

Atmospheric Monitoring Systems for the AUGER Observatory

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III School on Cosmic Rays and Astrophysics
Arequipa - 9/2008

Cloud Detection in FD data

- The principle:
 - The variance of FD pedestals can be used to measure the photon flux in each pixel
- The goal:
 - Derive cloud coverage information from variance data
- The advantages:
 - no transformation needed from another pixel space.
 - Background data and FD data almost completely overlap in time coverage.
- The disadvantages:
 - Understanding background data is not at all trivial

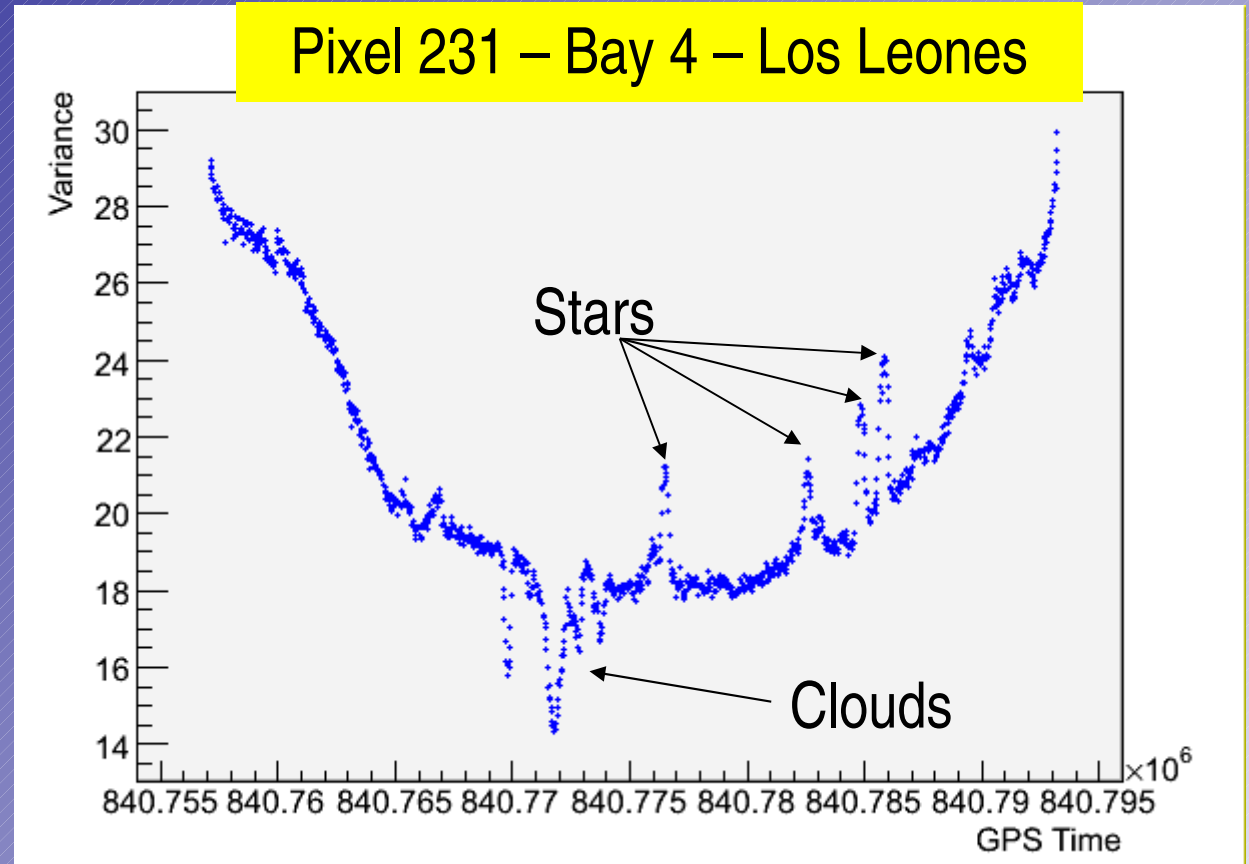
Sky background from 1 FD pixel

Stars are easily visible as peaks

Smooth background due to many sources:

- Milky Way
- Moonlight (Rayleigh)
- AirGlow (hard to model)

Clouds are identified as dips in sky background, but can have smooth edges and can even reflect light from the moon.



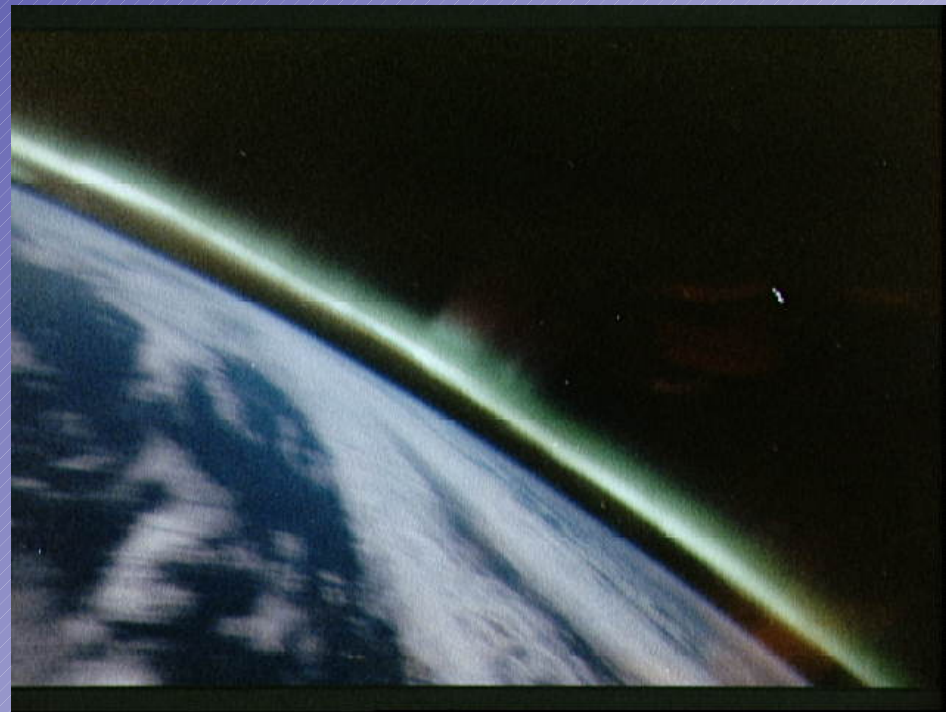
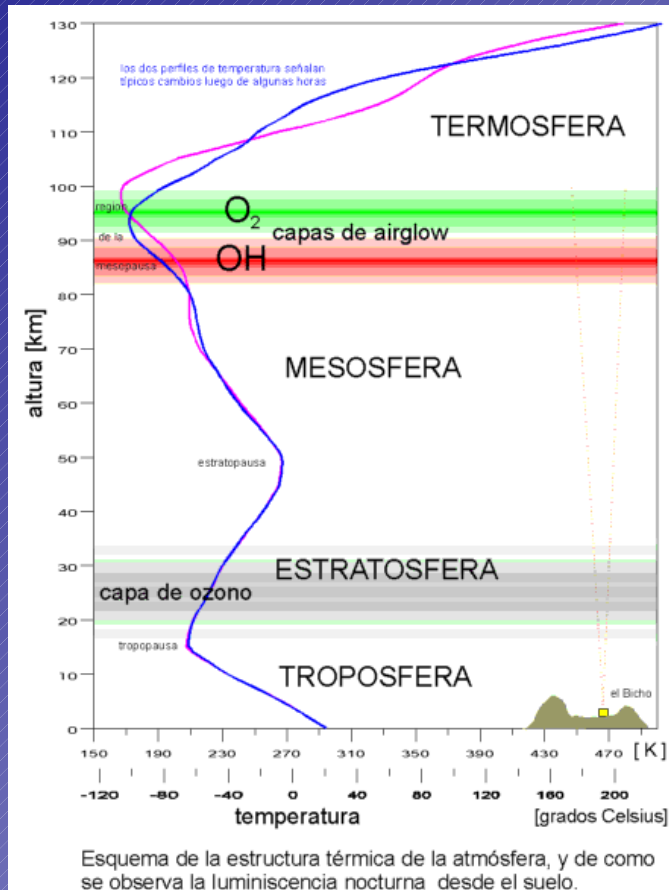
← one night →

Air Glow

Solar radiation dissociates N_2 , O_2 , O_3 , H_2O , N_2 in atoms N , O , OH , H or ions O^{2+} , N^{2+} , O^+ , N^+

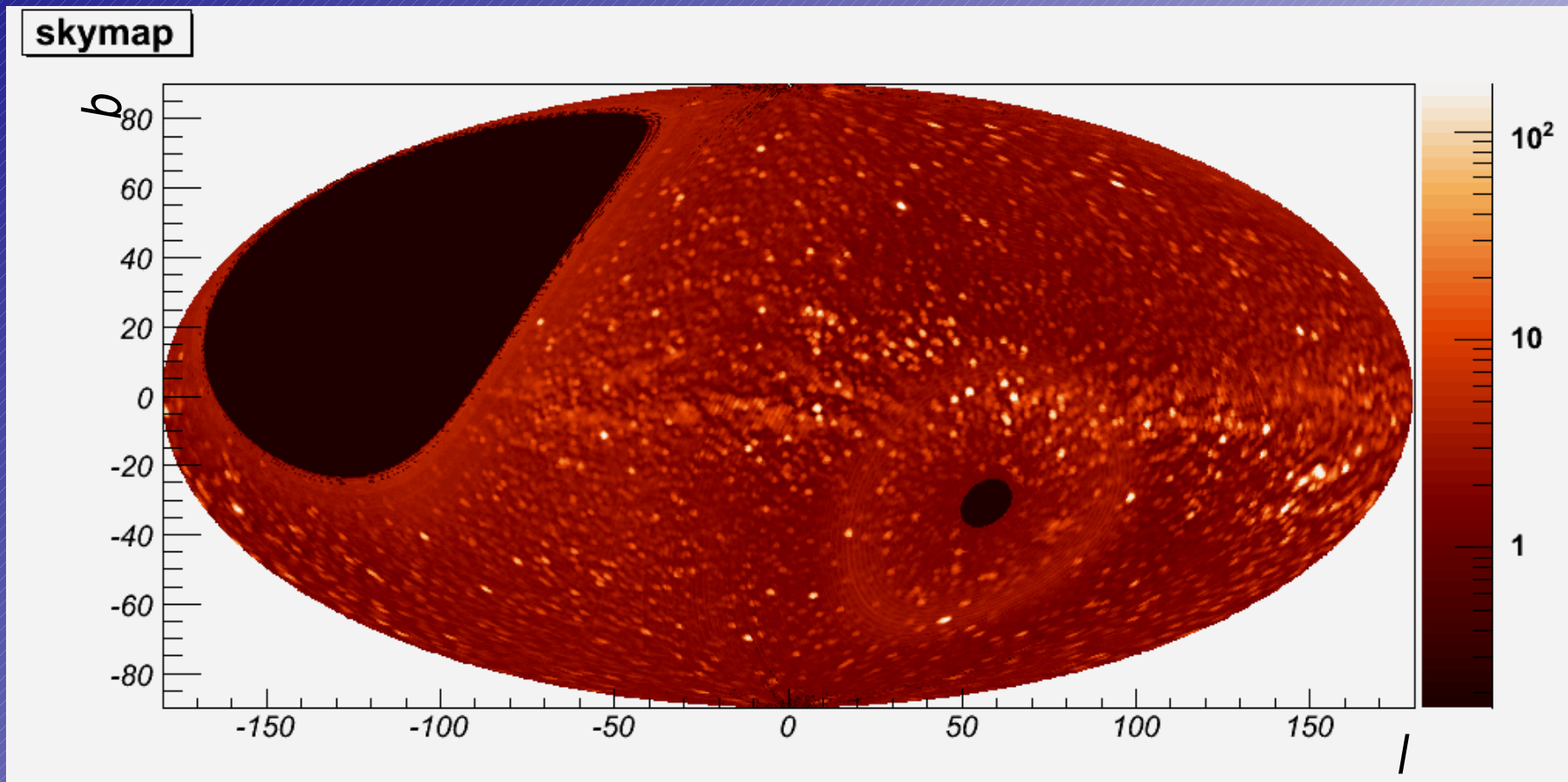
About 100 km in altitude the following reactions occur:

