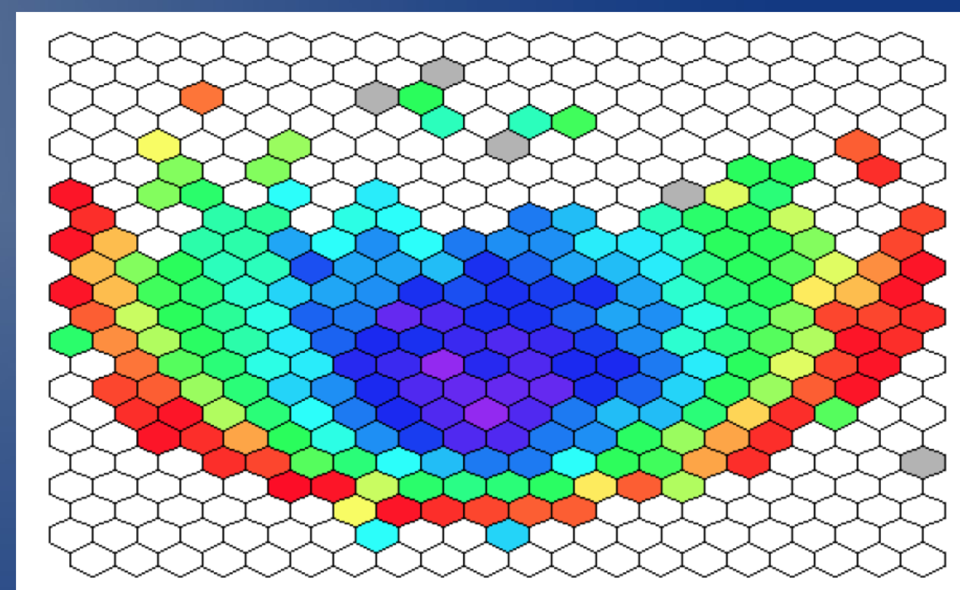
2004-2009: discovery of 3 ELVES events in FD data

R.Mussa et al., proc."IS @ AO Workshop", Cambridge, EPJ Plus 127,94 (2012)
A.Tonachini et al., proc. ICRC2011, Beijing 2011

Cosmic Ray



ELVES



Colors represent the start time of the pulse: from BLUE(earlier) to RED (later)

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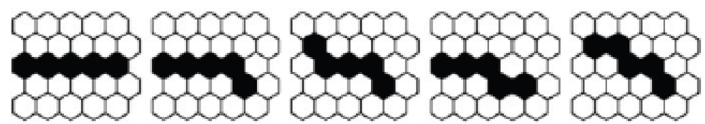
A.Tonachini et al., proc. ICRC2011, Beijing 2011

2008-2011: search for ELVES in FD-SLT data

	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 ↓			
Third Level Trigger (TLT)	SW	Lightning rejection	0.02 Hz / site



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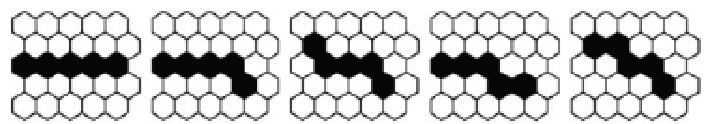
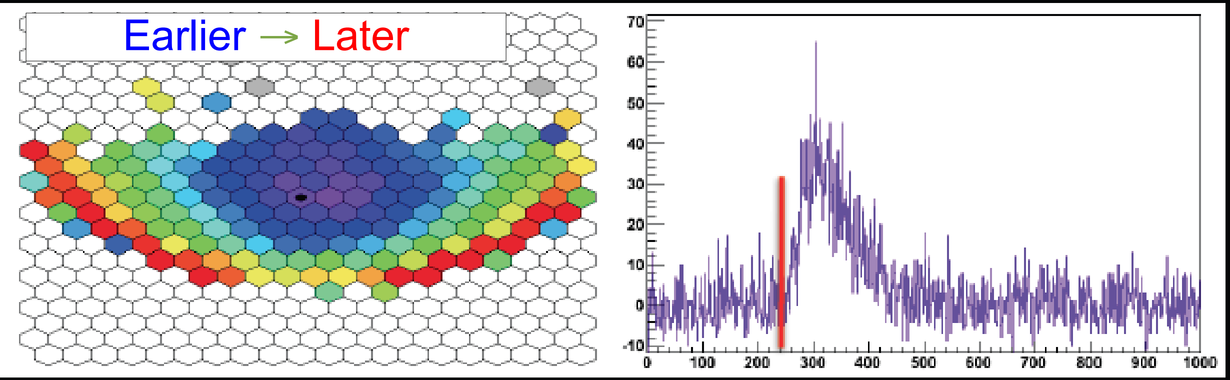


We decided to analyze the fraction of events which pass the 2nd level of trigger, which is saved with prescaling factor 1/100 in a separate data stream (*minimum bias*) and is used for measuring efficiencies and testing new trigger algorithms. 58 new events were found.
R.Mussa et al., poster at AGU FALL 2012
A.Tonachini et al., proceedings ICRC 2013

Online trigger algorithm for ELVES

Tonachini et al Proc.ICRC 2013

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

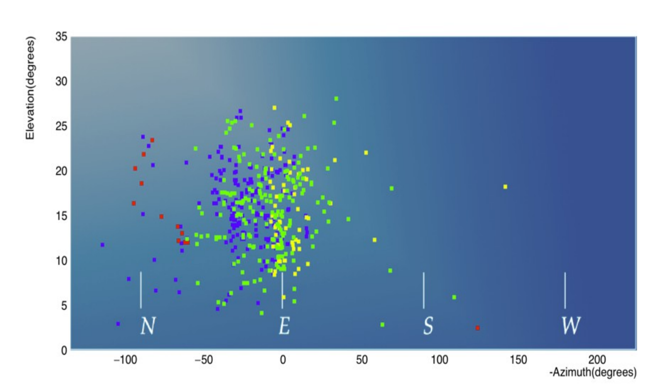
5. **Check signal amplitude**
   - **for each pixel measure average ADC counts before trigger**
   - **find signal peak**
   - ***at least ONE pixel with > 50 ADC counts***

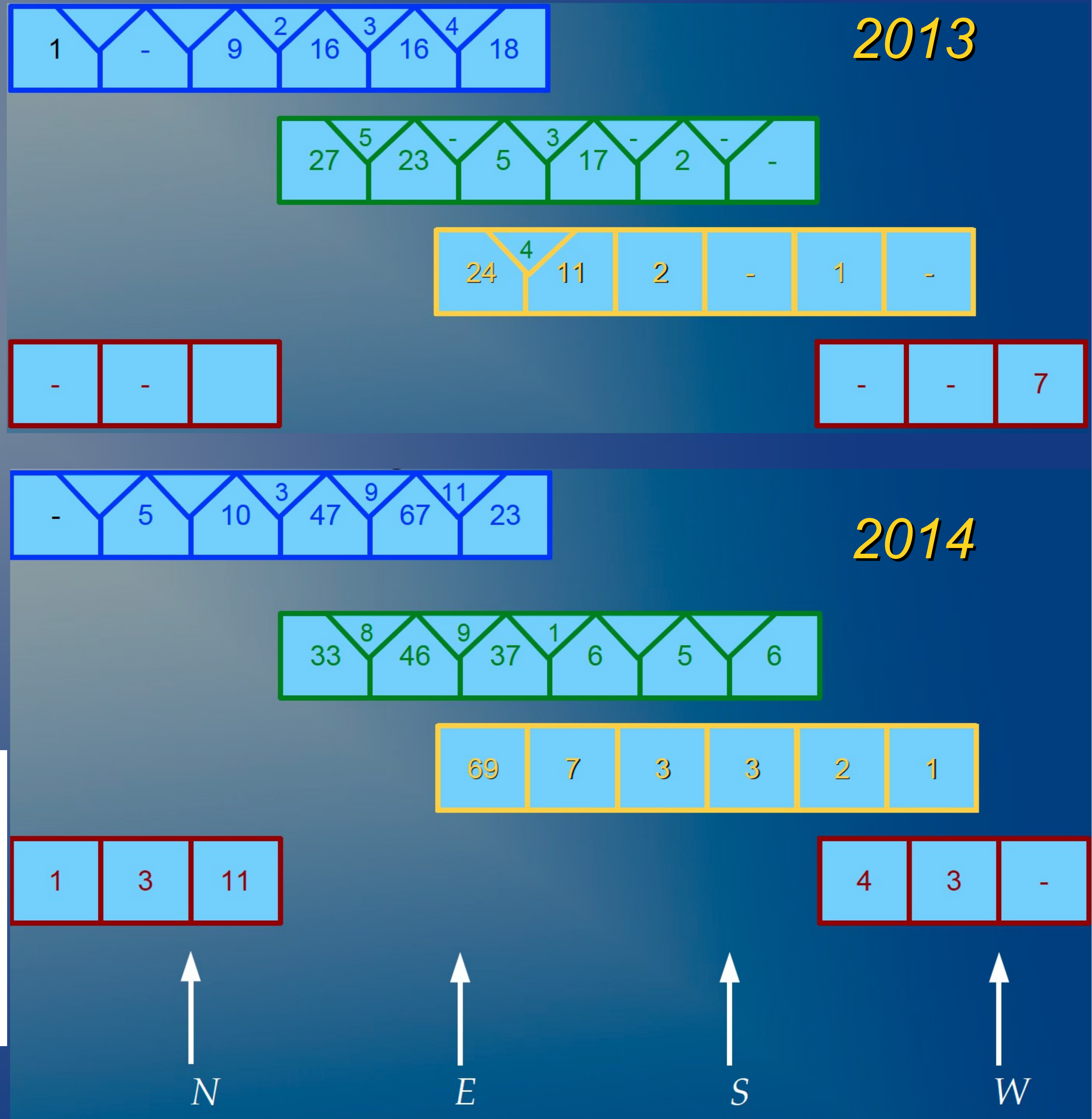
Elves statistics

	2013(*)	2014
1-eye	214	434
2-eye	83	127
3-eye	8	20
Total	305	581

(*) no data from Jan-Feb-May

Best night Oct.9 Feb.2
Nevents 47 98





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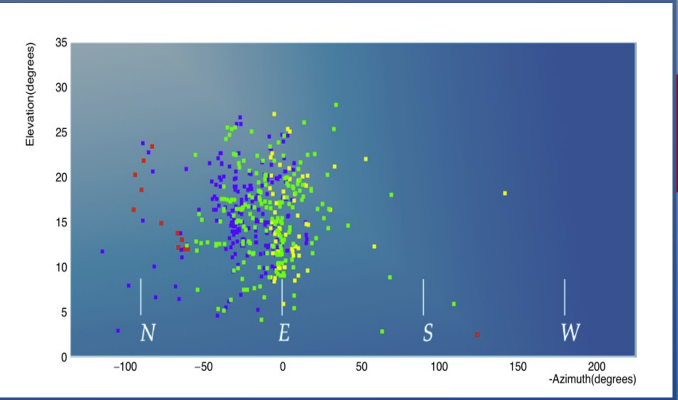
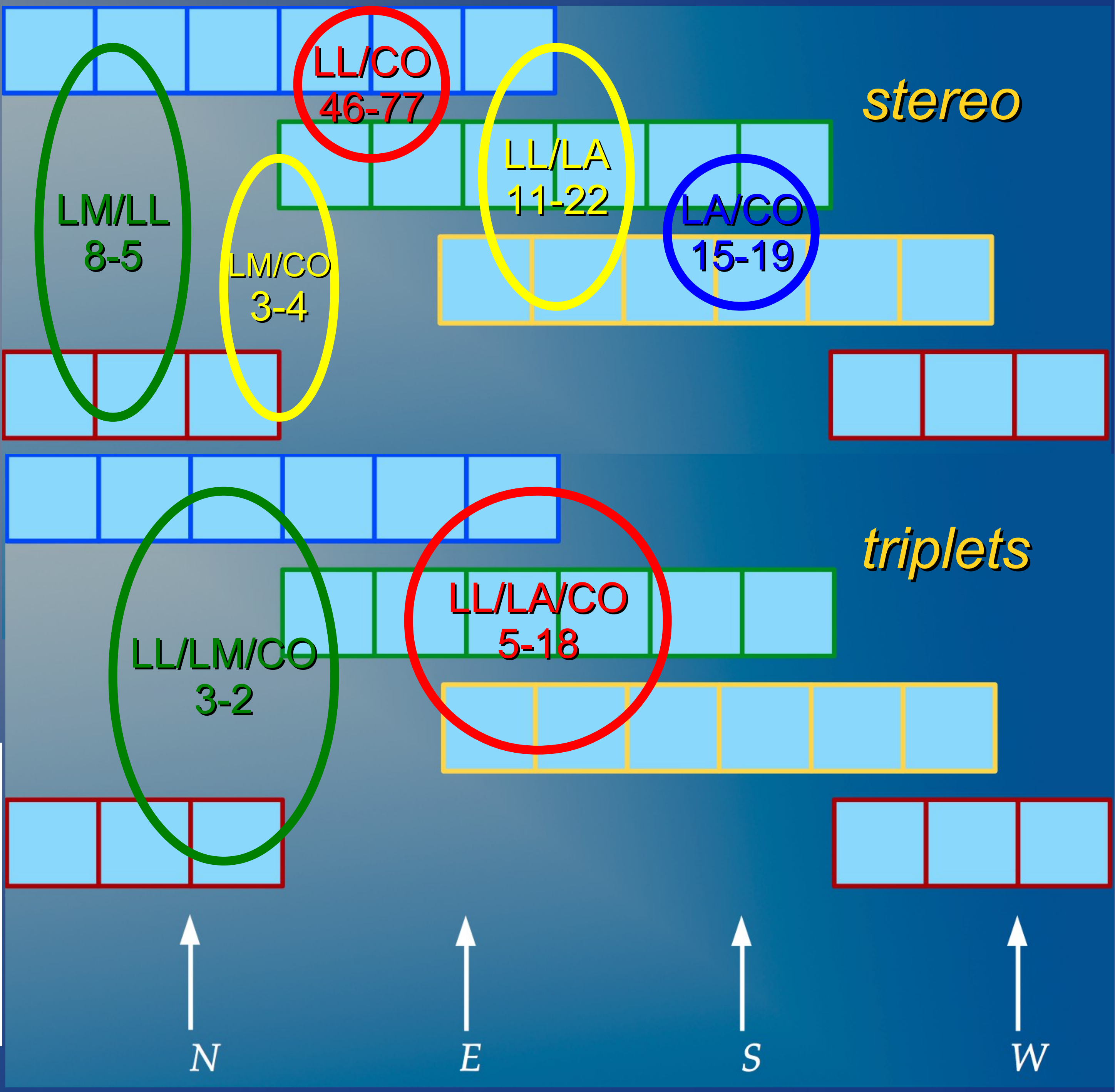
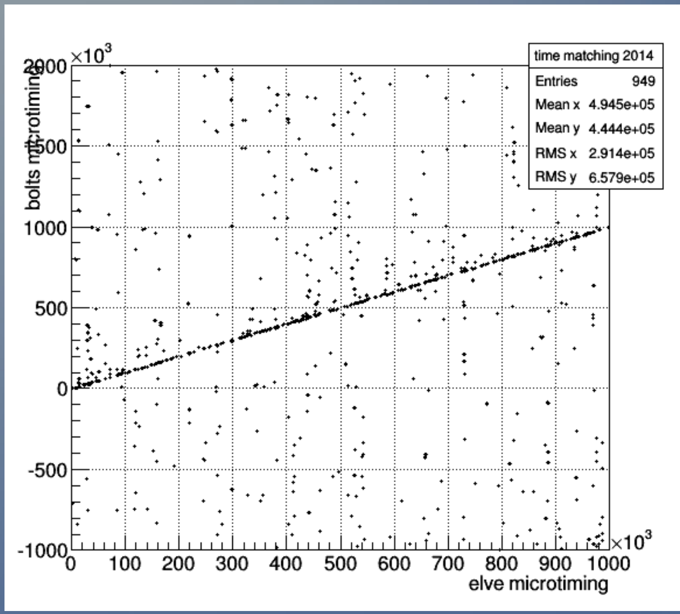
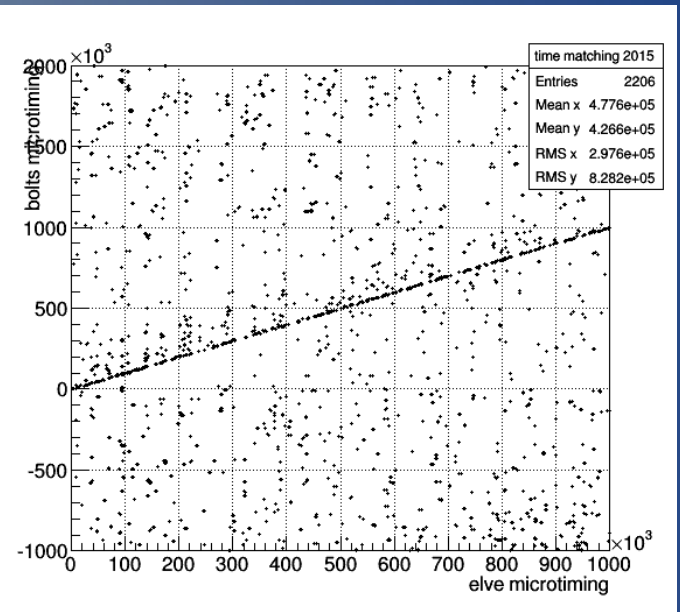