- $H + O_3 \rightarrow OH + O_2 + \gamma$
- $O + O + X \rightarrow X + O_2 + \gamma$ (in presence of a third body X)



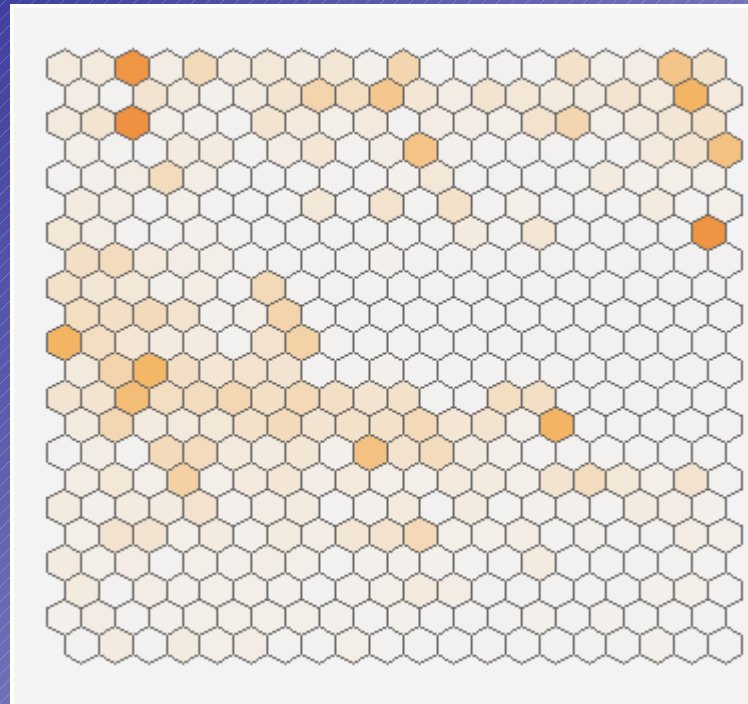
Full sky map from FD pedestals

Transform each pixel from local to galactic coordinates
Integrate over long period of time
Correct for different exposures of each pixel