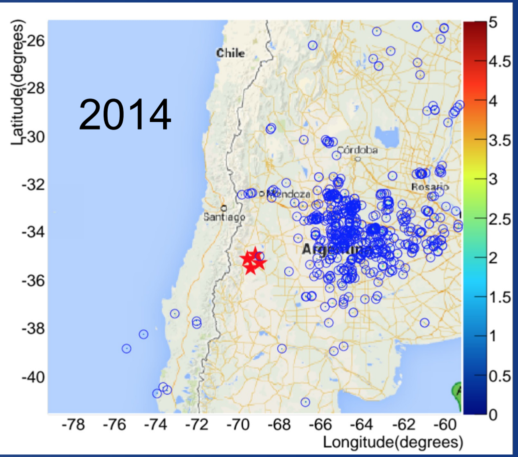


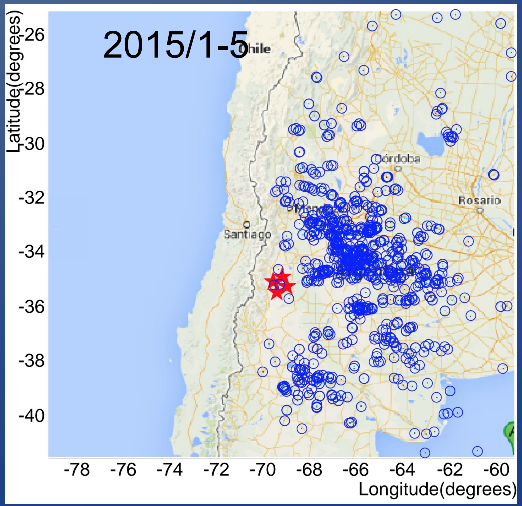
Comparison with WWLLN data

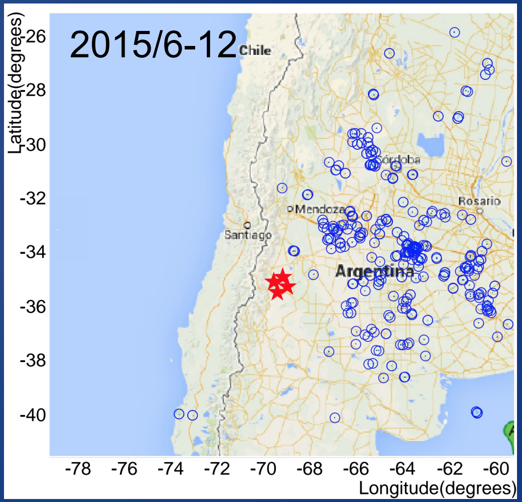
Selection of WWLLN lightnings in a 2000x2000 km^2 region around Auger Observatory
More than 40% of the ELVES have a WWLLN correlation within 20 us.



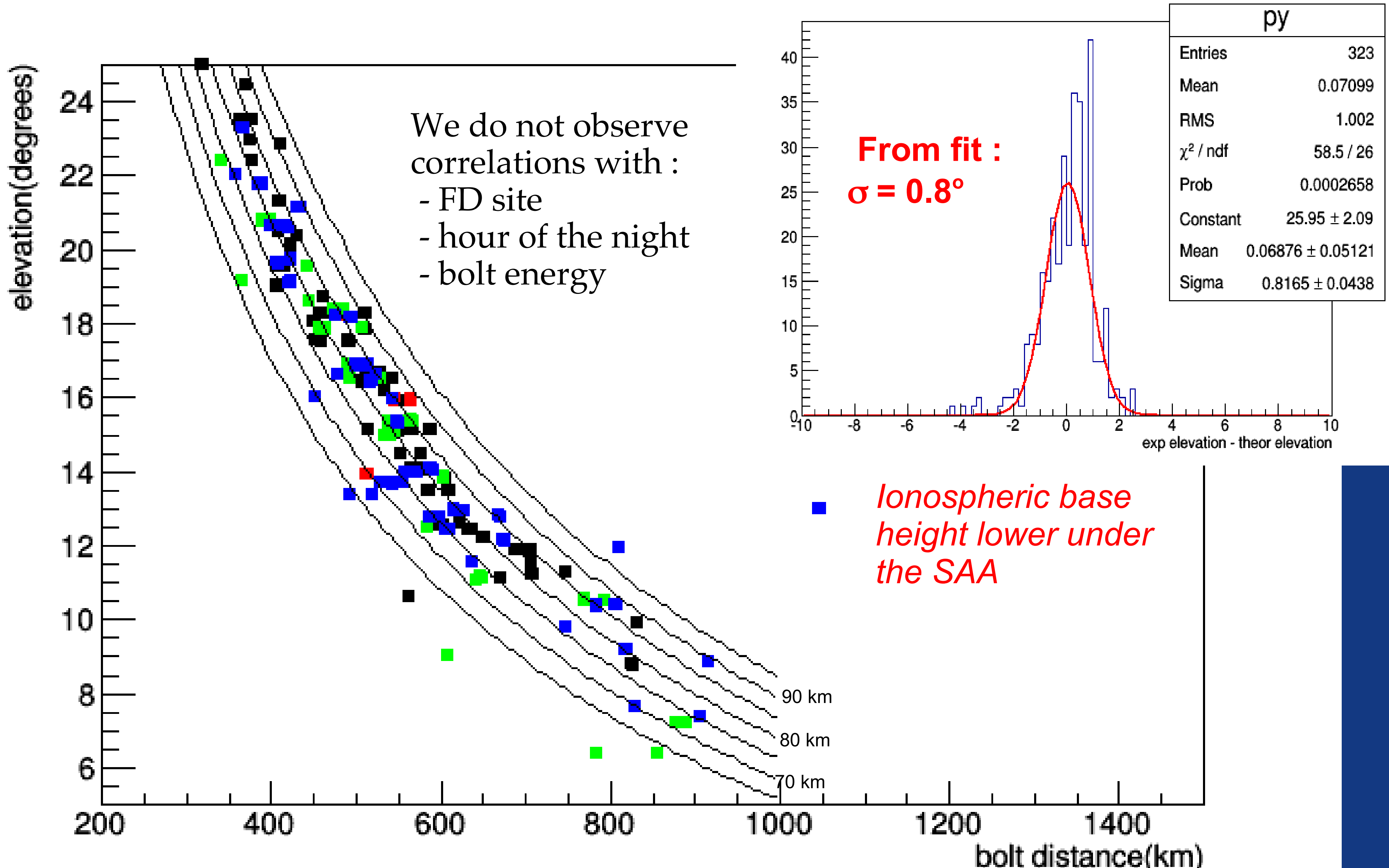








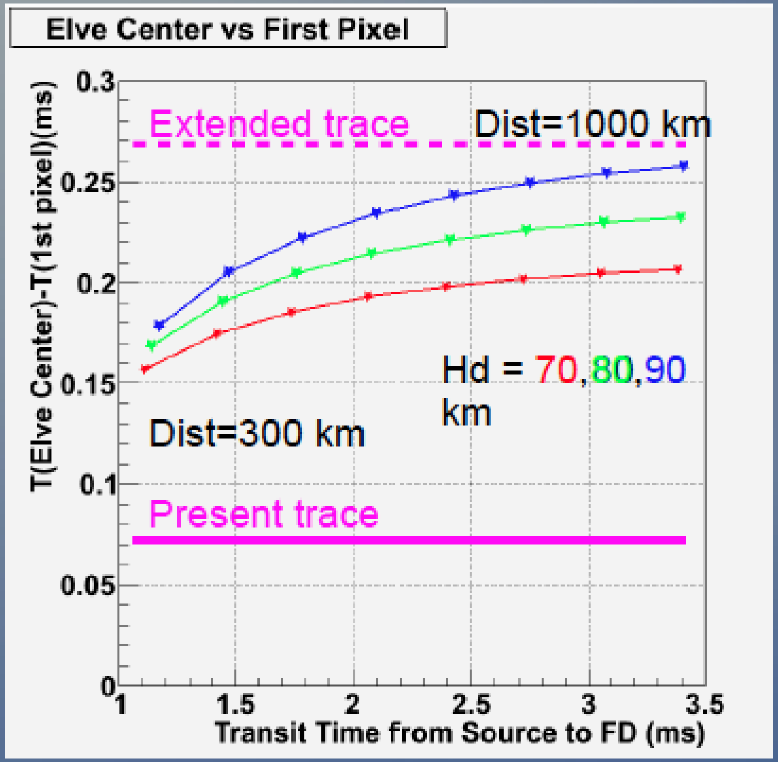
Light emission altitude

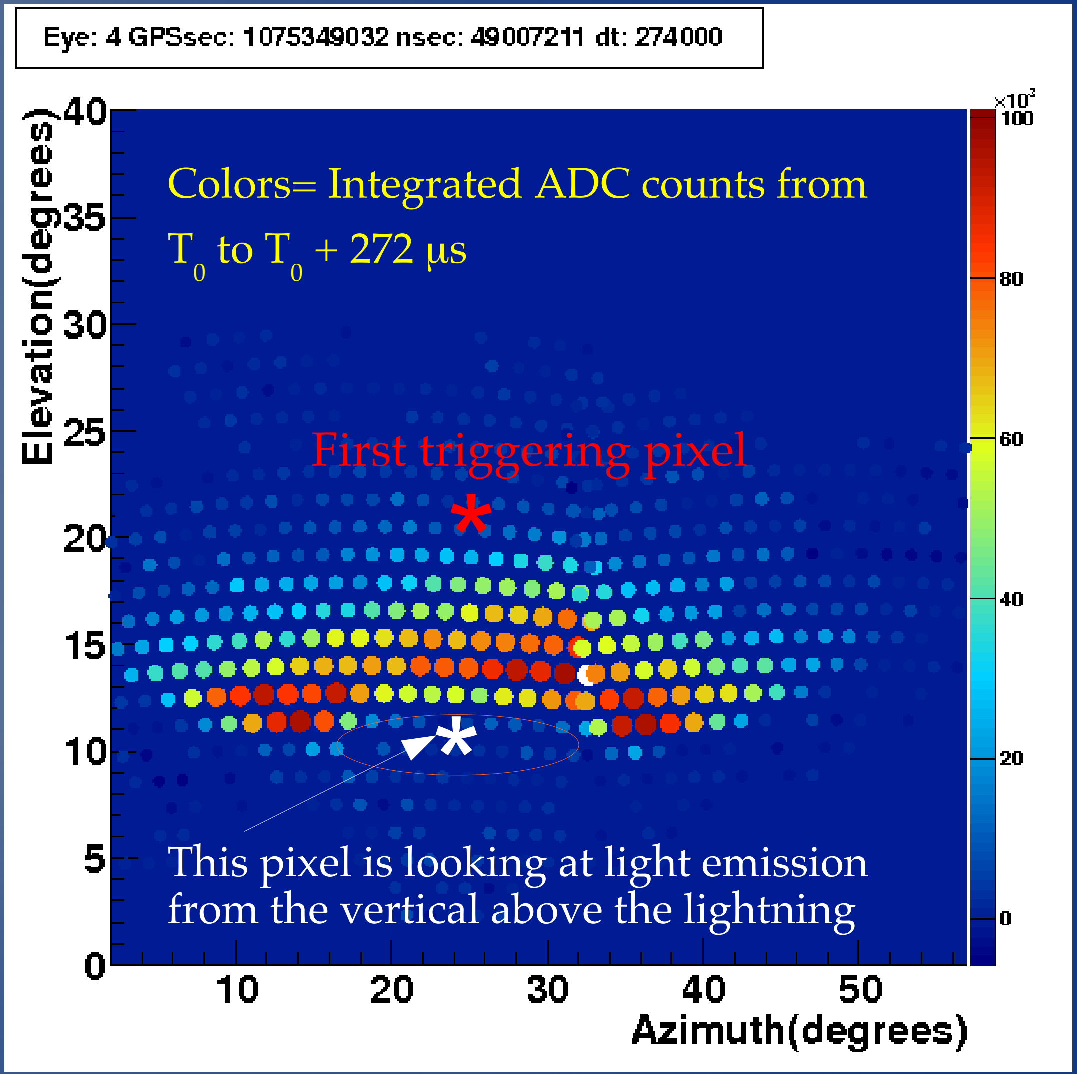


We do not observe correlations with :
- FD site
- hour of the night
- bolt energy

Ionospheric base height lower under the SAA

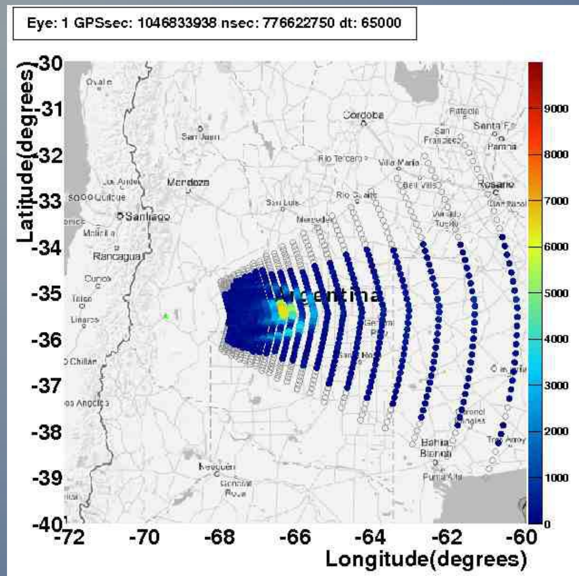
Extended readout

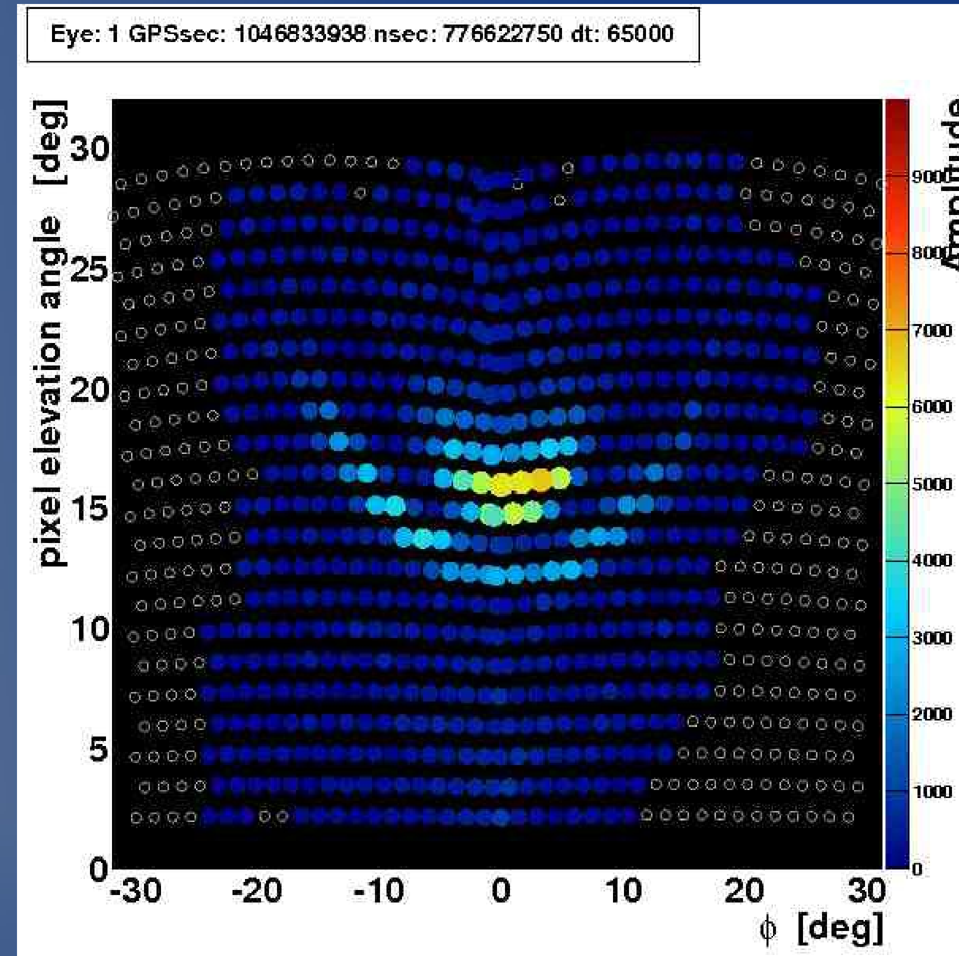




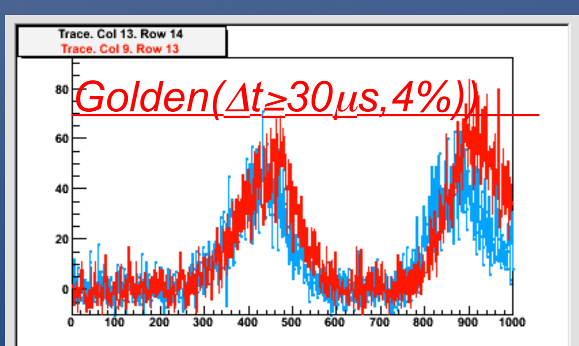
Standard FD traces are 72 μs long, after the trigger: this prevents to see most of the light of the ELVES.
In particular, it prevents to see light from the vertical above the lightning source.
Therefore, we modified the FD readout scheme, allowing to acquire 3 consecutive frames for these special triggers. This allows to study the angular distribution of light emission above the lightning.
In particular, the size of the central gap is related to electron speed in the lightning stroke.

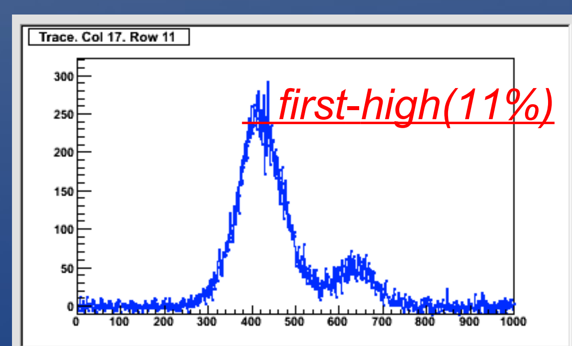
Double ELVES

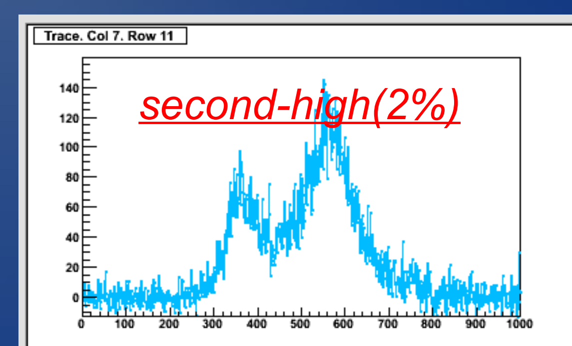




Not simply double return strokes
A rich variety of types, not completely understood. Simulations needed to compare with different models.





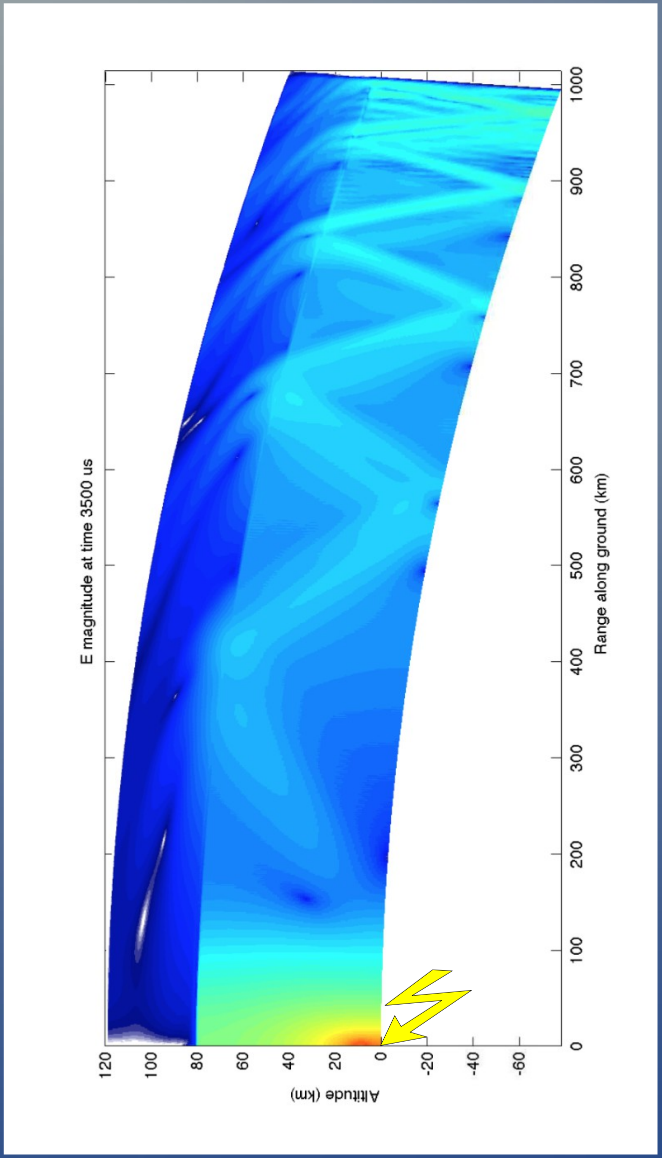


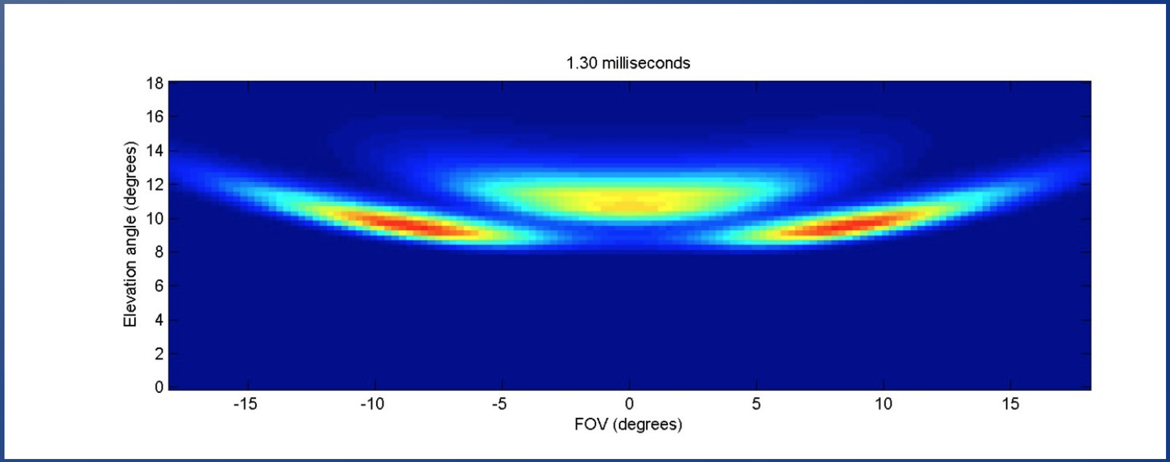
ELVES simulations

Lightning EMP model and interactions with Lower Ionosphere studied by the Stanford VLF Group

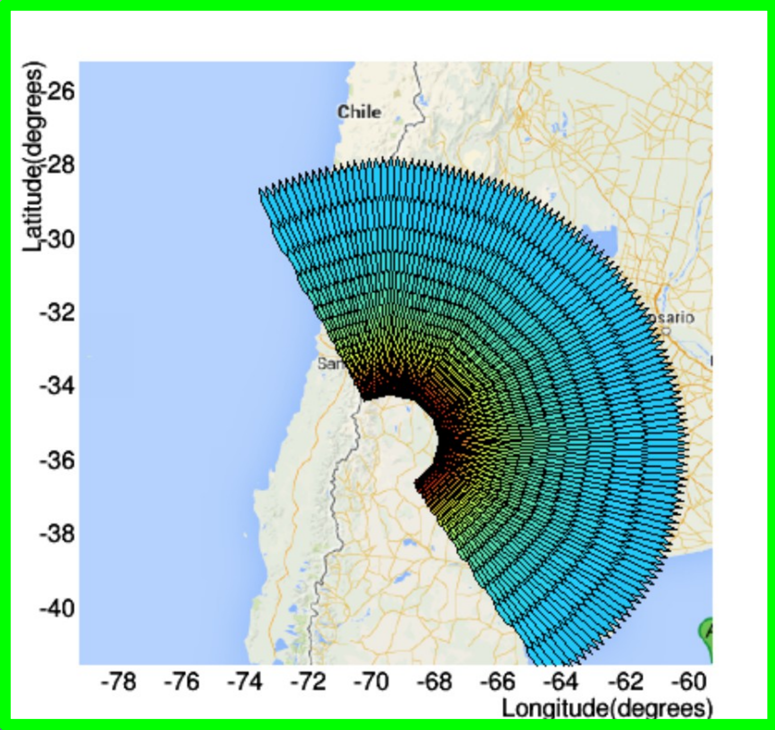
Finite element simulations of EM fields in atmosphere (from 70 to 150 km) to produce 2D and 3D models of light emission

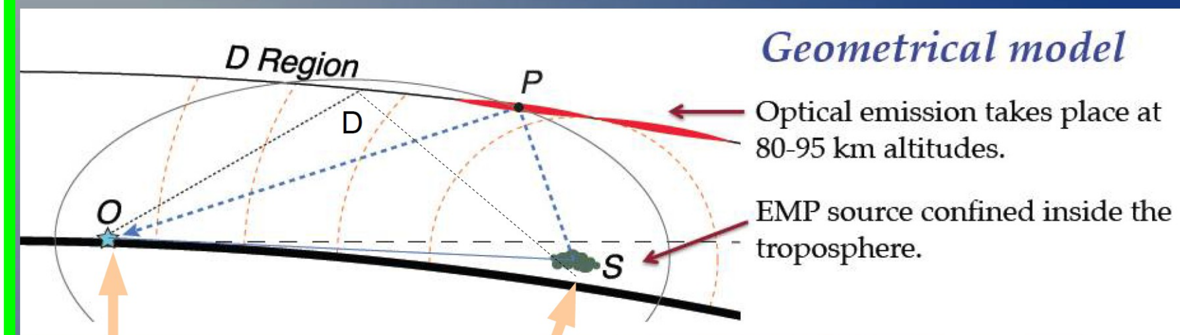
Matlab and C++ simulations by R.Marshall (now at U.Colorado, Denver)
- https://github.com/ram80unit/empmodel

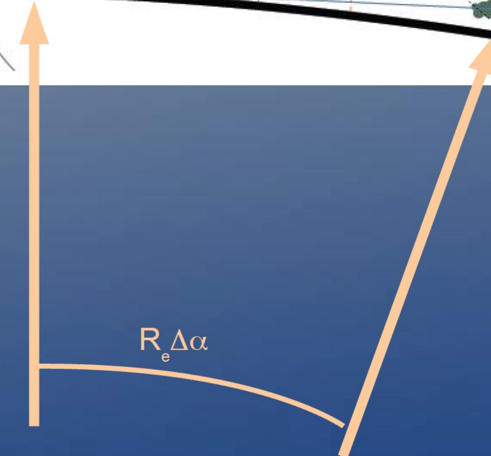




Light emission normalization







Distance of the lightning: $R_e\Delta\alpha$

$\Delta\alpha = \mathrm{acos}(K)$

$K = \cos(90\text{-}LAT_S)\cos(90\text{-}LAT_O)+\sin(90\text{-}LAT_S)\sin(90\text{-}LAT_O)\cos(LONG_S\text{-}LONG_O)$