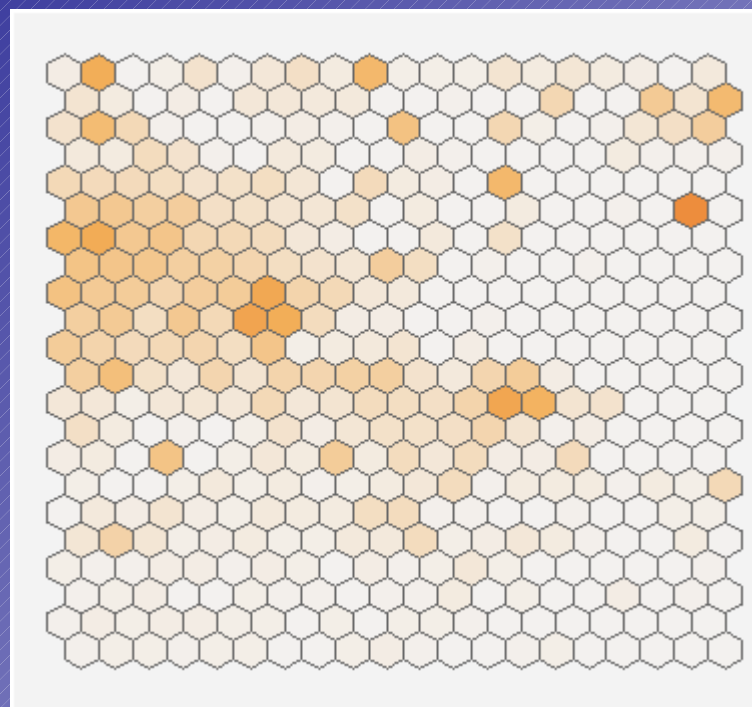


Galactic coordinates

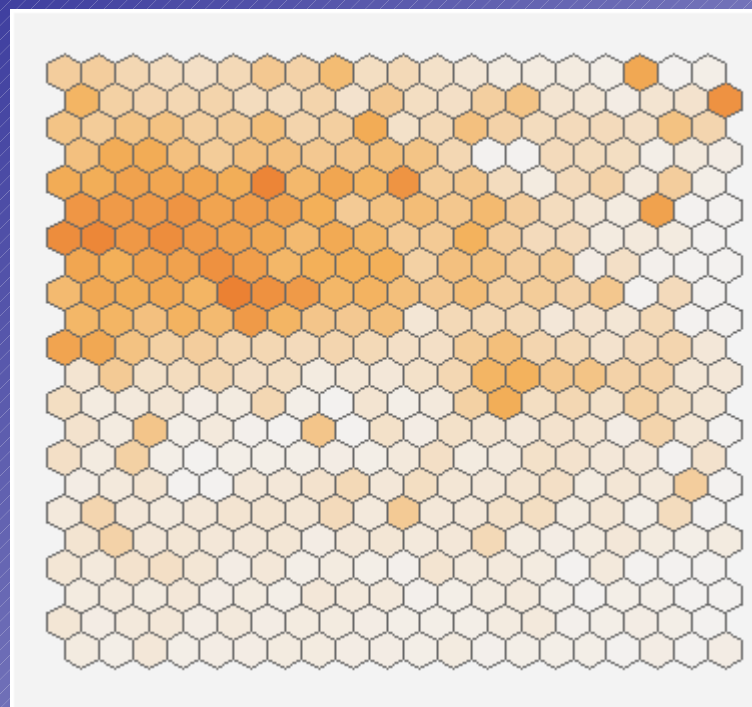
Background Sky variance: frame 1/7



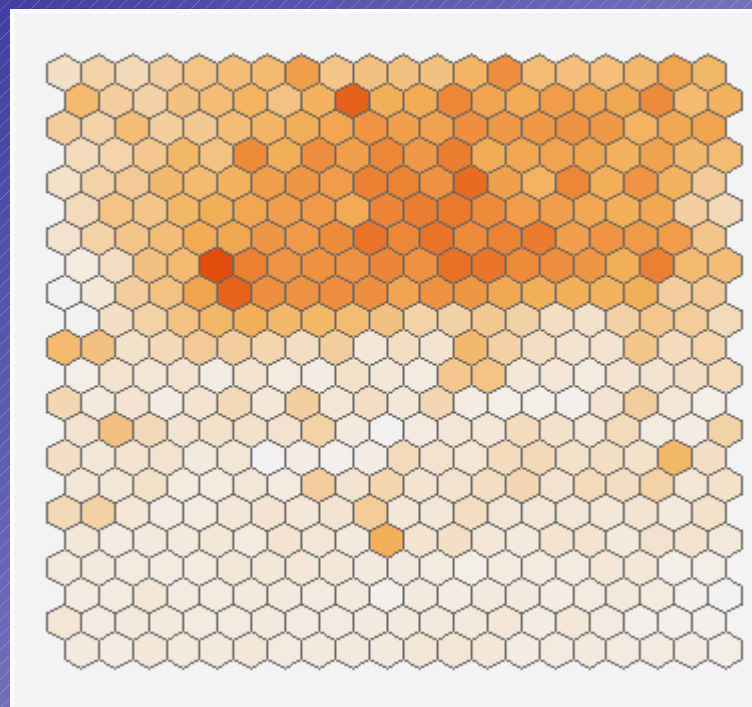
Background Sky variance: frame 2/7



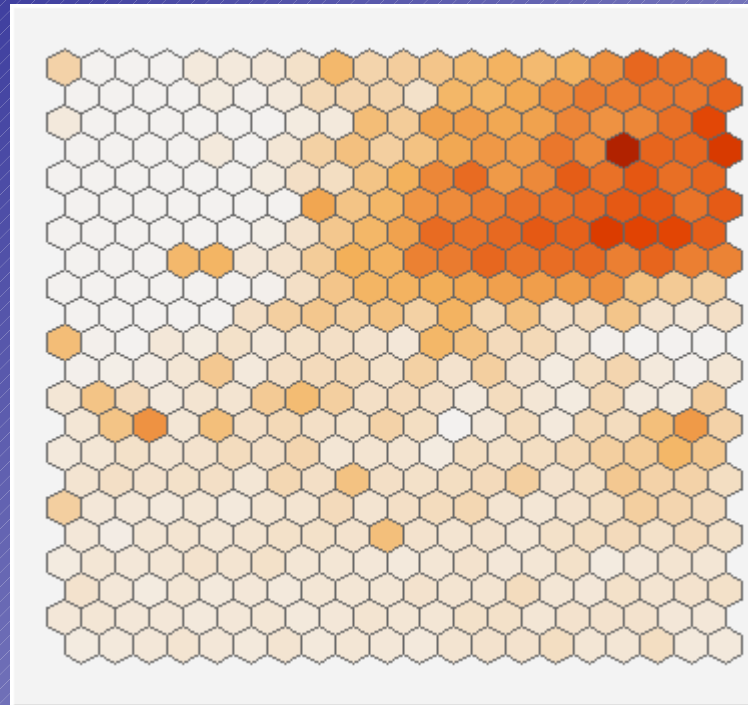
Background Sky variance: frame 3/7



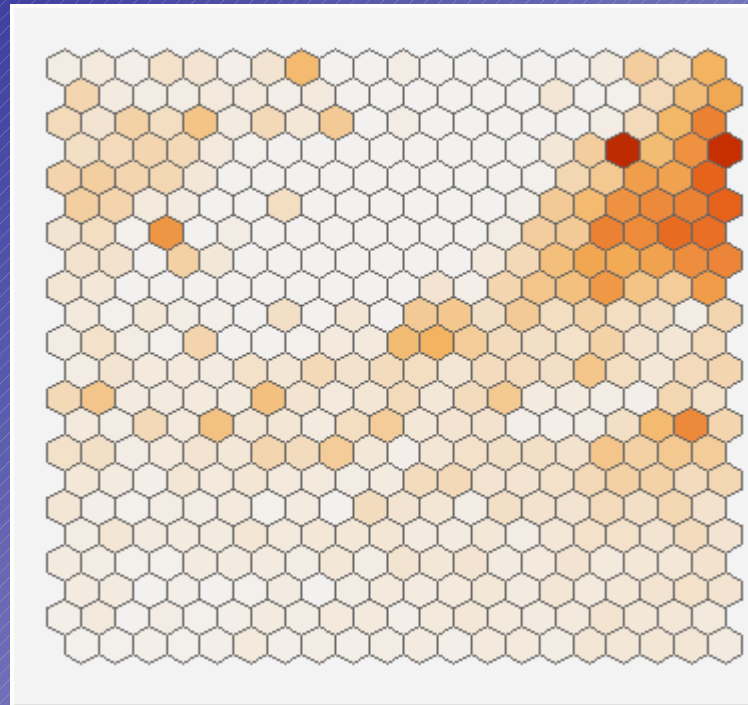
Background Sky variance: frame 4/7



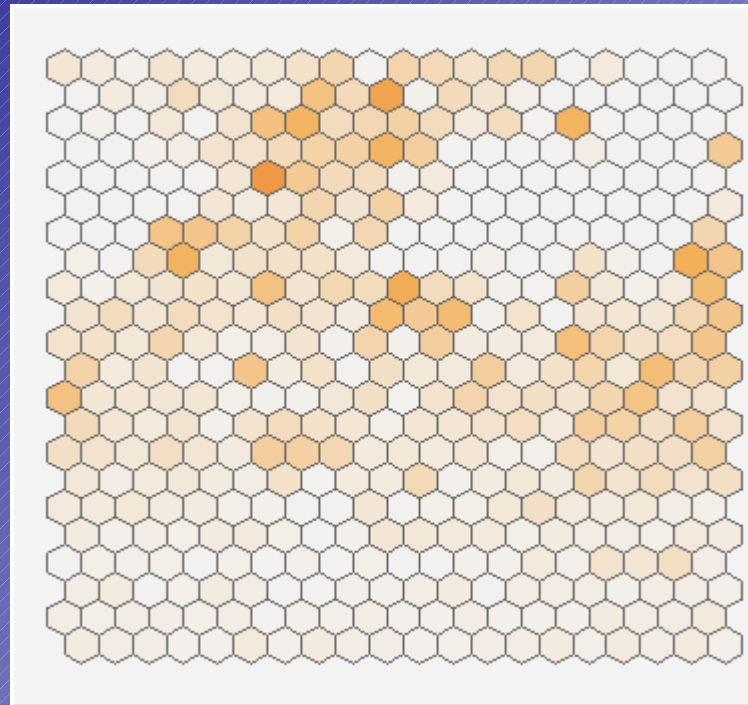
Background Sky variance: frame 5/7



Background Sky variance: frame 6/7



Background Sky variance: frame 7/7



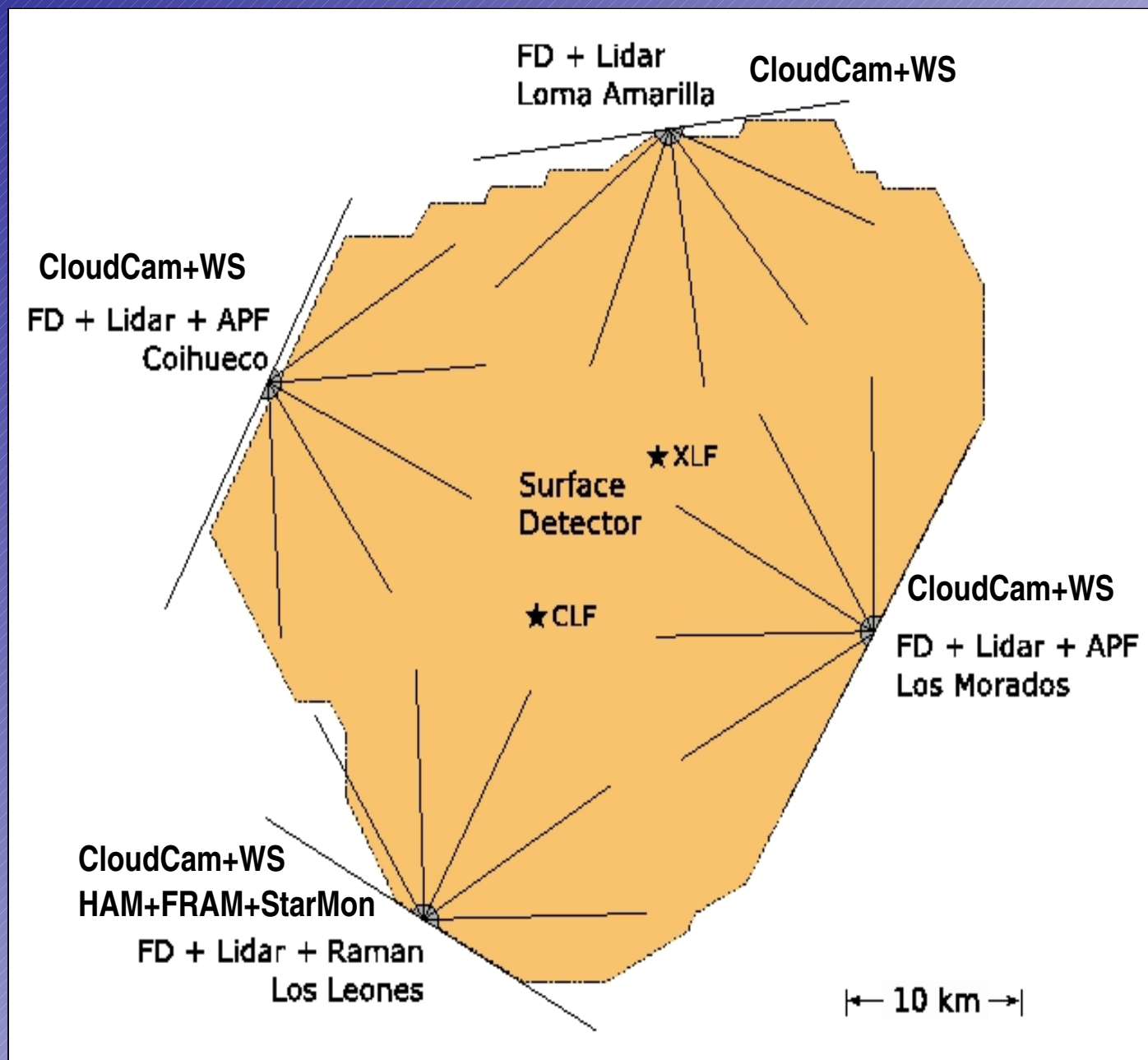
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Non invasive devices:

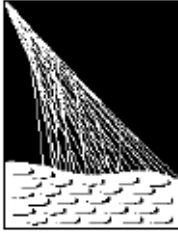
- Weather Stations
- Radiosondes
- Cloud Cameras
- StarMonitor
- FRAM

Light Sources:

- LIDARs
- CLF, XLF
- APF
- HAM



Raytheon 2000B IR camera



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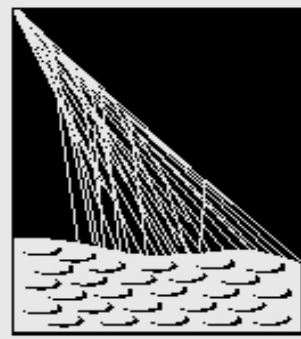
- Spectral range: 7-14 microns
- Resolution: 320x240 pixels



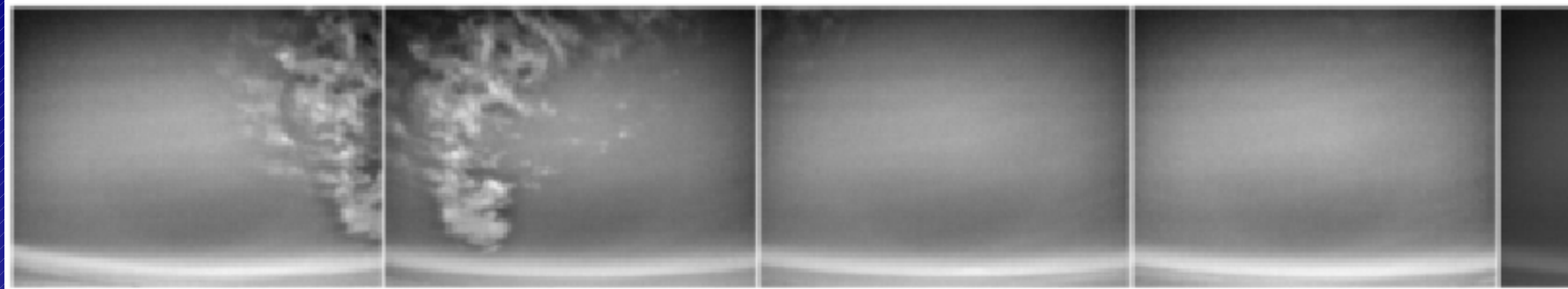
Total of four cameras now installed, one at each FD site

Housed within a weather protective box and mounted on a pan-and-tilt device

IR Cloud Cameras: Modes of Operation



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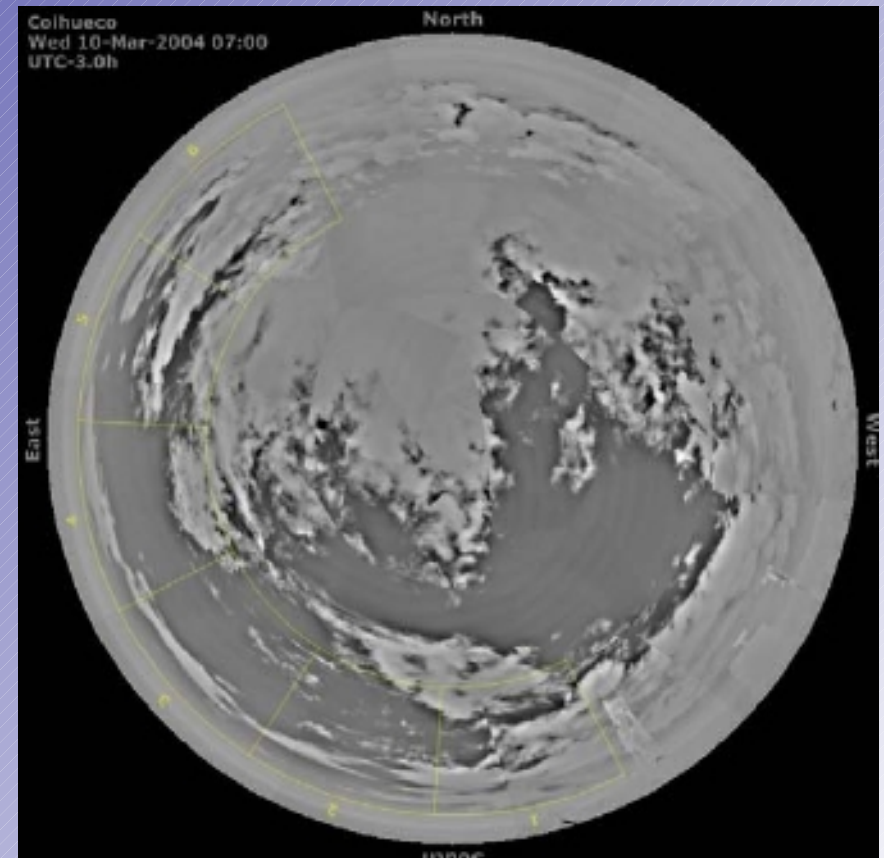
Every 5 min: 5 images across FD FoV

Every 15 min: Full Sky Mosaic

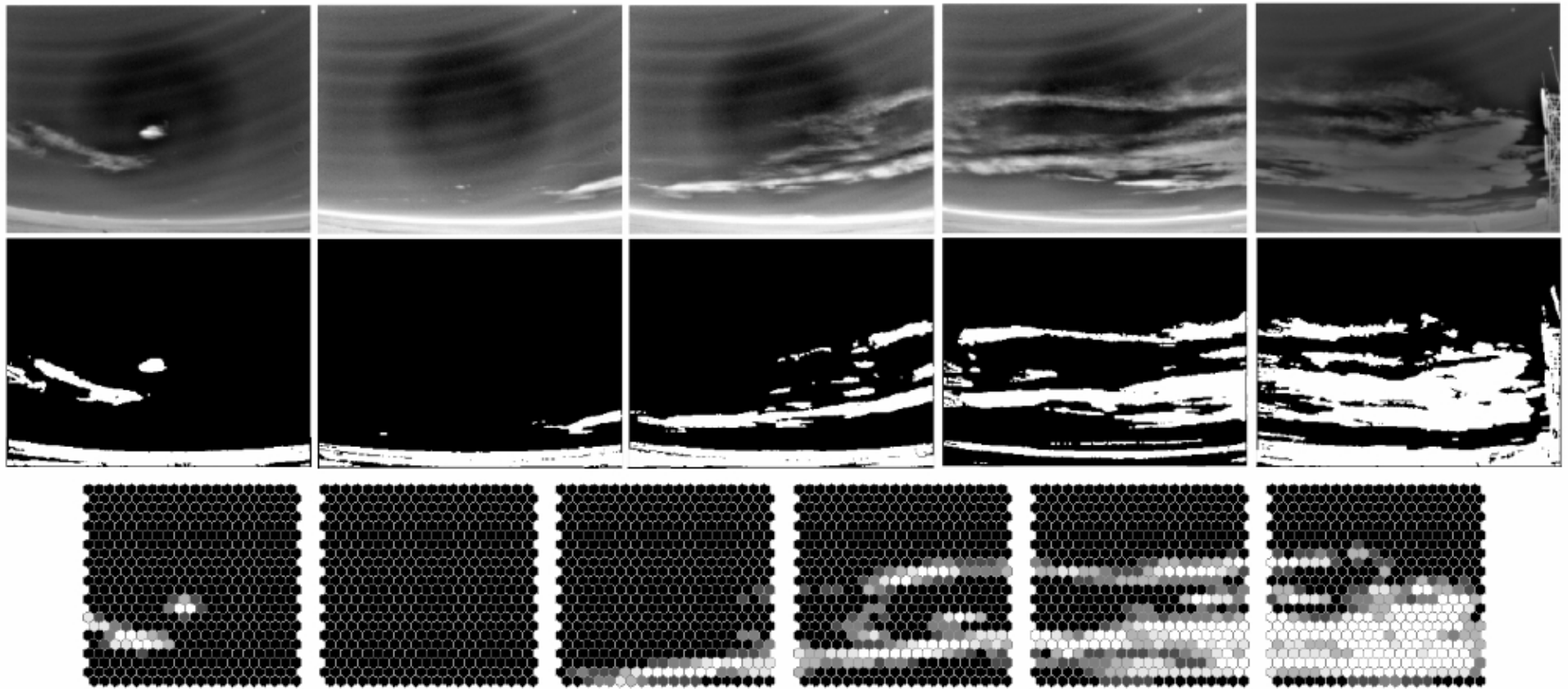
Principle of Operation:

Werner J, Appl. Meteorology 12, 1394 (1973)

- ◆ Clouds are warmer than clear sky
- ◆ Clouds emit infrared light
- ◆ IR emission depends on T
- ◆ Temperature depends on height



IR CloudCam: Digital Image Processing



Record images \longrightarrow Find cloud \longrightarrow Cloud in each FD pixel

Want cloud index value between 0-5 for all times,
for each pixel, in each mirror, for each fluorescence detector.

IR CloudCam: Digital Image Processing

Huge Picture Database:

> 300k images, ~7k eye hours

3.7 Gigabyte database

Digital Processing is required

Many cloud detection algorithms are needed to cover all the range of cloud conditions:

- Thresholding
- Differentiation
- Edge Detection



CloudCam is NOT a radiometer (no absolute T scale) :


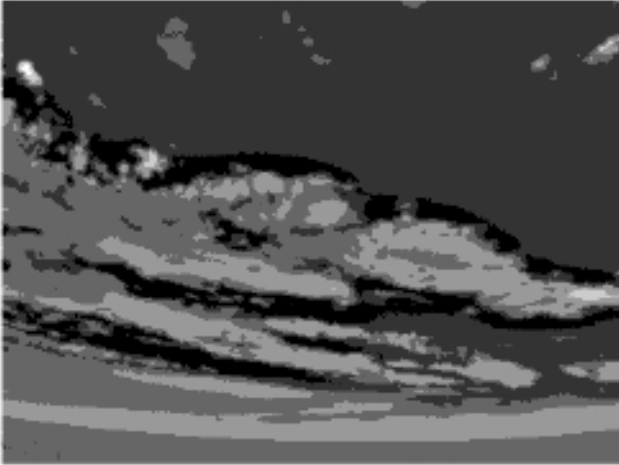
Pixel signal is proportional to the sky temperature in a given direction and the **average temperature** of the entire scene.

IR CloudCam: PACMan

PACMan - Pierre Auger Cloud Manager v1.2

Attributes

Local time: 01:10 05/11/2007
Gps time: 878271013 Seconds
Eye: Loma Amarilla
Image number: 4
Group number: 01
Elevation angle: +015.59 Degrees
Azimuth angle: -152.11 Degrees



Exit Veto image set LA200711.irp Back 1199 Next

Pre-processing

Use ED Filter?
 Use Image Differencing?

Time Range (min): 5

Compare with Mean of Lower Signals
 Compare with Lowest Signal

Processing

Process

Automatic Thresholding
 Manual Thresholding 1
 RD Algorithm
 SOP Algorithm
 EBT Algorithm

Lower Threshold	500	Show Edges	Check Boundaries
Upper Threshold	2000	Buffer	1
Gaussian	0.0	Segments	0

Process then go next

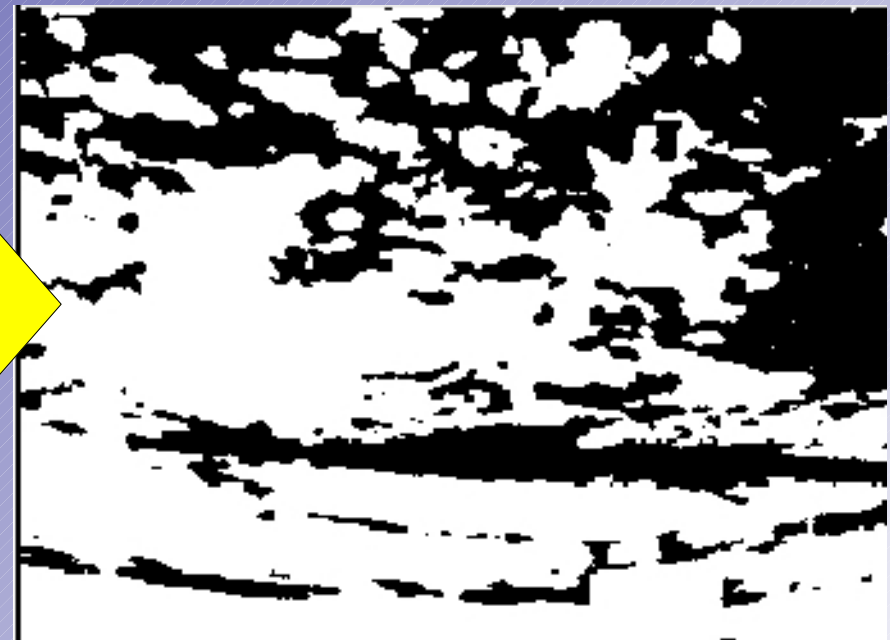
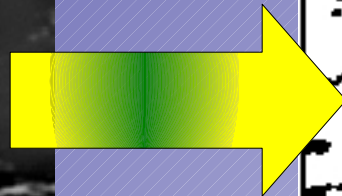
Approx 5hrs needed to process 1 FD shift per 1 eye

IR CloudCam: Thresholding

Simplest approach: all pixels above a given threshold are labeled as cloudy

Pro: fast and simple

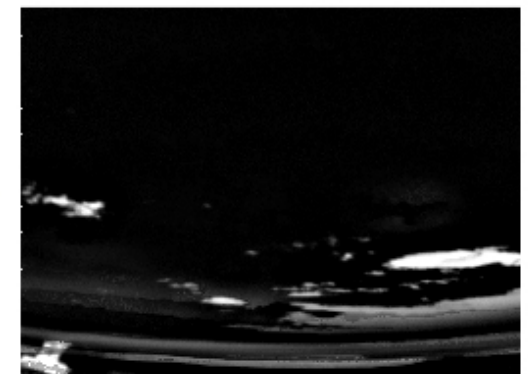
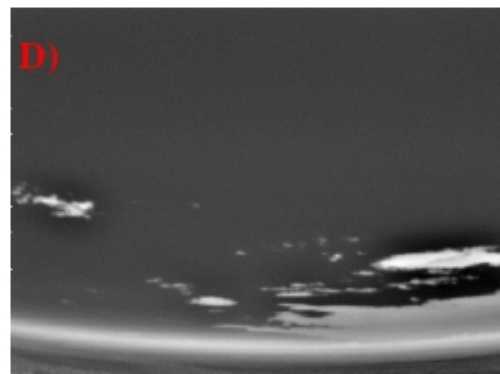
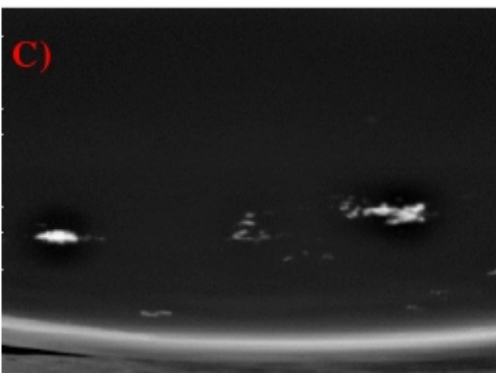
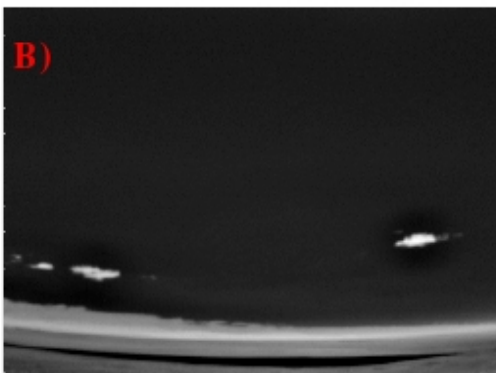
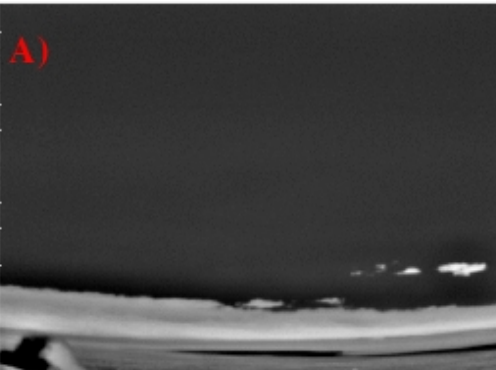
Contra: Impossible to define the threshold uniquely. It depends on overall contents of the scene, on humidity, on pixel elevation (i.e. on cloud height) .



IR CloudCam: Image Difference

Determine a clear-sky template from recent images, and subtract from the image in question.

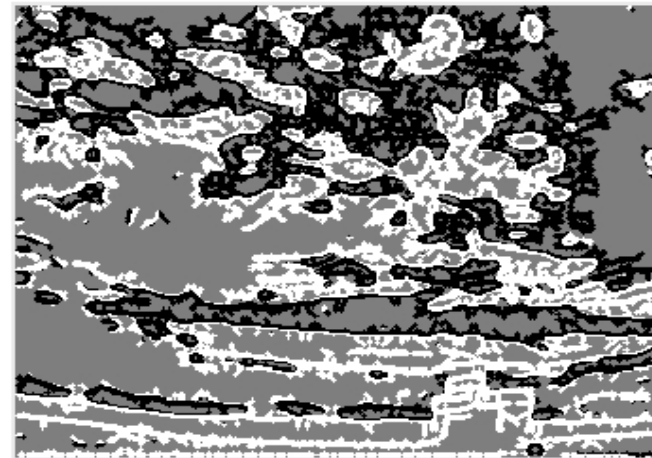
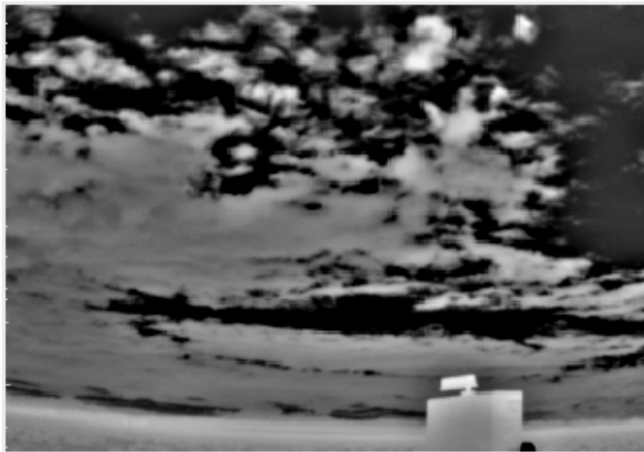
For each pixel in image **D**, check the corresponding pixel in **A**, **B** and **C** (images close in time). Take the mean of any pixels with lower intensity than that in **D** as the clear sky background for that pixel. Subtract the 'clear sky background' from the original image



Can either apply edge detection to the new image or threshold it

Does not work well when confronted by static situations or very bright cloud
- due to auras causing us to underestimate the background clear sky signal

IR CloudCam: Edge Detection



Canny edge detection algorithm

- Noise reduction with Gaussian filter
- Dual threshold on edge intensity gradient

Localized thresholding in image of pixels identified as edges to identify cloud

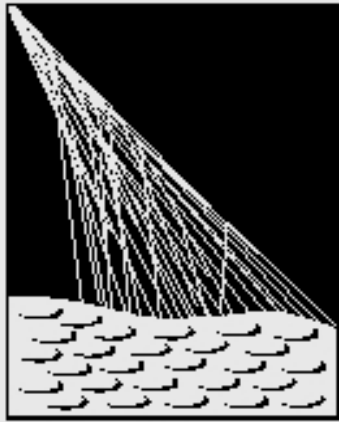
Cannot distinguish between clear/overcast situations due to lack of strong edge gradients



Overlapping cloud layers are also problematic, as the algorithm will sometimes decide that the less bright layer of cloud is clear sky

Canny, J., A Computational Approach To Edge Detection,
IEEE Trans. Pattern Analysis and Machine Intelligence, 8:679-714, 1986

see also : <http://matlabserver.cs.rug.nl> for online examples



LIDARs

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LIDAR : working principles

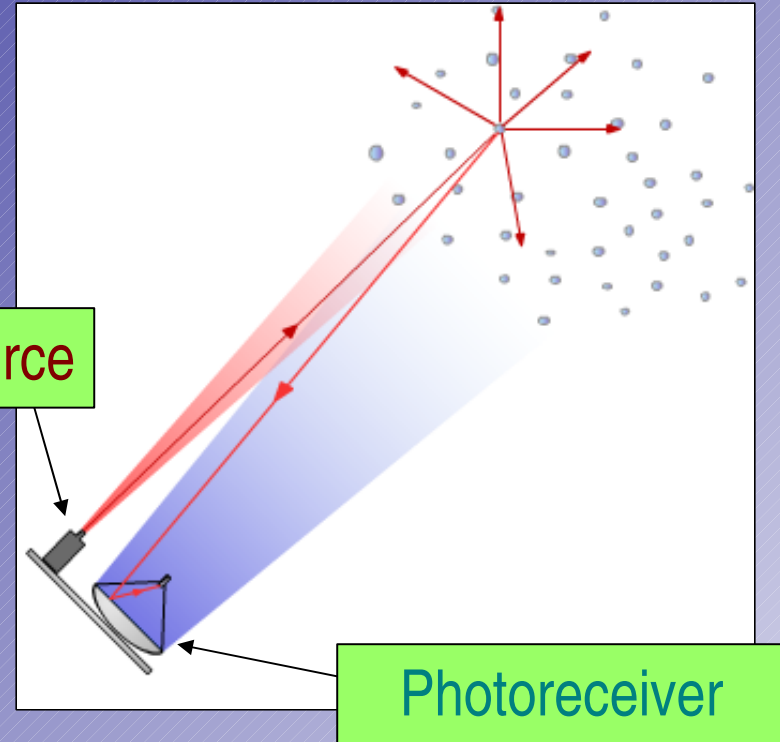
LIDAR = **L**ight **D**etection **A**nd **R**anging

- A short ($t_0 \sim 10^{-8}$ sec) **light pulse** is **emitted** in the atmosphere
- A fraction of the light is **scattered back** toward the lidar system
- This light is **collected** by a **telescope** and focused upon a photodetector



We measure the amount of backscattered light as a function of time \rightarrow distance.

Light source



Photoreceiver

$$P(r) = P_0 \frac{ct_0}{2} \left(\frac{A}{r^2} \right) \beta(r) e^{-2\tau(r)}$$

LIDAR equations

Raw Signal : Power Return ($r = ct/2$)

$$P(r) = P_0 \frac{ct_0}{2} \left(\frac{A}{r^2} \right) \beta(r) e^{-2\tau(r)}$$

Optical Depth

$$\tau(r) = \int_0^r dr' \alpha(r')$$

Extinction coefficient

$$\alpha(r) = \alpha_{mol}(r) + \alpha_{aer}(r)$$

==

$$\sigma_{mol} N_m(r) + \sum_k \sigma_k N_k(r)$$

Backscattering Coefficient :

$$\beta(r) = \beta_{mol}(r) + \beta_{aer}(r)$$

==

$$\left[\frac{d\sigma_{mol}}{d\Omega} \right]_{\theta=\pi} N_m(r) + \sum_k \left[\frac{d\sigma_k}{d\Omega} \right]_{\theta=\pi} N_k(r)$$

==

$$\mathcal{P}_{mol}(\theta = \pi) \alpha_{mol}(r) + \sum_k \mathcal{P}_k(\theta = \pi) \alpha_k(r)$$

where

$$\mathcal{P}(\Omega) = \frac{1}{\sigma} \left(\frac{d\sigma}{d\Omega} \right)$$

Range corrected Power Return:

$$S(r; r_n) = \ln \frac{P(r)r^2}{P(r_n)r_n^2} = \ln \frac{\beta(r)}{\beta(r_n)} - 2\tau(r_n, r)$$

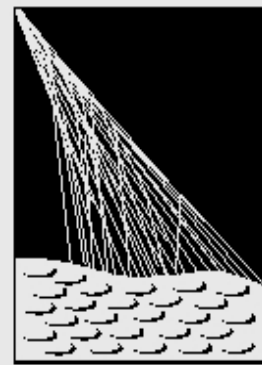
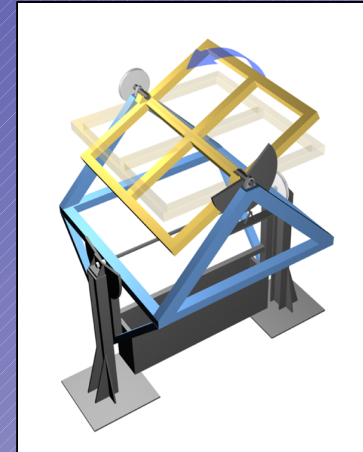
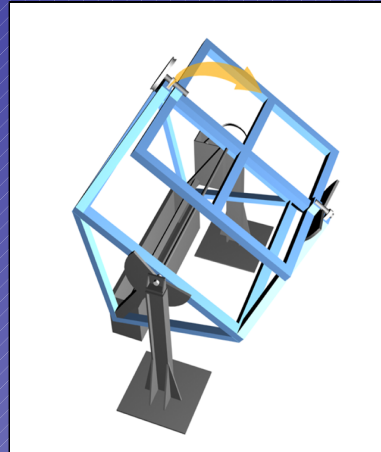
■ normalized at fixed distance

$$S(h; h_n) = \ln \frac{P(h)h^2}{P(h_n)h_n^2} = \ln \frac{\beta(h)}{\beta(h_n)} - 2\tau(h_n, h) \sec\theta$$

■ normalized at fixed height

LIDAR : mechanics

- Alt-altazimuthal motorized mount
- Encoder controlled steering
- Aligned to the axis of each FD
- Fully retractable cover



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Lidar : scanning patterns

Every hour, each Lidar performs a set of scans :

- **Horizontal Shots**

Horizontal omogeneity

Aerosol extinction at ground

- **Continuous Scans**

Cloud coverage

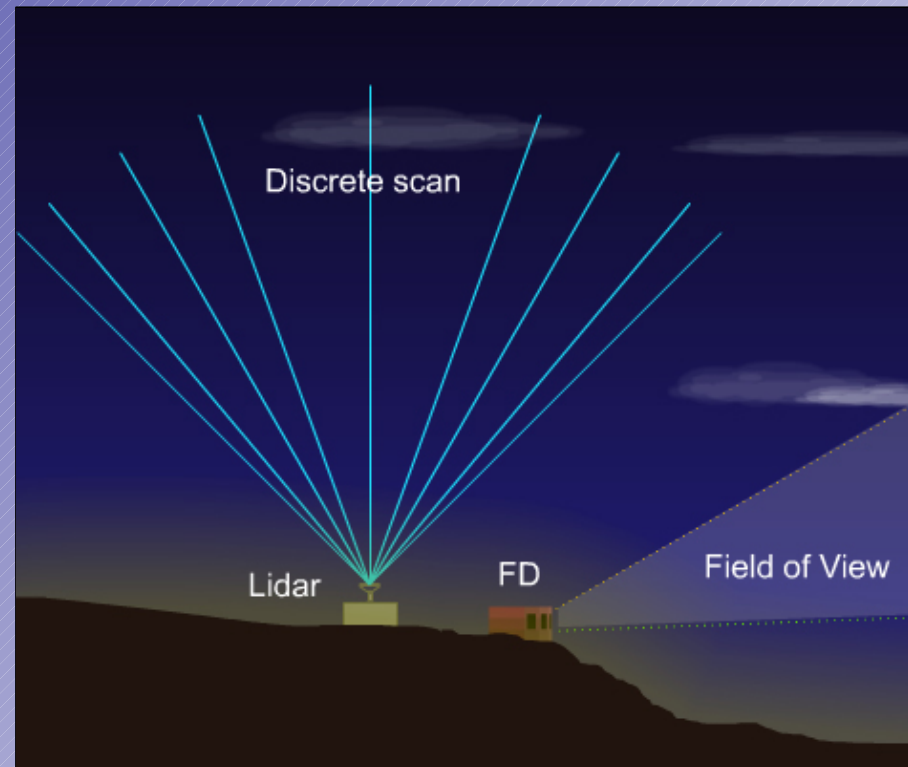
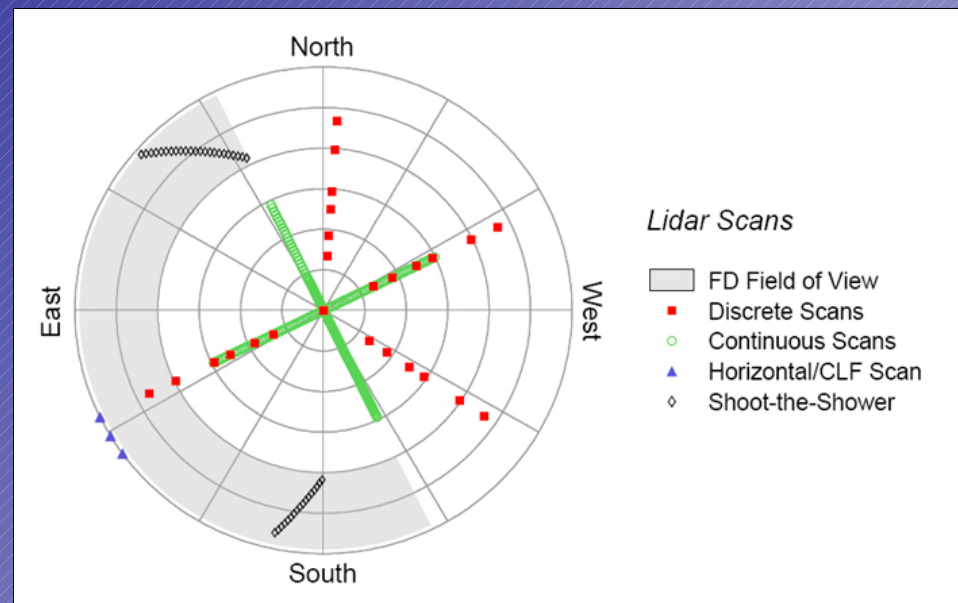
Cloud characterization

- **Discrete Scans**

Vertical Aerosol optical depth (VAOD)
with multiangle inversion technique

- **Vertical Shots**

VAOD with Fernald inversion technique



Lidar: photonics

LASER Photonics DC30-351

Laser Type: Nd:YLF
Main wave length: 351 nm
Pulse Energy: 0.1 m J
Pulse width: 15 ns
Repetition rate: 0.333 kHz