Light path for the FIRST TRIGGERED PIXEL:

$\overline{ODS} = c\,(T_{FD}-T_{WWLLN})$

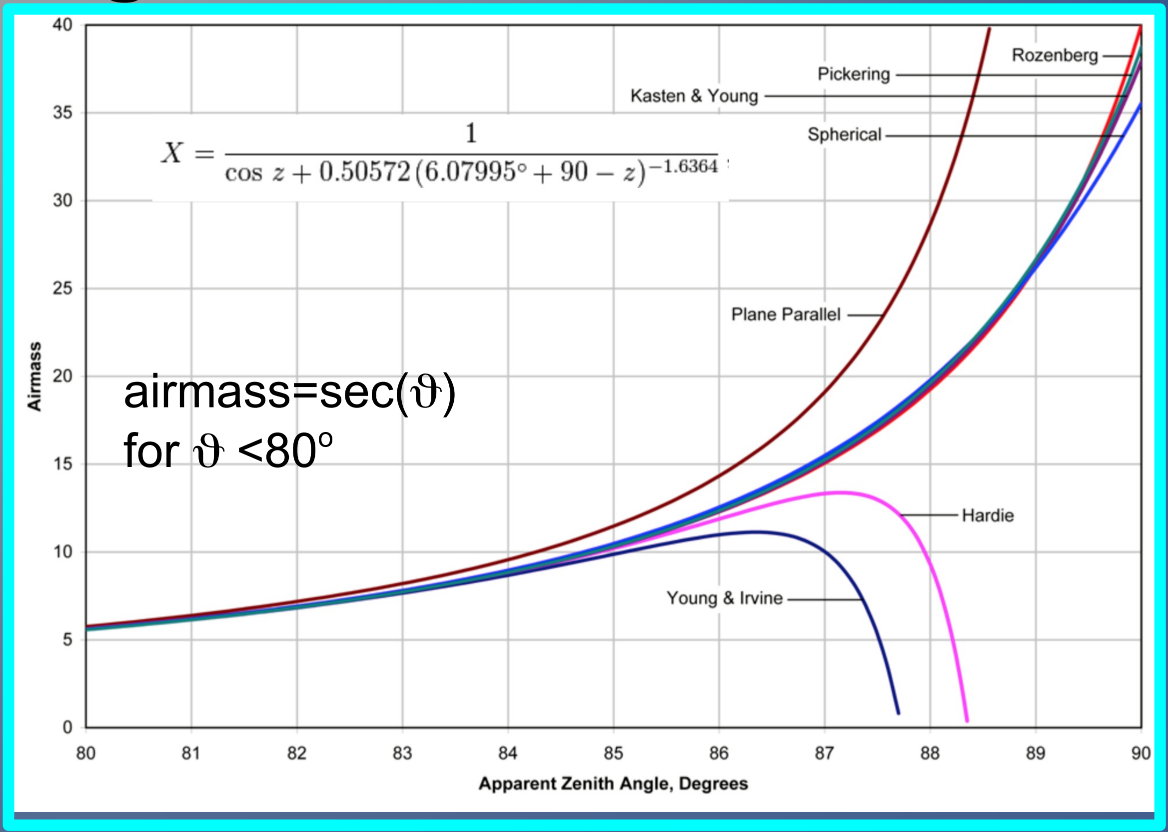
$\overline{OD} = \overline{OS} = \mathrm{sqrt}[R_e^2+(R_e+H_d)^2-2R_e(R_e+H_d)\cos(\Delta\alpha/2)]$

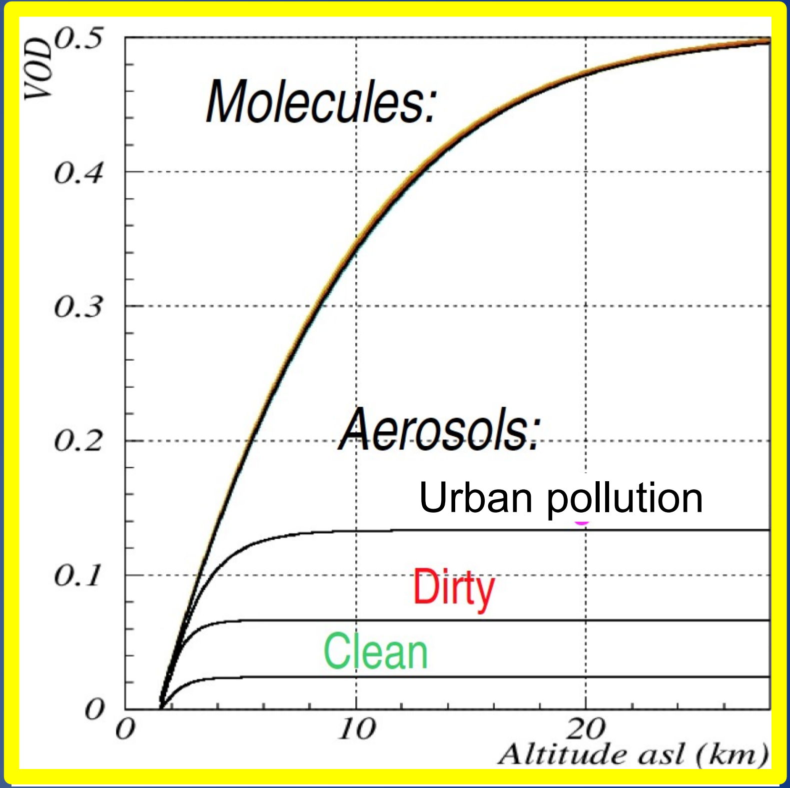
Photons detected by the FD camera are corrected for distance from the base of ionosphere (assumed at 85 km), and for the surface observed by each pixel.

$\Phi(i) = P_{FD}(i)$ *Geom_corr* Atmo_corr

Geom_corr = (R^2_{PO}/A_{mirror}) /Area($h=H_d$) ; Atmo_corr = $\exp((OD_{mol}+OD_{aer})^*\mathrm{airmass}(\theta))$

Light emission normalization





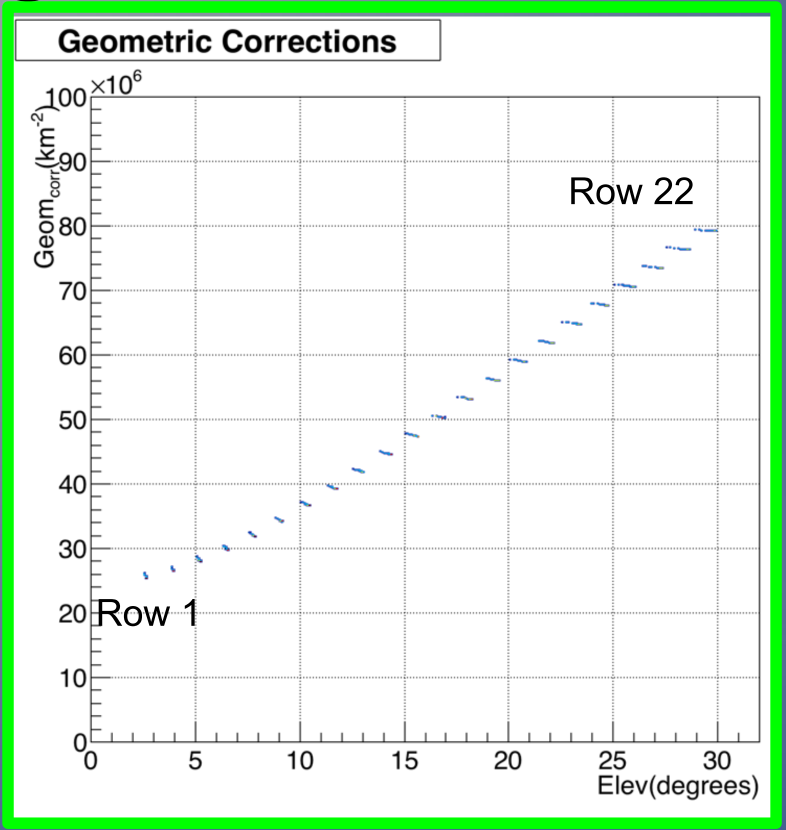
Photons detected by the FD camera are corrected for distance from the base of ionosphere (assumed at 85 km), and for the surface observed by each pixel.

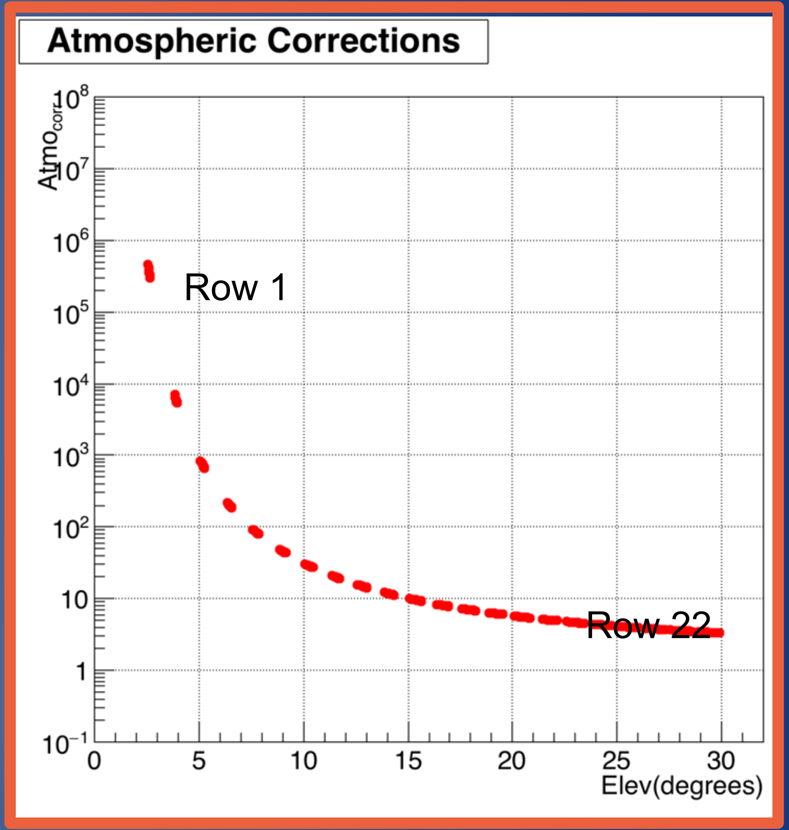
$$\Phi(i) = PFD(i) * Geom\_corr * Atmo\_corr$$

$$Geom\_corr = (R^2_{PO}/A_{mirror})\ Area(h=Hd) \quad ; \quad Atmo\_corr = \exp((OD_{mol}+OD_{aer})*airmass(\theta))$$

Atmospheric optical depth OD is calculated from Vertical Molecular (by weather stations, radiosondes, GDAS) and Aerosol profiles (hourly LIDAR measurements).
Airmass is calculated from *Kasten, F.; Young, A. T. (1989).. Applied Optics 28: 4735–4738*.

Light emission normalization





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Large Atmospheric corrections are optical depth OD is calculated from Vertical Molecular (by weather stations, radiosondes, GDAS) and Aerosol profiles (hourly LIDAR measurements).

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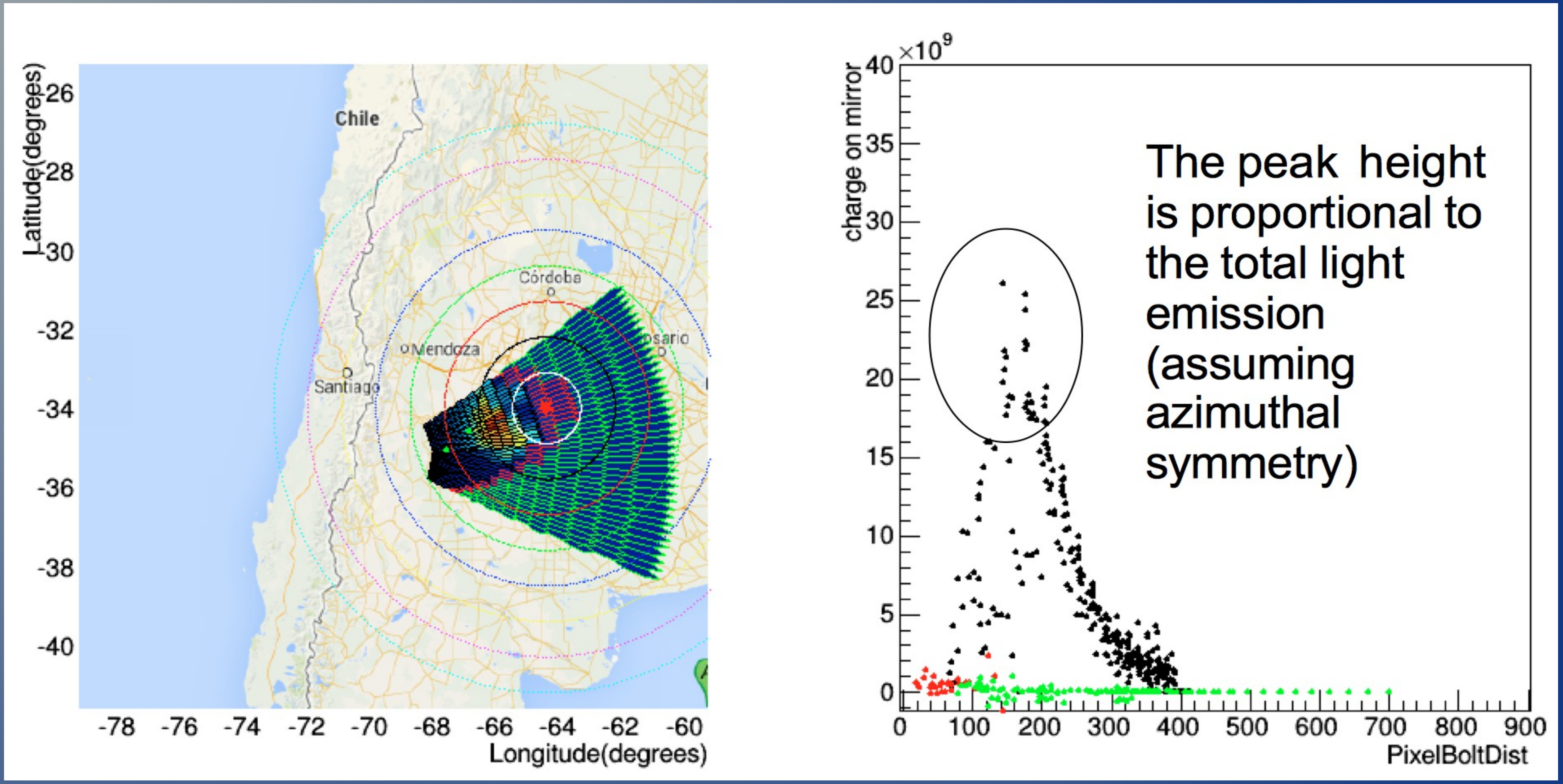
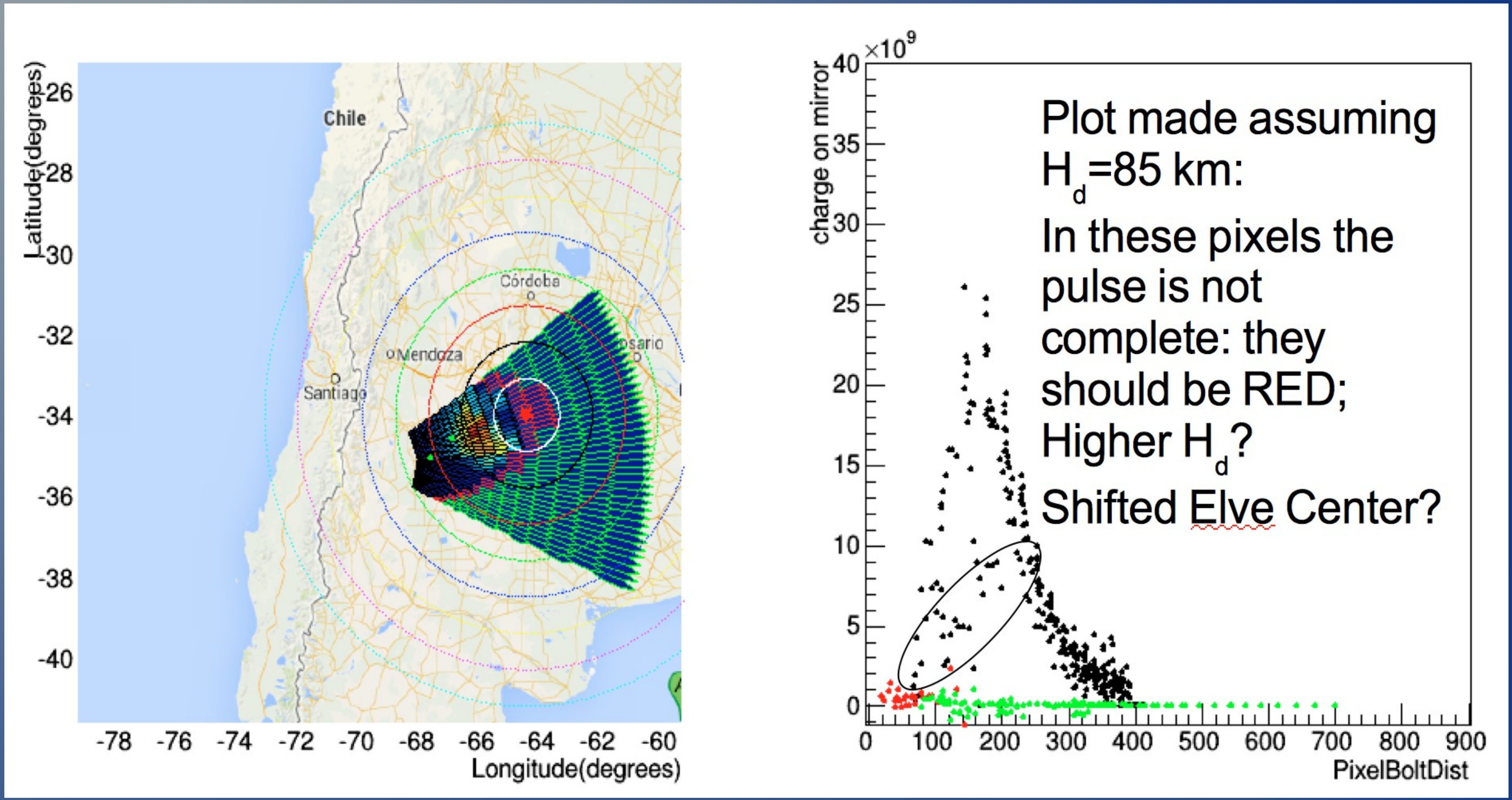
Corrected light emission versus distance from Lightning Strike



Red star: WWLLN bolt location
The colors indicate the ionospheric surface density of light emission
Circles at 100,...,800 km
Elve pulse containment: Full, Partial, Zero
In Green pixels the light emitted will arrive AFTER our time window (272 microseconds)

Corrected light emission versus distance from Lightning Strike



Red star: WWLLN bolt location
Circles at 100,...,800 km
Elve pulse containment: Full, Partial, Zero
In Green pixels the light emitted will arrive AFTER our time window (272 microseconds)

Events from large distance: Study of Stereo Events

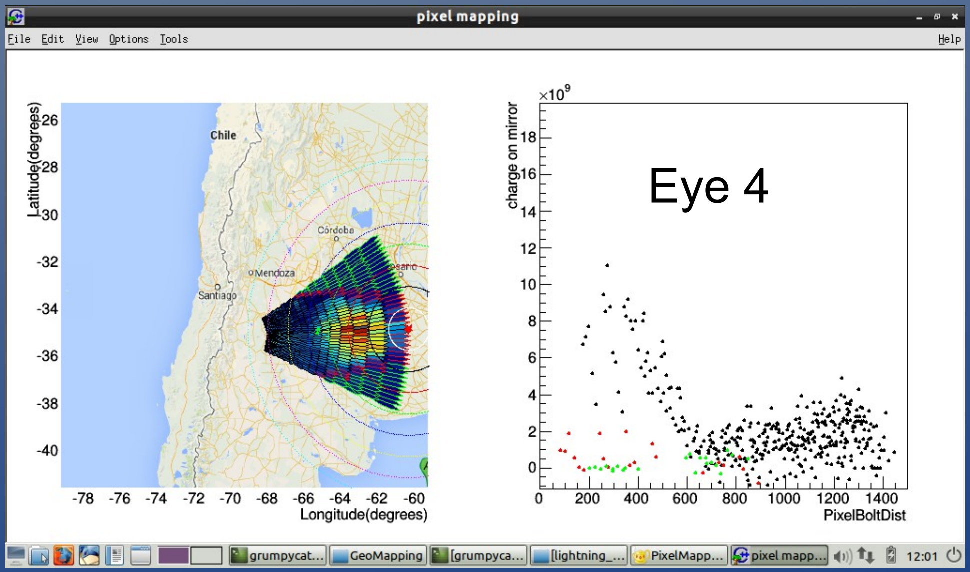
- Large atmospheric corrections are the biggest challenge for elves from far lightning

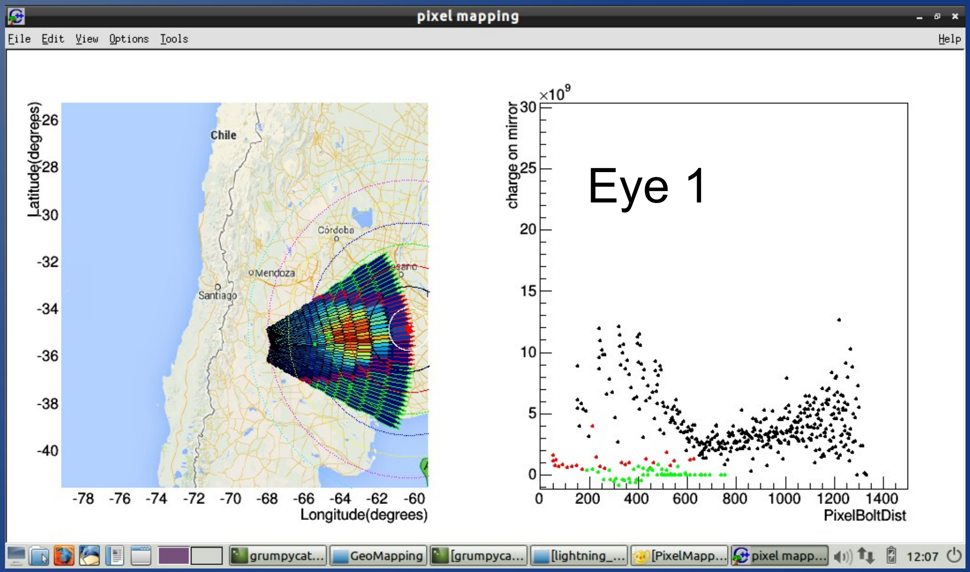
- WWLLN information is not needed to determine lightning location

- Normalization of light emission can be double checked

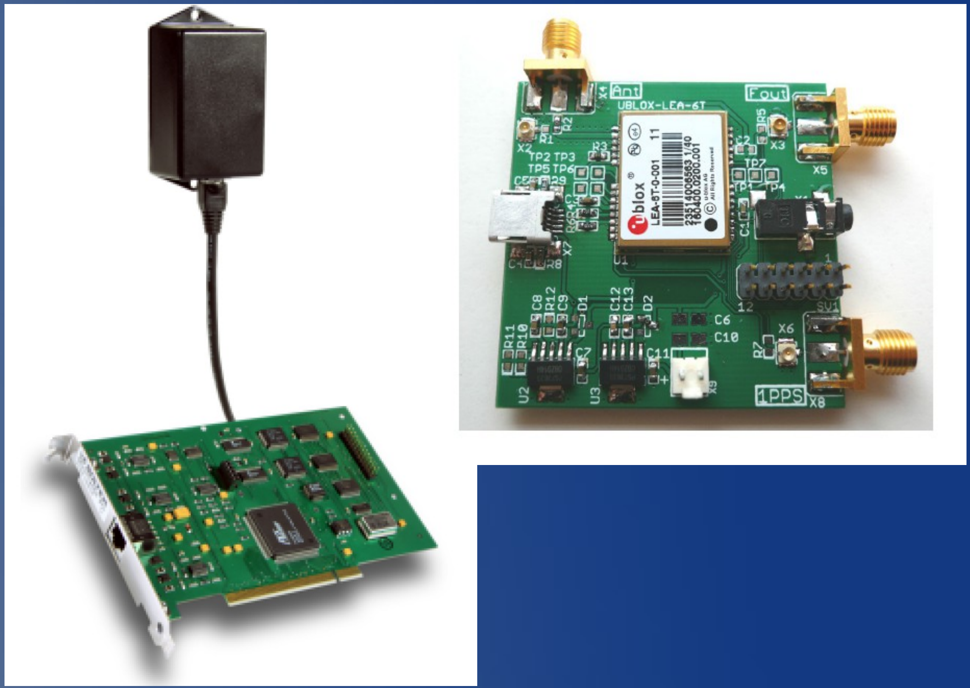
- We can do better studies of exotic behaviors, excluding local cloud effects

- We can improve time and space resolution using amplitude information





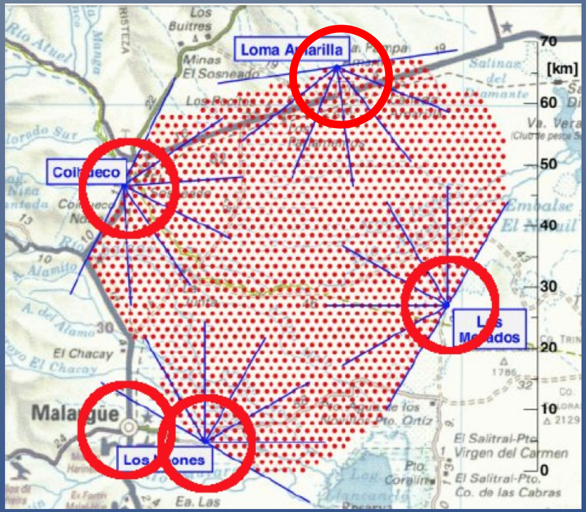
More instrumentation



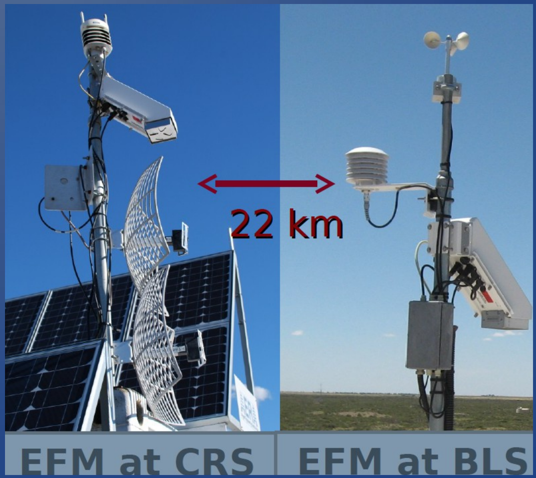
Recently installed on-site
(AERA group) :

- 5 Boltek Storm trackers with
 GPS antenna (30 ns resolution)
Range: up to 500 km

Locations:



- 2 E-field mills
Campbell Scientific CS110



Summary and prospects

Since 2013, Auger Observatory has a very intense program of studies on ELVES using the Fluorescence detector. Since 2014, more than 1.2 k events have been acquired in extended readout mode, to record light up to 272 us after its first appearance

A special trigger allows to extend the standard traces, in order to study the light emission from the vertical above the lightning , where we expect to see a decrease in light intensity.

After performing Geometry and Atmospheric corrections we can compare our results with WWLLN measurement of lightning Energy to check correlations with light emission

The Auger Observatory is currently being upgraded to continue operations until 2023.
A proposal is under way to extend operations through the whole moon cycle, with reduced PMT gain, which will allow to double ELVES statistic per year.

A public web page with all elves data is in preparation at INFN Torino

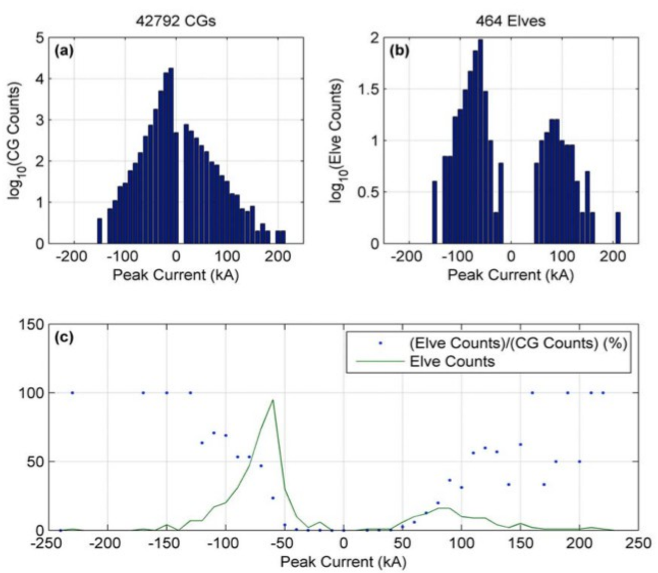
More ionospheric studies are ongoing at the Observatory: stay tuned!