PMT 3xHamamatsu R7400 U-03

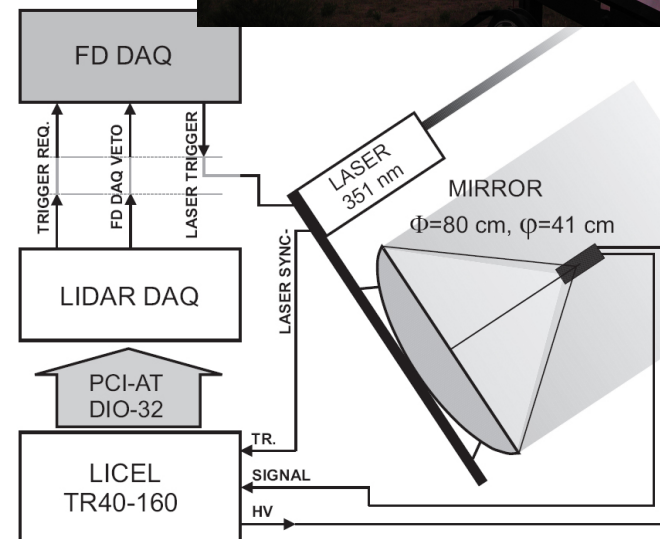
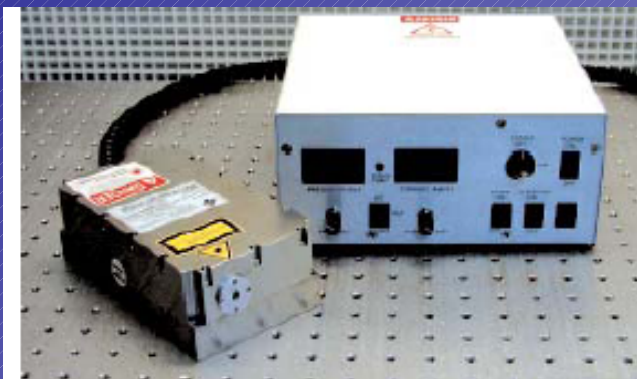
HV: 770, 850 V

FWHM single photon: 2 ns

photocathode diameter: 8 mm,

peak wavelength: 420 nm (at 25°C),

UG1 filter (PMT entrance window)



DATA ACQUISITION Licel TR40-160 (3 channels)

A/D converter

Resolution: **12 bit**

Sampling frequency: **40 MHz**

→ Spatial resolution: **3.75 m**

Trace length: **16k (60 km)**

High speed discriminator

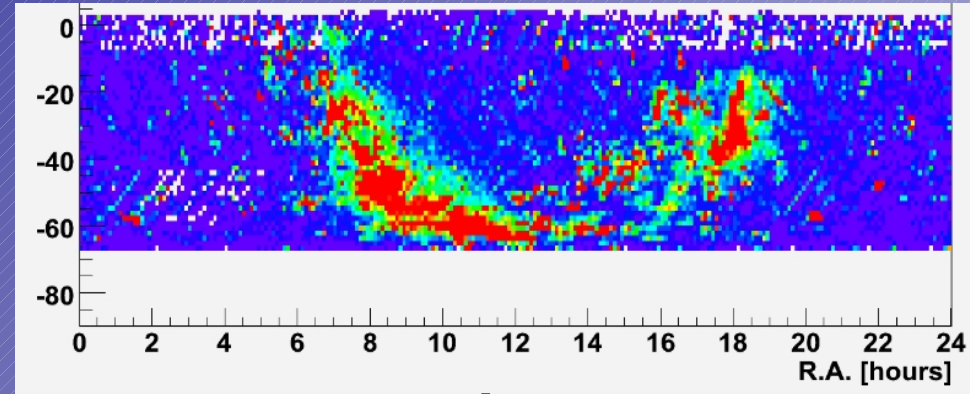
Frequency: **250 MHz**

Configurable threshold level

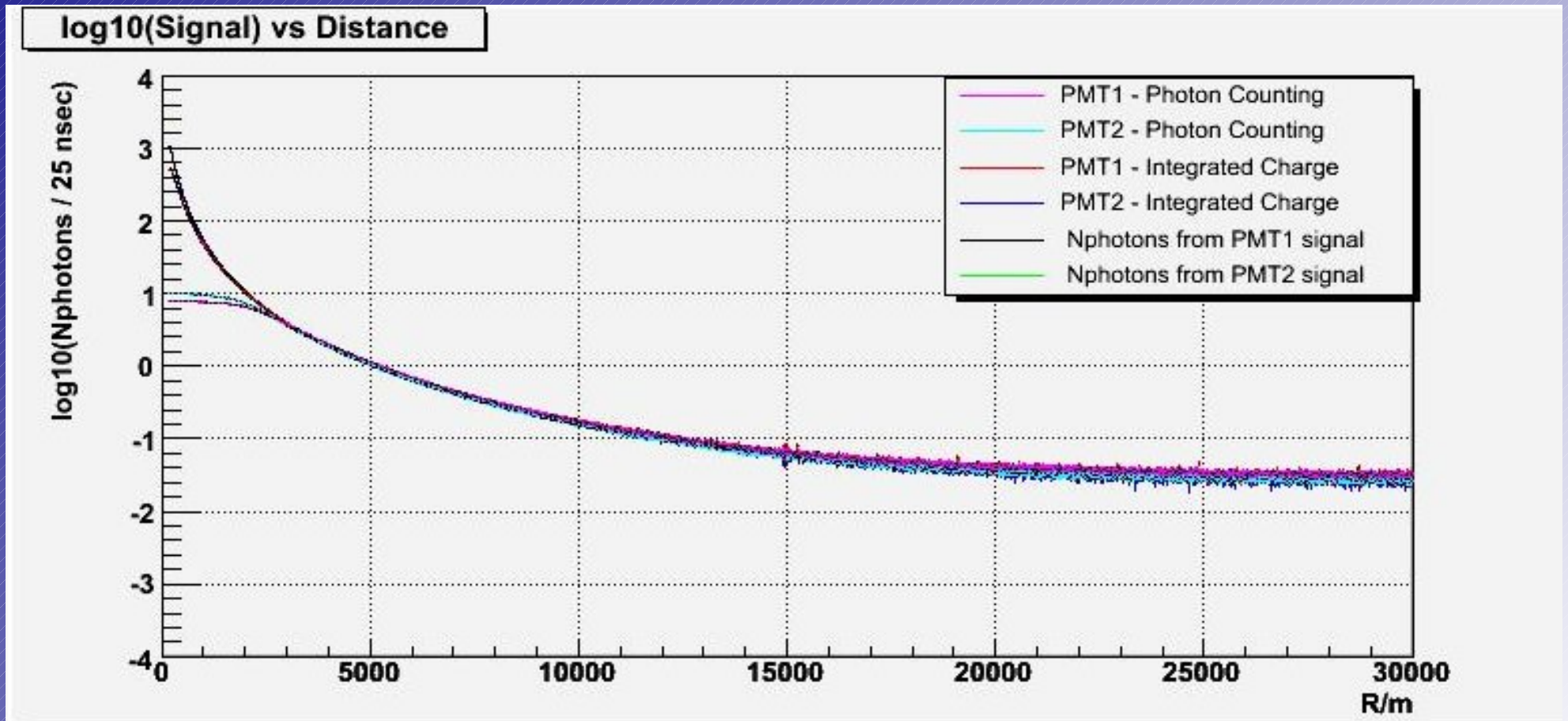
(64 levels between 0 and -100 mV)

Lidar: typical signals

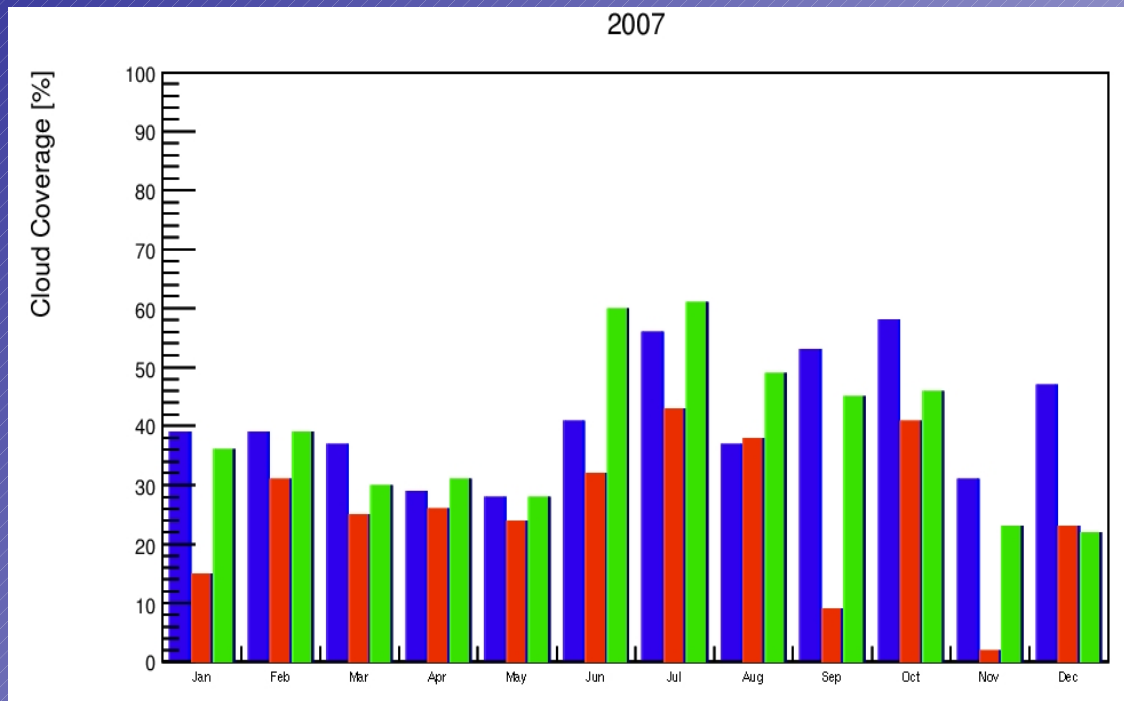
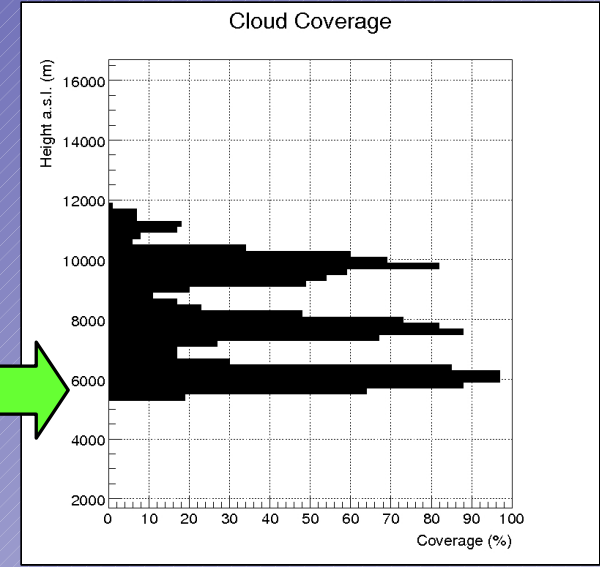
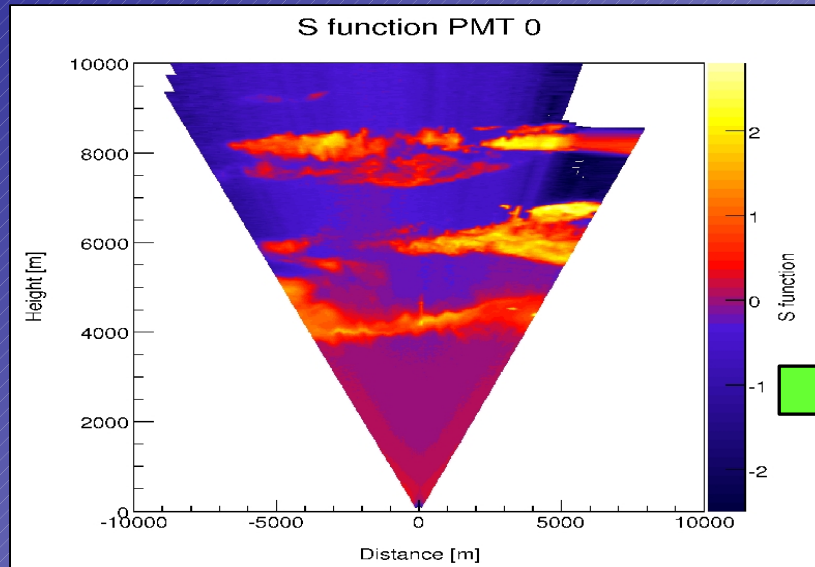
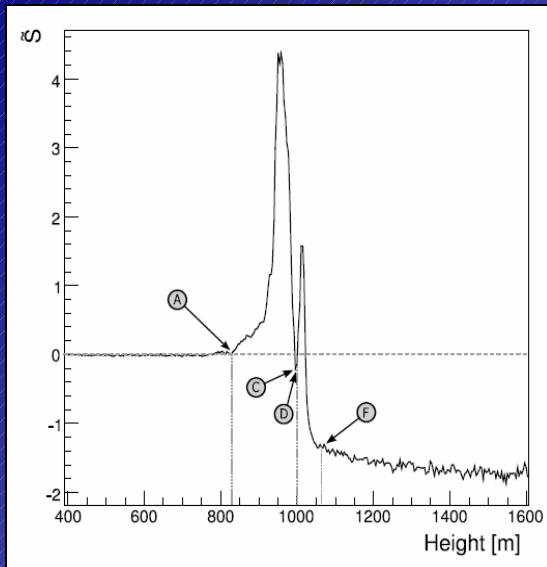
- Signal is the sum of 1000 shots in 3 seconds
- Dynamic range : almost 5 orders of magnitude
- Lower limit: sky background (stars, airglow)
- Range: almost 30 km