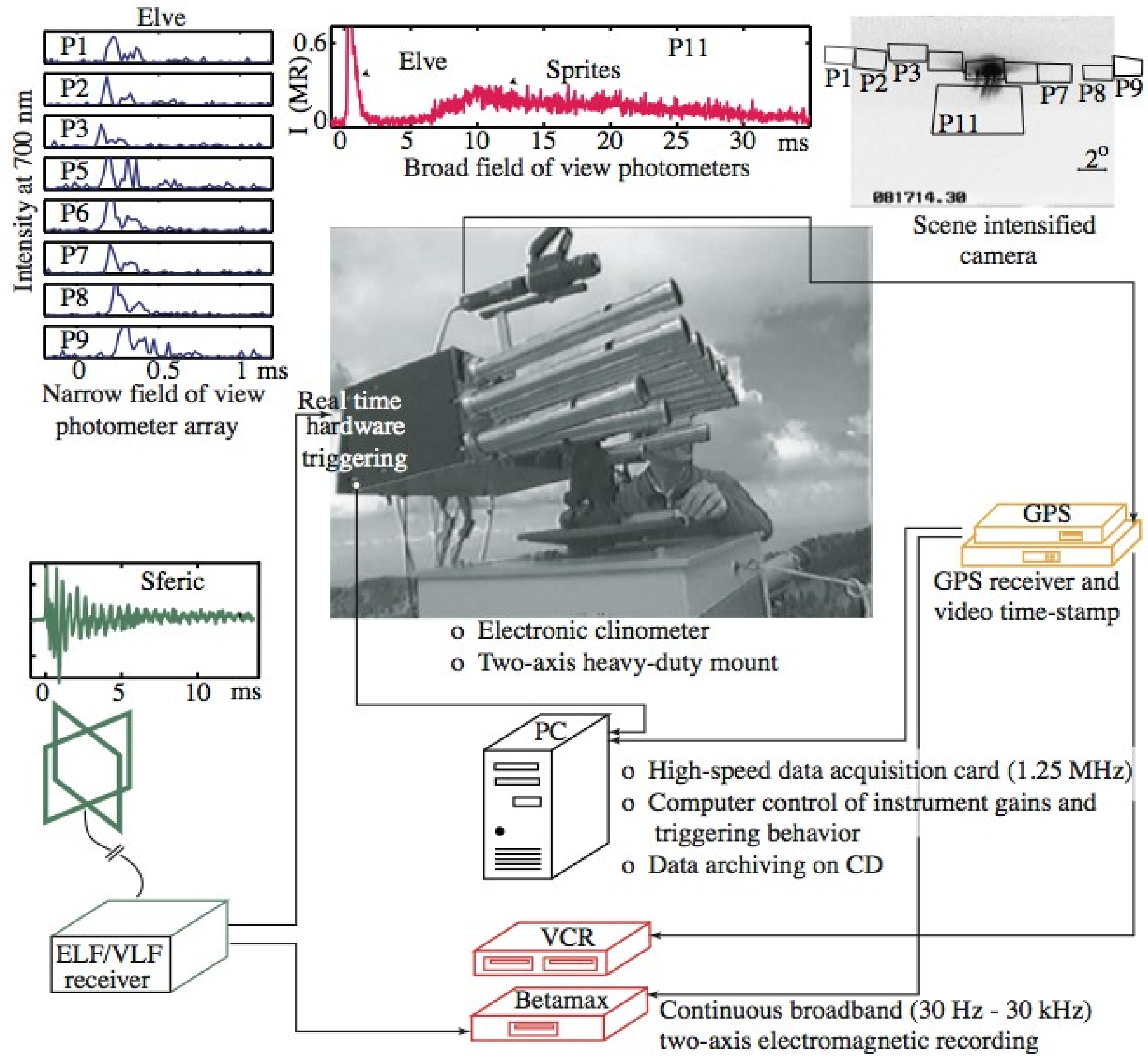

Thank you!

Ground based ELVES studies

Theoretically predicted by Unran Inan (Stanford's VLF group) in late 80's.
ELVES: Emissions of Light and Very low frequency perturbations due to Electromagnetic pulse Sources

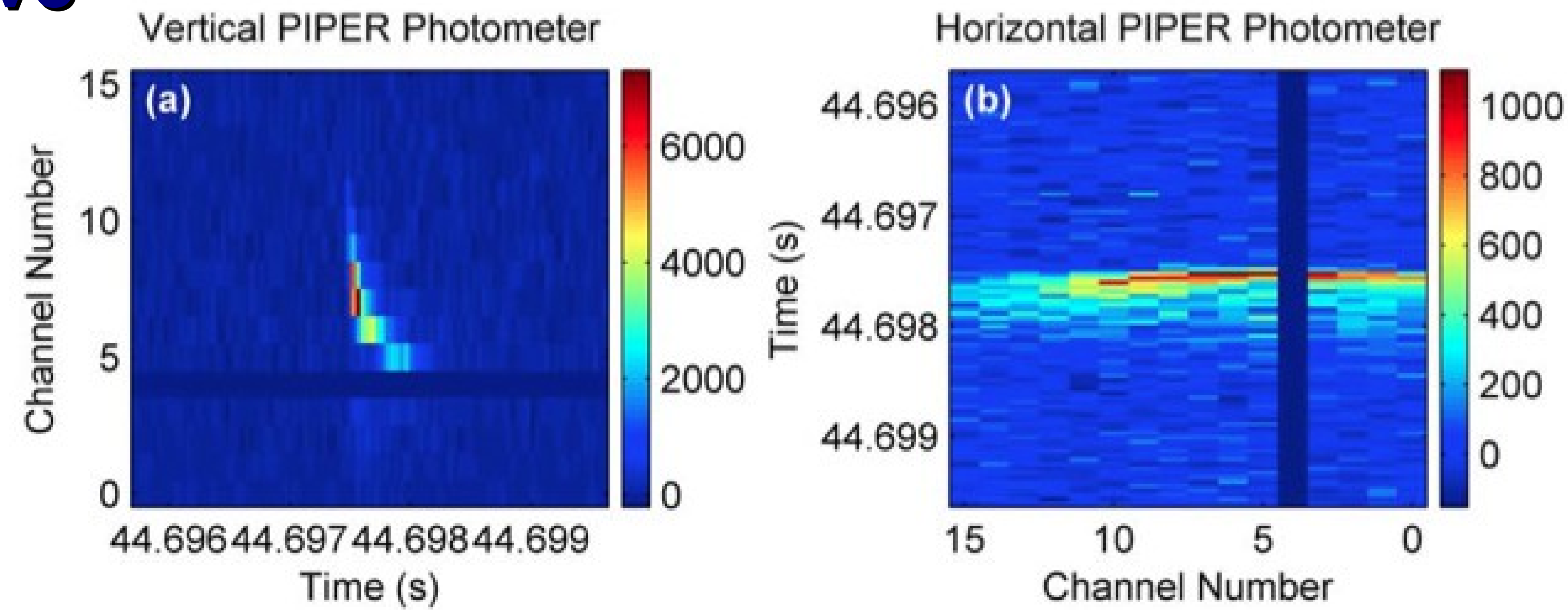
References:
- U.S. Inan, T.F. Bell, J.V. Rodriguez, Geophys. Res. Lett. 18, 705 (1991).
- U.S. Inan et al., Geophys. Res. Lett. 24, 583 (1997).
- R.T. Newsome, U.T. Inan, J. Geophys. Res. 115, A00E41 (2010).



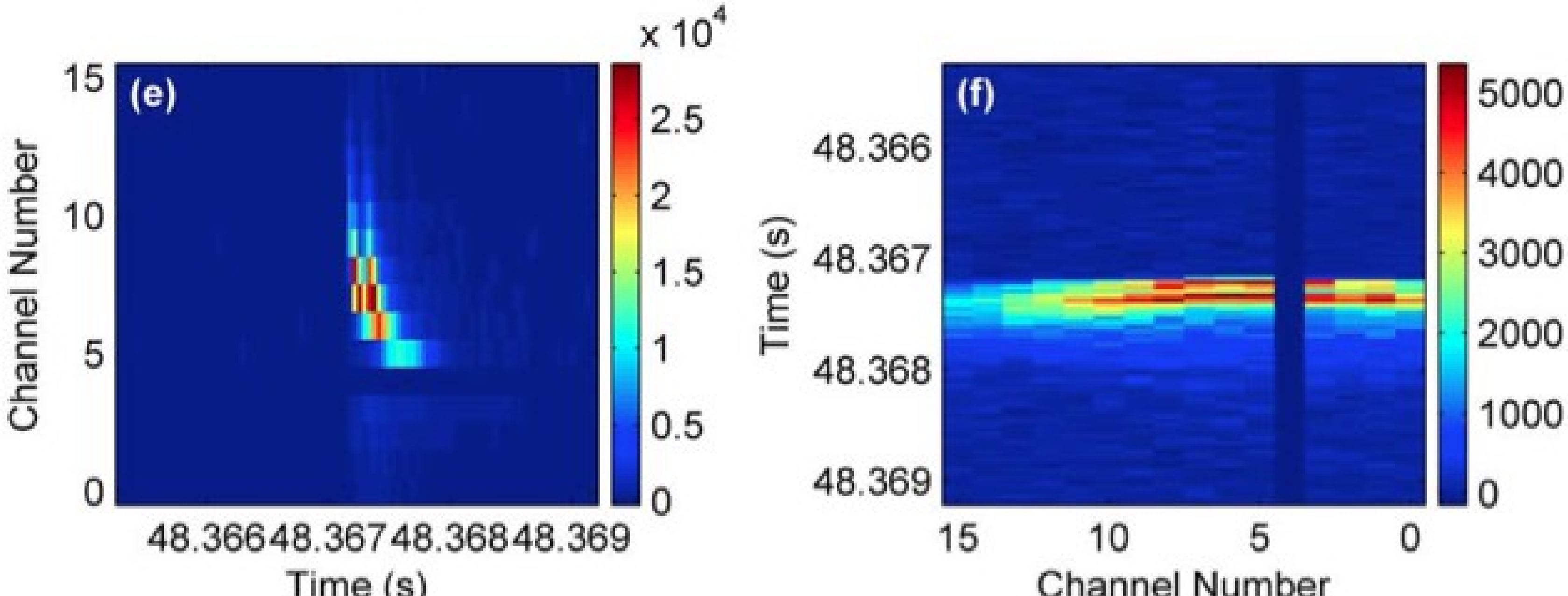


Detectors: FLY'S EYE, PIPER
- Linear arrays: 16 vert pixels +16 horiz pixels
- Time resolution: 40 microseconds

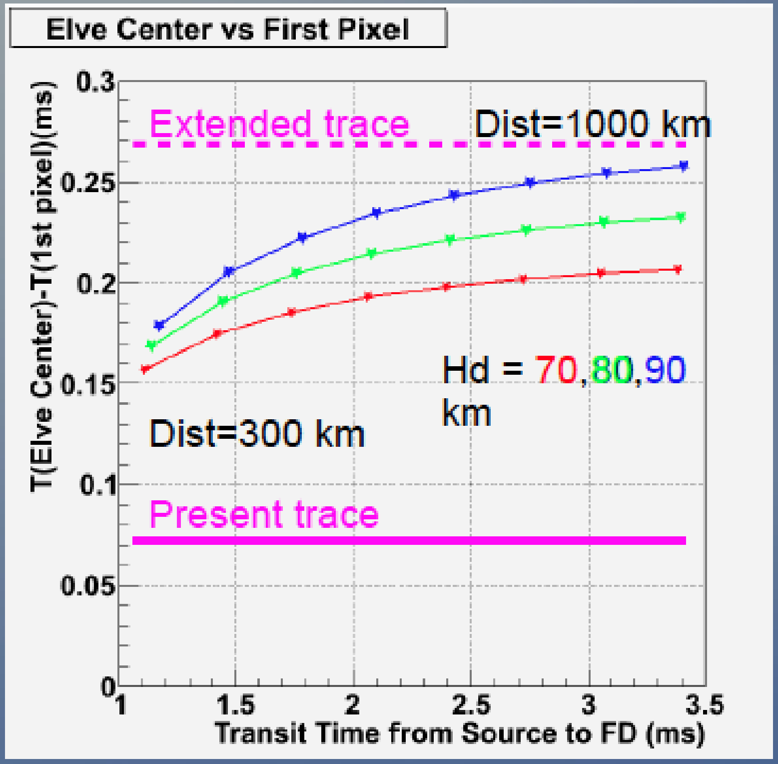
Std Elve

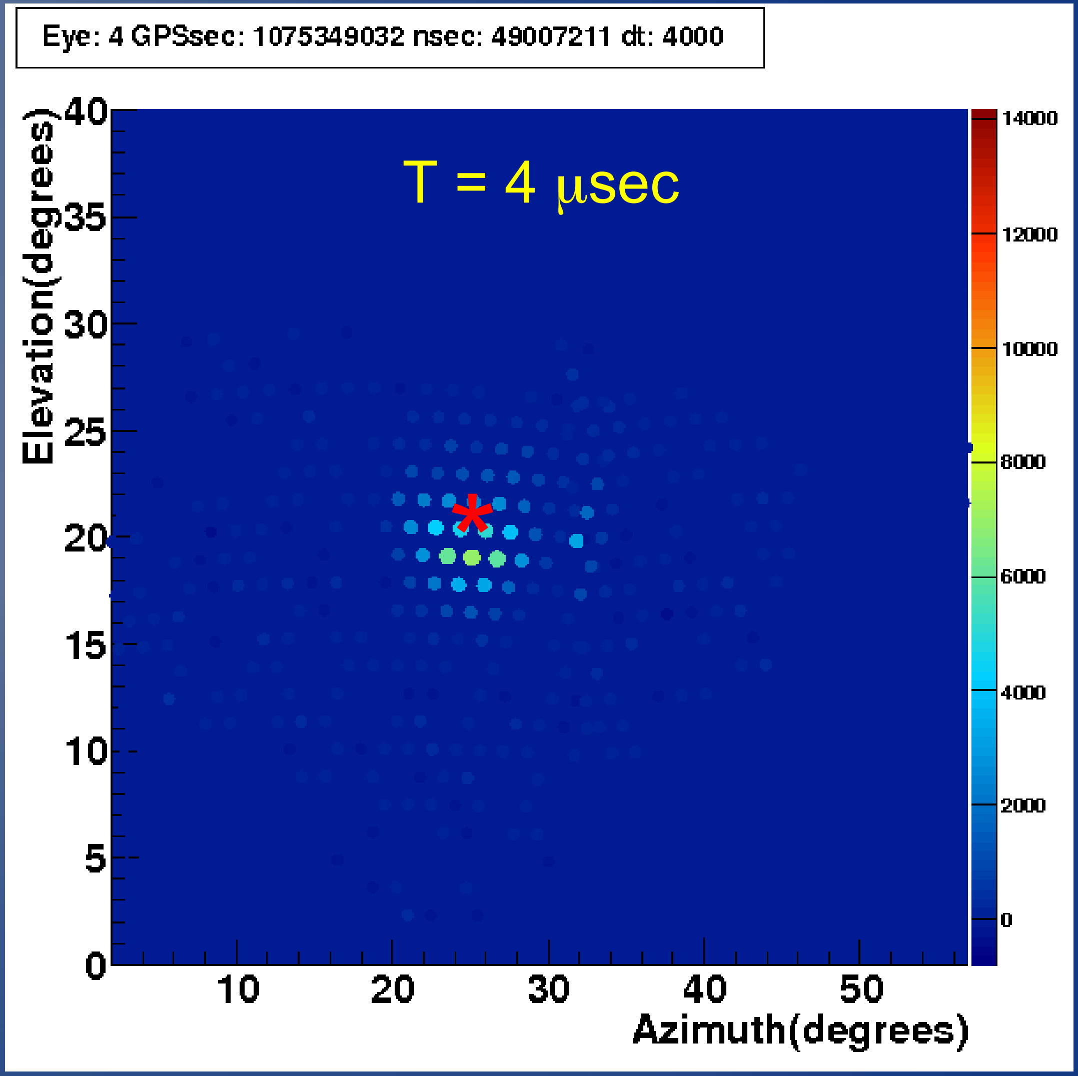


Double Elve



Extended readout

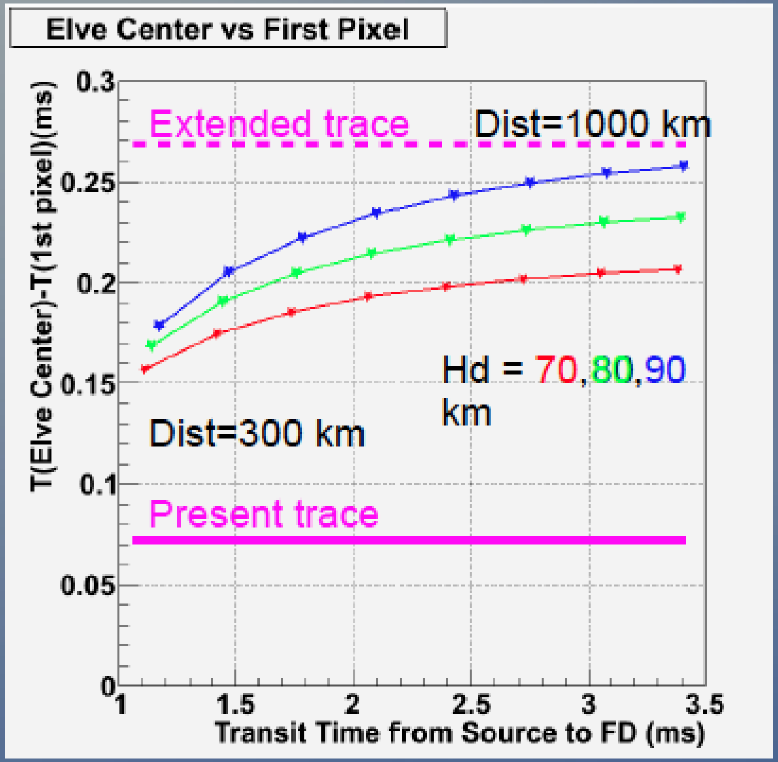


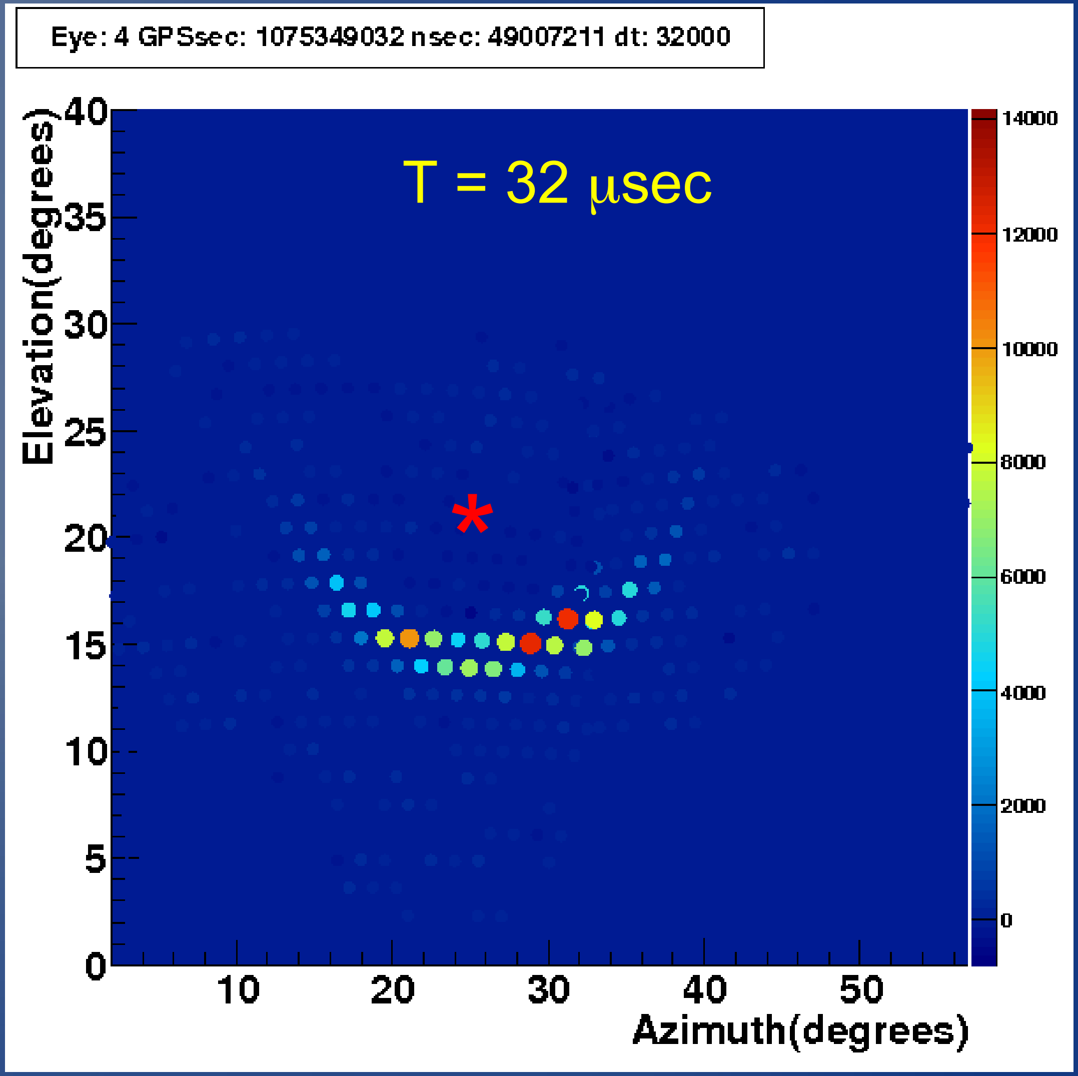


	Total	OK	1	2
LL	334	276	39	19
LM	32	21	6	5(0)
LA	145	125	11	9(3)
CO	307	224	49	34(25)

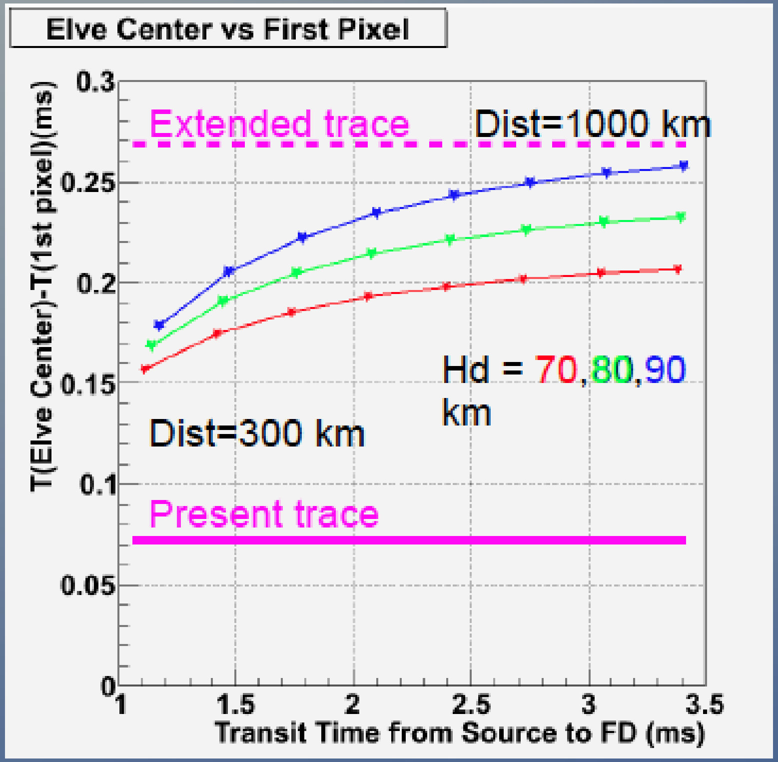
790 total records, 145 (18%) have only 1 or 0 followers