Southern Sky with Lidar Pedestals



Lidar: Cloud Detection and Cloud Coverage



Hourly average of cloud conditions above each FD site:

- Cloud base height
 - Cloud layer count
 - OD of each cloud layer
- is sent to Cloud Database

LIDAR information on the web

LIDAR Information Database

Your IP: 192.84.137.202 - toj2xl.to.infn.it - Updating Calendar: NO
Display:
Run by Run
Cloud Coverage
@ Ground

Jun 2007

Su	Mo	Tu	We	Th	Fr	Sa
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

[View All](#)

Search StS:

sec:

nsec:

[Submit](#)

Select scan type:

Shoot The Shower

Discrete

Continuous

Horizontal

Vertical

Test run

[Submit](#)

View sites:

[1] Los Leones

[2] Los Morados

[3] Loma Amarilla

Eye	Run	Root file	Mode	Hour	Clouds (%)	PMT status
8 Jun 2007						
+	2	lidar-lm-20070607-225927-R10269.root	Azimuth Discrete	02:00	<div style="width: 20px; height: 10px; background: linear-gradient(to right, yellow, orange, red);"></div>	■■■
+	4	lidar-ch-20070607-225804-R15749.root	Zenith Discrete	02:01	<div style="width: 20px; height: 10px; background: linear-gradient(to right, orange, red);"></div>	■■■
+	1	lidar-ll-20070607-230102-R18330.root	Azimuth Continuous	02:01	<div style="width: 20px; height: 10px; background: linear-gradient(to right, orange, red);"></div>	■■■
<p>Started at GPS: 865303332</p> <p>Finished at GPS: 865303923</p> <p>Lasted: 591 sec</p> <p style="text-align: right;">Show Details</p>						
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;"> <p>PMT 0</p> </div> <div style="text-align: center;"> <p>PMT 1</p> </div> <div style="text-align: center;"> <div style="border: 1px solid gray; padding: 5px; width: 60px; height: 60px; display: flex; align-items: center; justify-content: center;"> image not found </div> <p>PMT 2</p> </div> <div style="text-align: center;"> <p>Detected Clouds</p> </div> <div style="text-align: center;"> <p>Sky Coverage</p> </div> </div>					<p style="font-weight: bold; color: gray;">Lowest Cloud</p> <p style="font-size: small; color: gray;">Height: 6554 m a.s.l. Thickness: 969 m OD: N.A. Lidar MAX height: 12076 m a.s.l. CloudFinder: Version 4</p>	
+	4	lidar-ch-20070607-231251-R15750.root	Zenith Continuous	02:13	<div style="width: 20px; height: 10px; background: linear-gradient(to right, red);"></div>	■■■
+	1	lidar-ll-20070607-231153-R18331.root	Horizontal Shots	02:13	N.A.	■■■
+	2	lidar-lm-20070607-231409-R10270.root	Azimuth Continuous	02:15	<div style="width: 20px; height: 10px; background: linear-gradient(to right, yellow, orange, red);"></div>	■■■
+	1	lidar-ll-20070607-231353-R18332.root	Vertical Shots	02:15	N.A.	■■■
+	1	lidar-ll-20070607-232032-R18333.root	Zenith Discrete	02:21	<div style="width: 20px; height: 10px; background: linear-gradient(to right, yellow, orange, red);"></div>	■■■
+	2	lidar-lm-20070607-232516-R10271.root	Horizontal Shots	02:26	N.A.	■■■
+	4	lidar-ch-20070607-232446-R15752.root	Shoot the Shower	02:27	<div style="width: 20px; height: 10px; background: linear-gradient(to right, green);"></div>	■■■

Web interface (AJAX) for displaying all the information, comparing results, and creating summary plots.

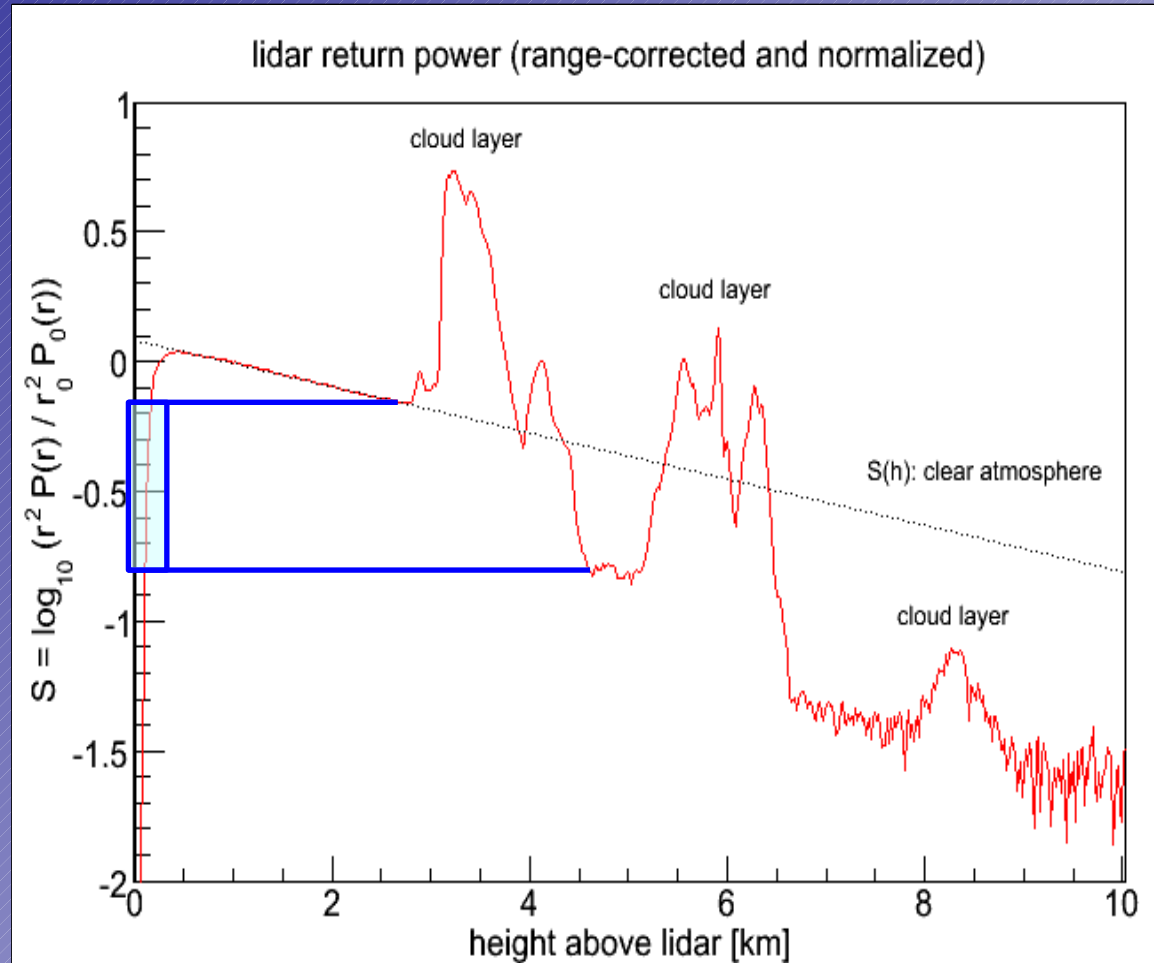
Lidar: Cloud Optical Depth measurement

Return power is corrected for the molecular contribution (from monthly profiles)

$$S_a(h, h_n) = S(h, h_n) - S_{mol}(h, h_n)$$

The drop in S_a , corrected for the polar angle, gives the VOD of the cloud:

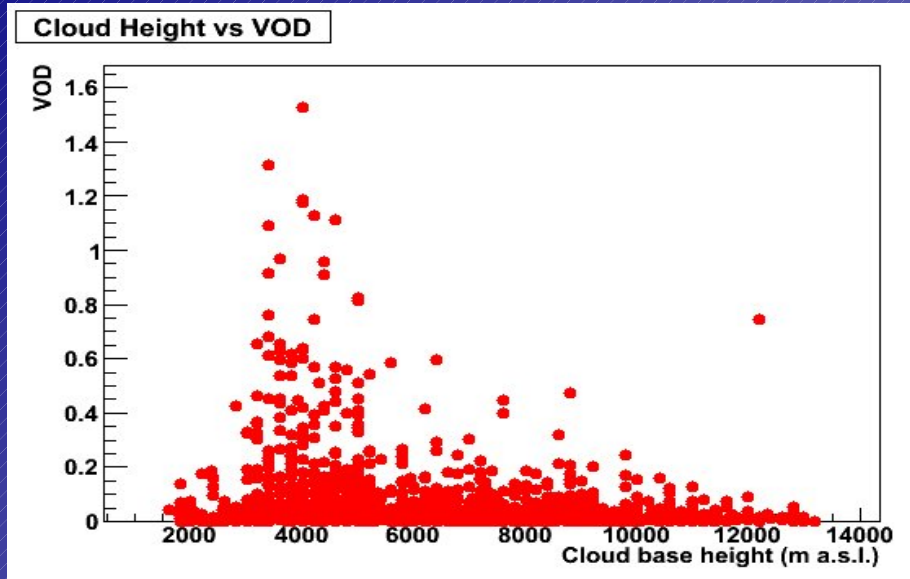
$$\tau(h_1, h_2) = \cos\theta [S_a(h_1) - S_a(h_2)]$$