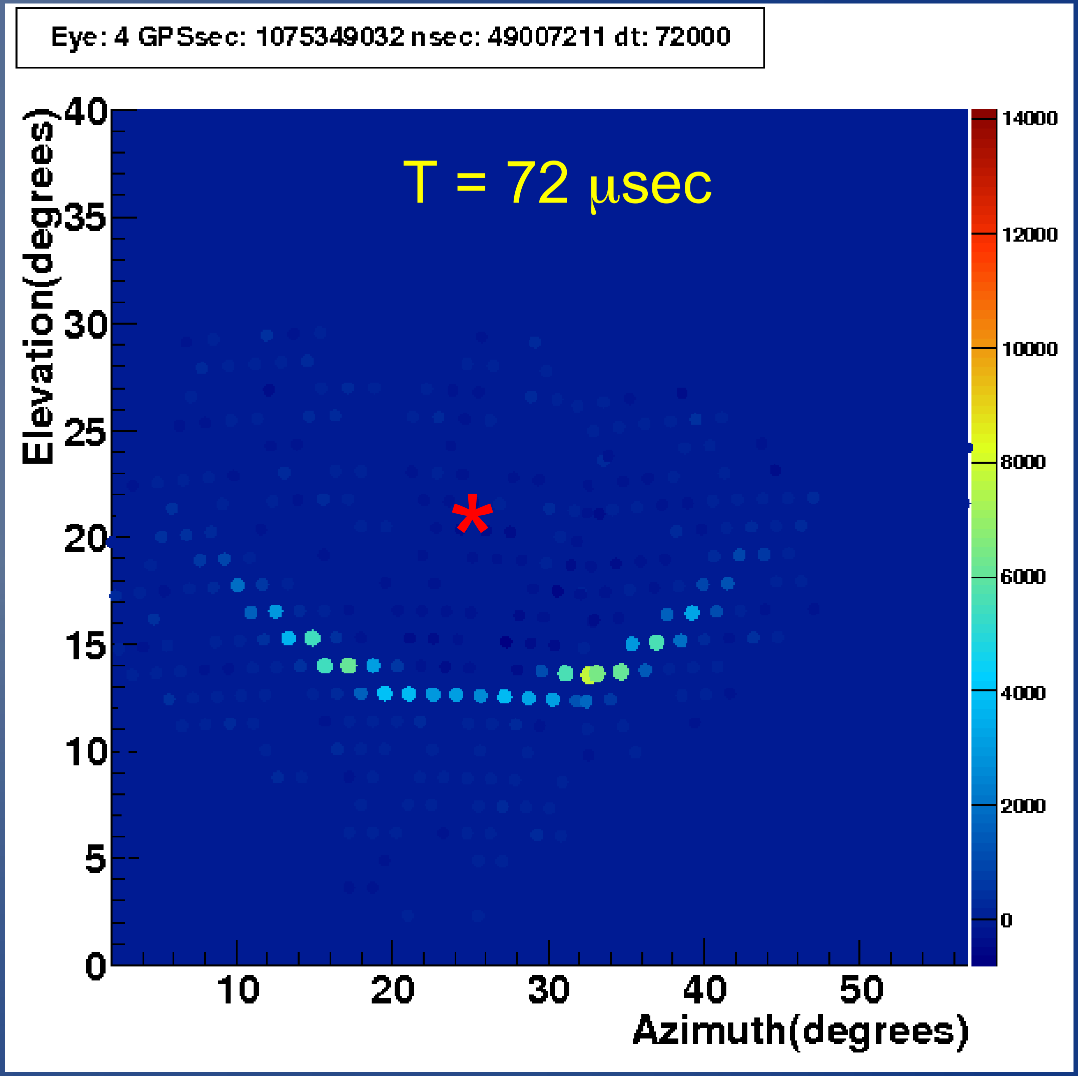
Extended readout



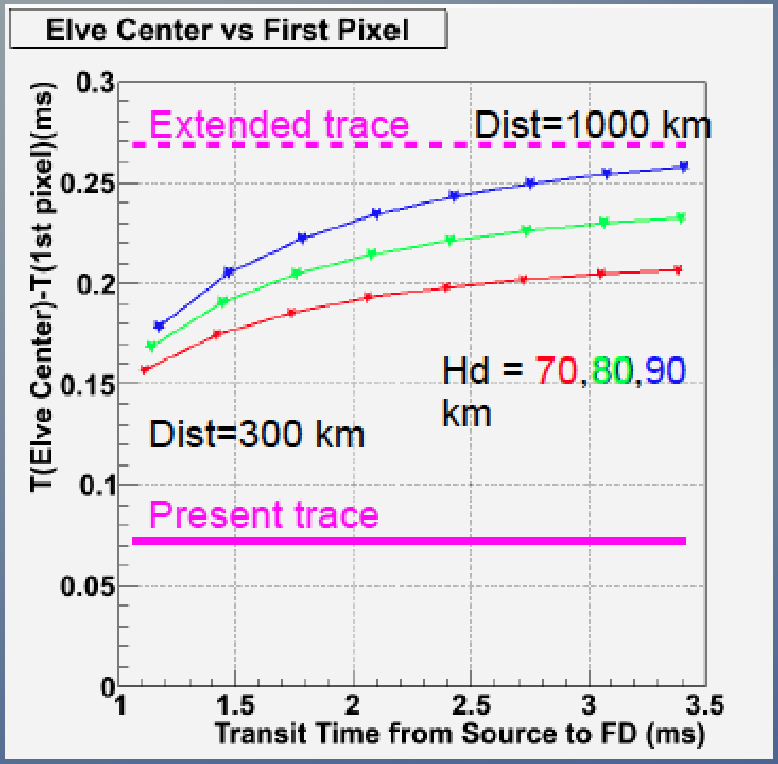


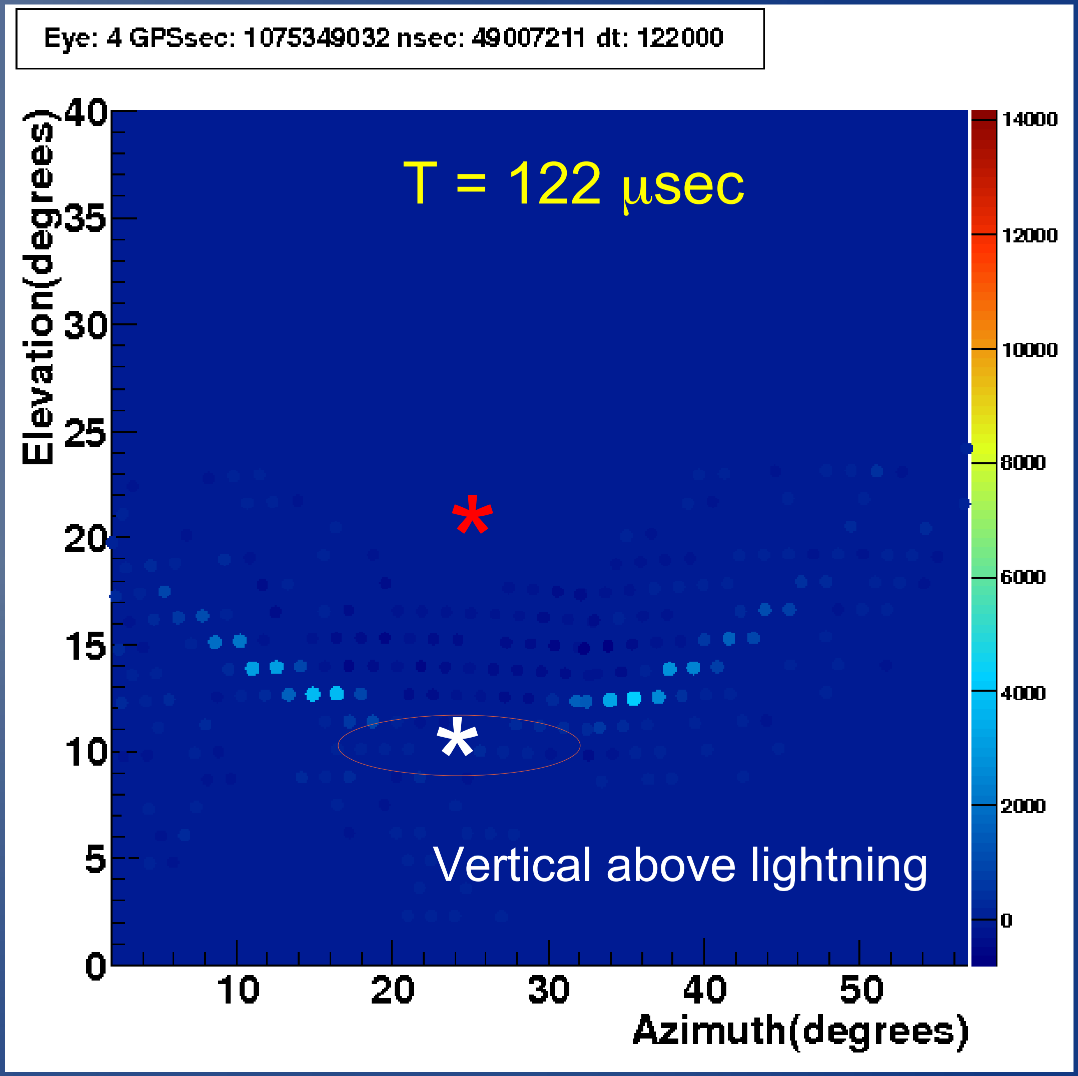
Extended readout





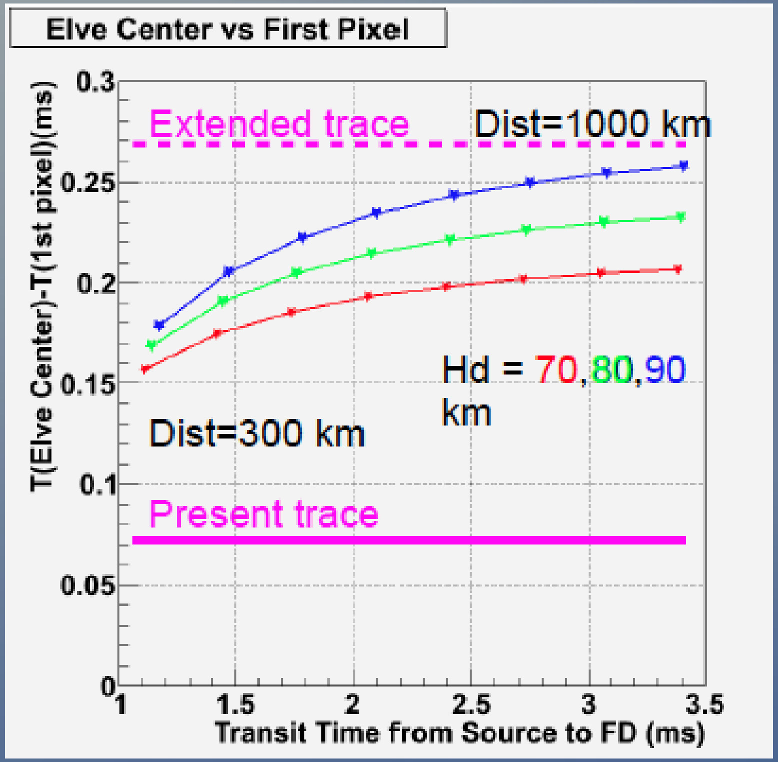
Extended readout

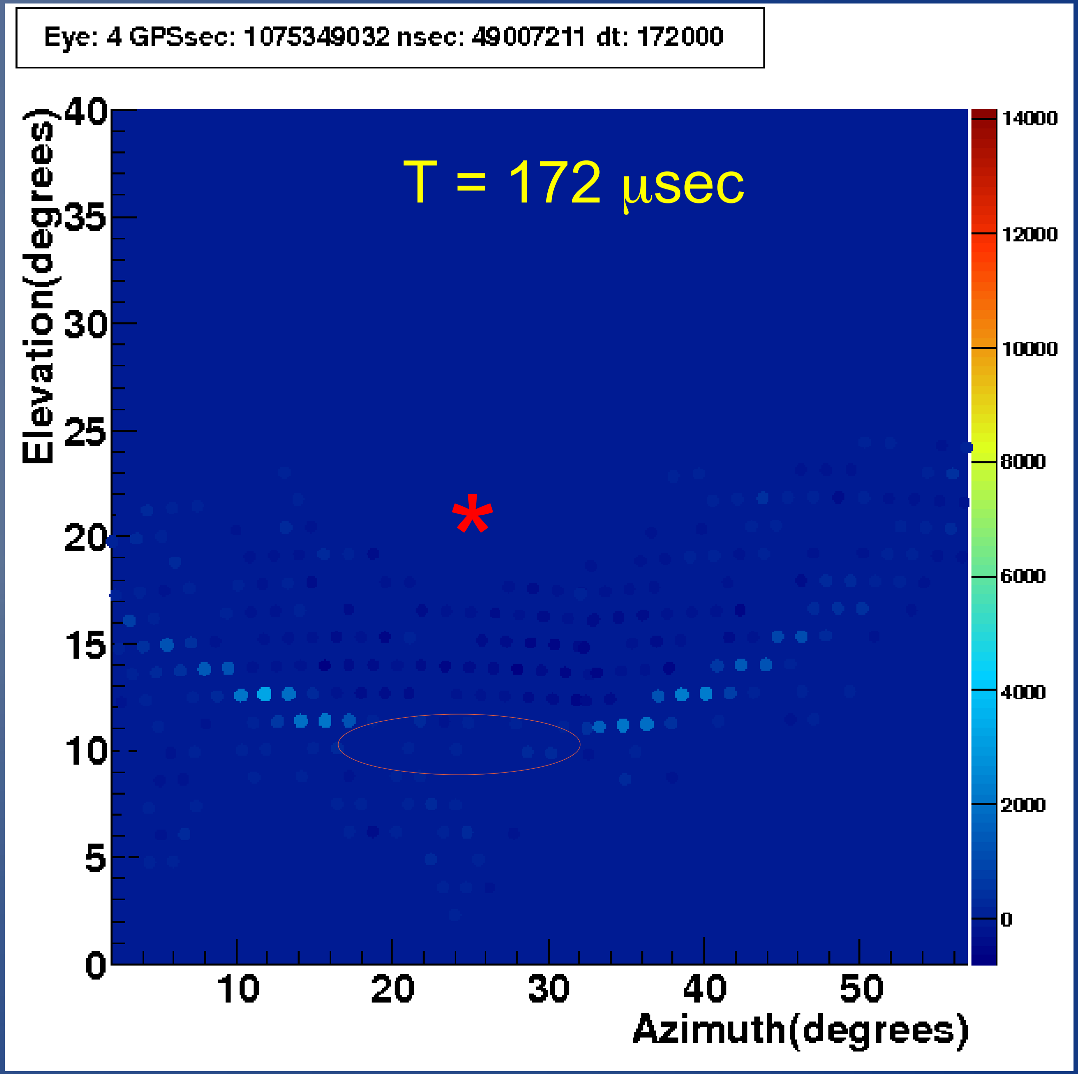




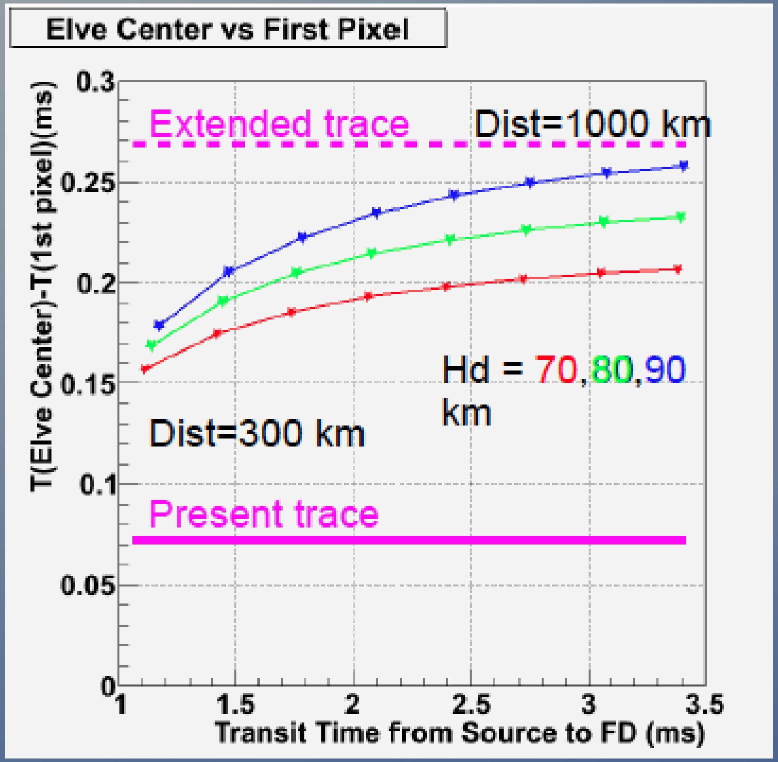
Here we start seeing the vertical above the lightning

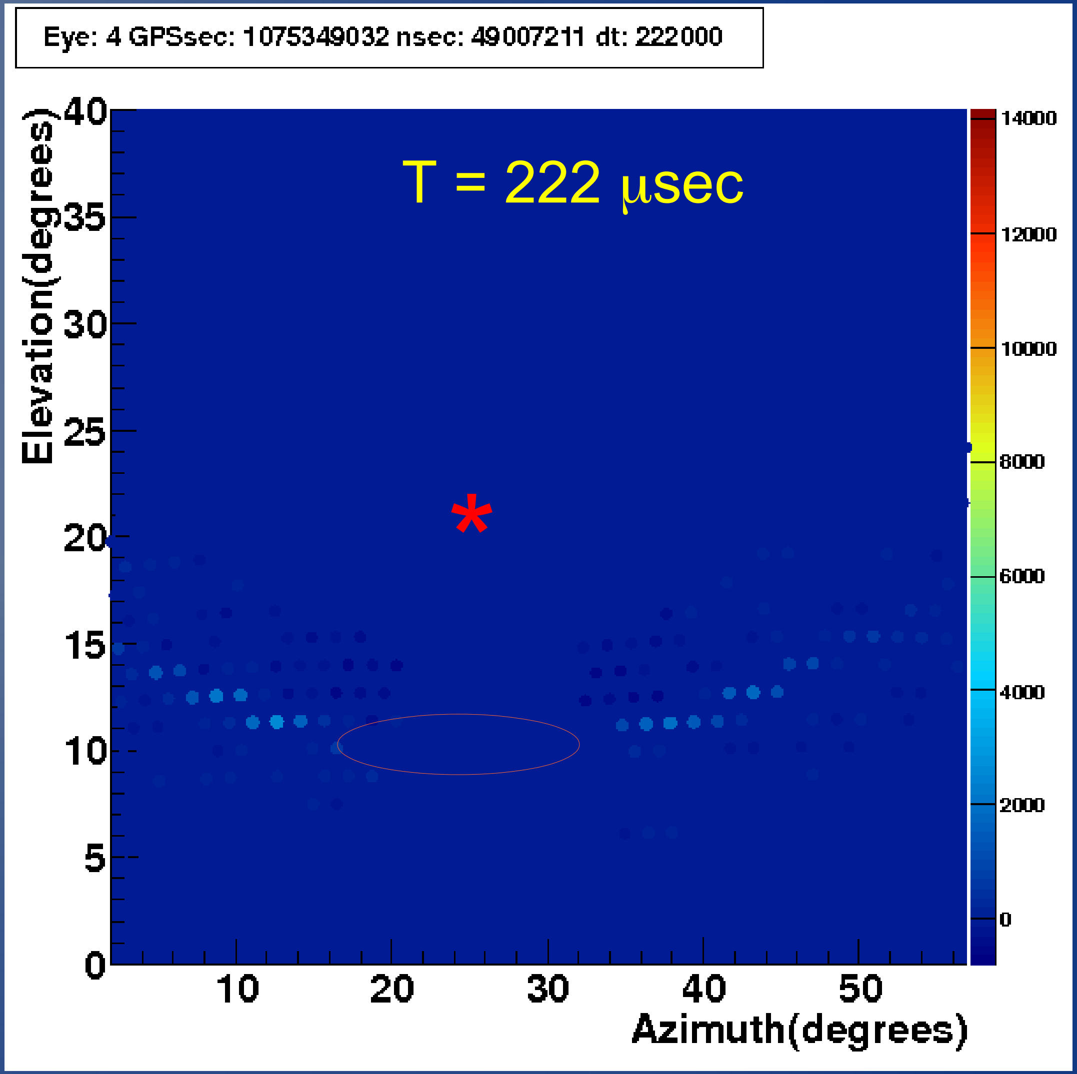
Extended readout





Extended readout





Extended readout