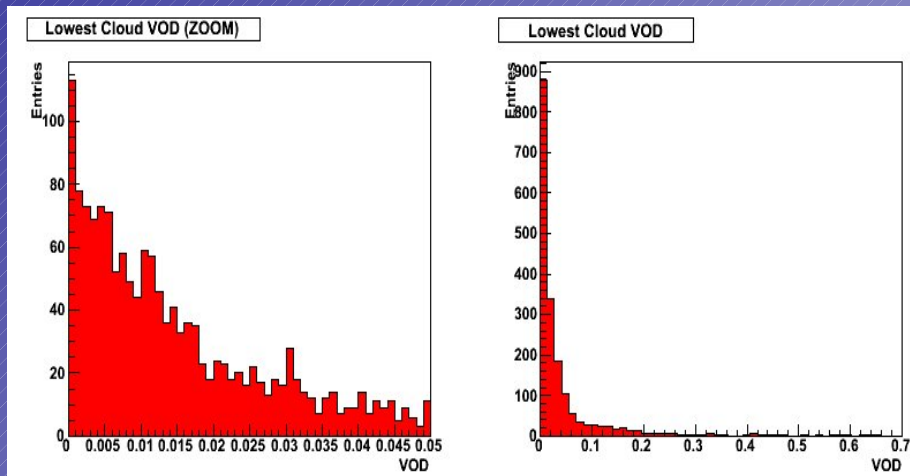
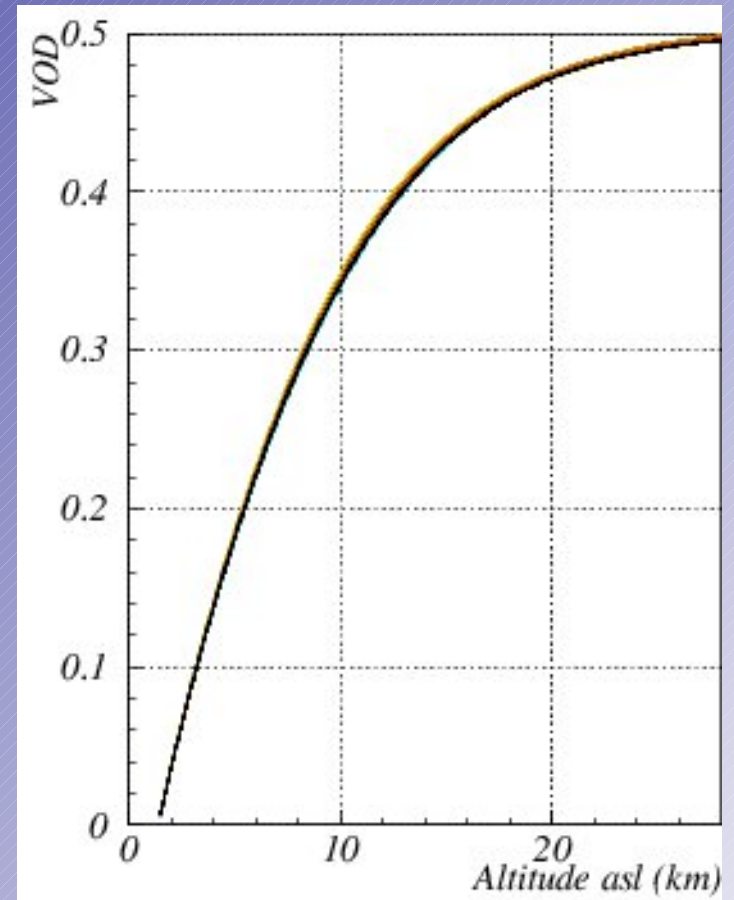
Reminder:

$$S(h; h_n) = \ln \frac{P(h)h^2}{P(h_n)h_n^2} = \ln \frac{\beta(h)}{\beta(h_n)} - 2\tau(h_n, h) \sec\theta$$

Lidar: Cloud Optical Depth

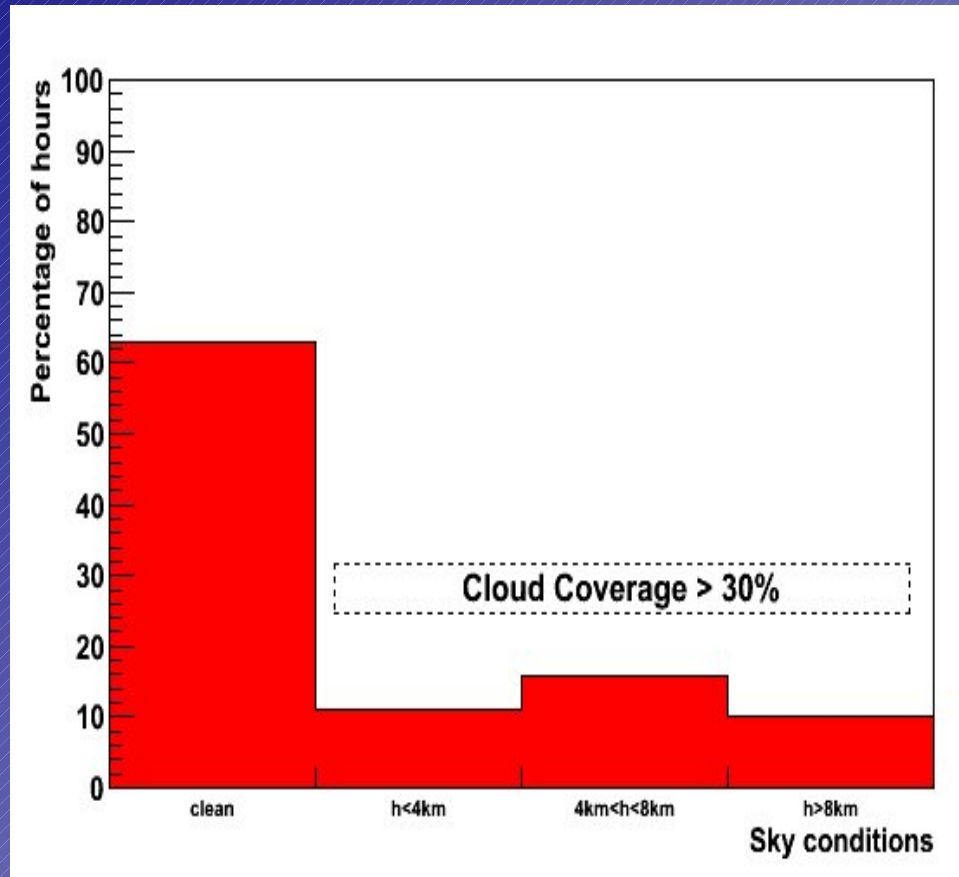


Molecular Optical Depth vs H

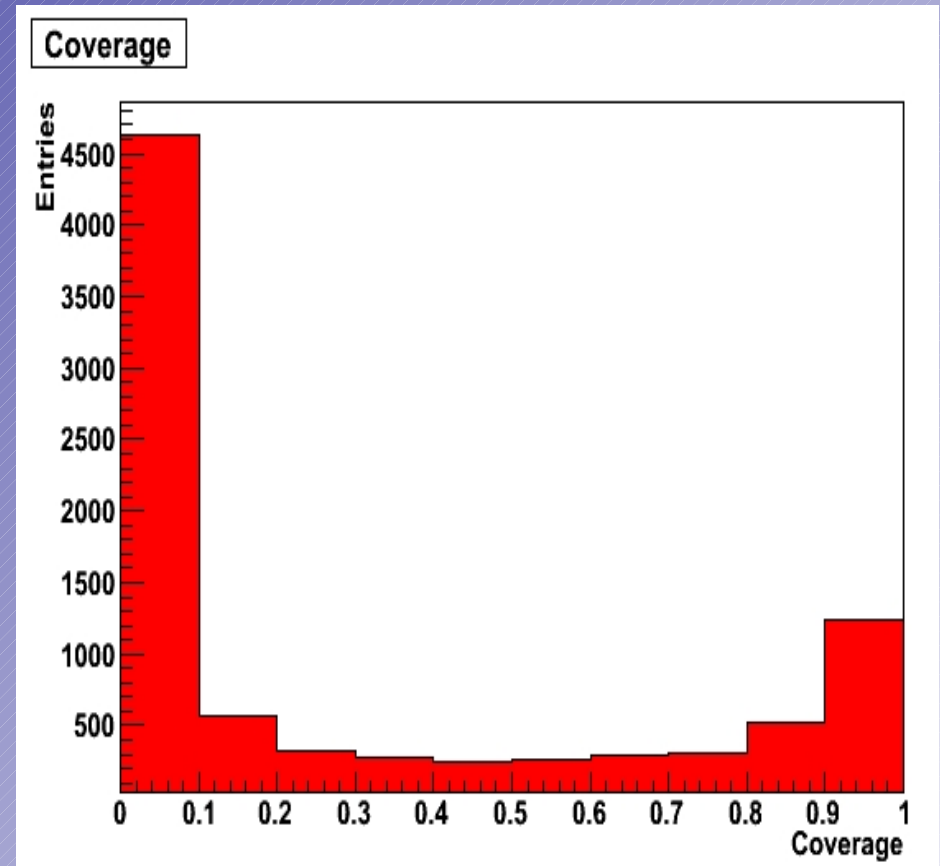


Lidar: Cloud Coverage

Cloud coverage vs Height of lowest cloud



Hours of data taking vs cloud coverage



About 30% of the cloudy hours have **more than 1 layer of clouds**

LIDAR network: Shoot-the-Shower mode

When a very interesting event is observed by FD and SD a precise characterization of the atmosphere is quite important.

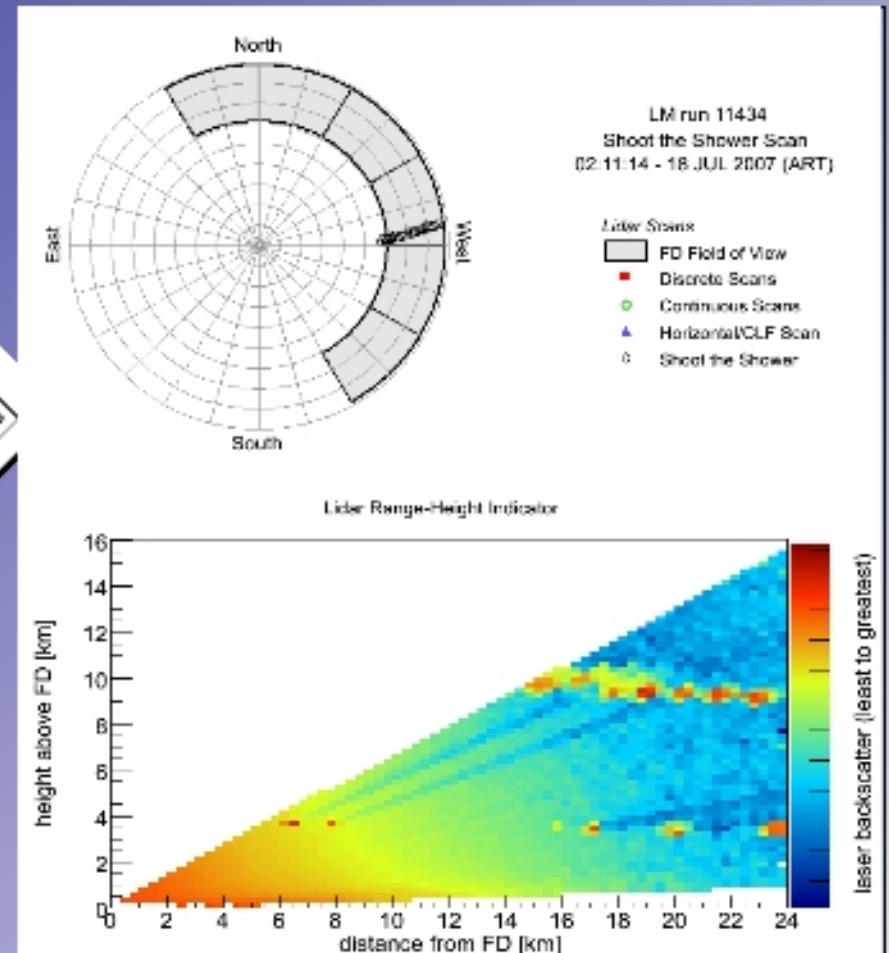
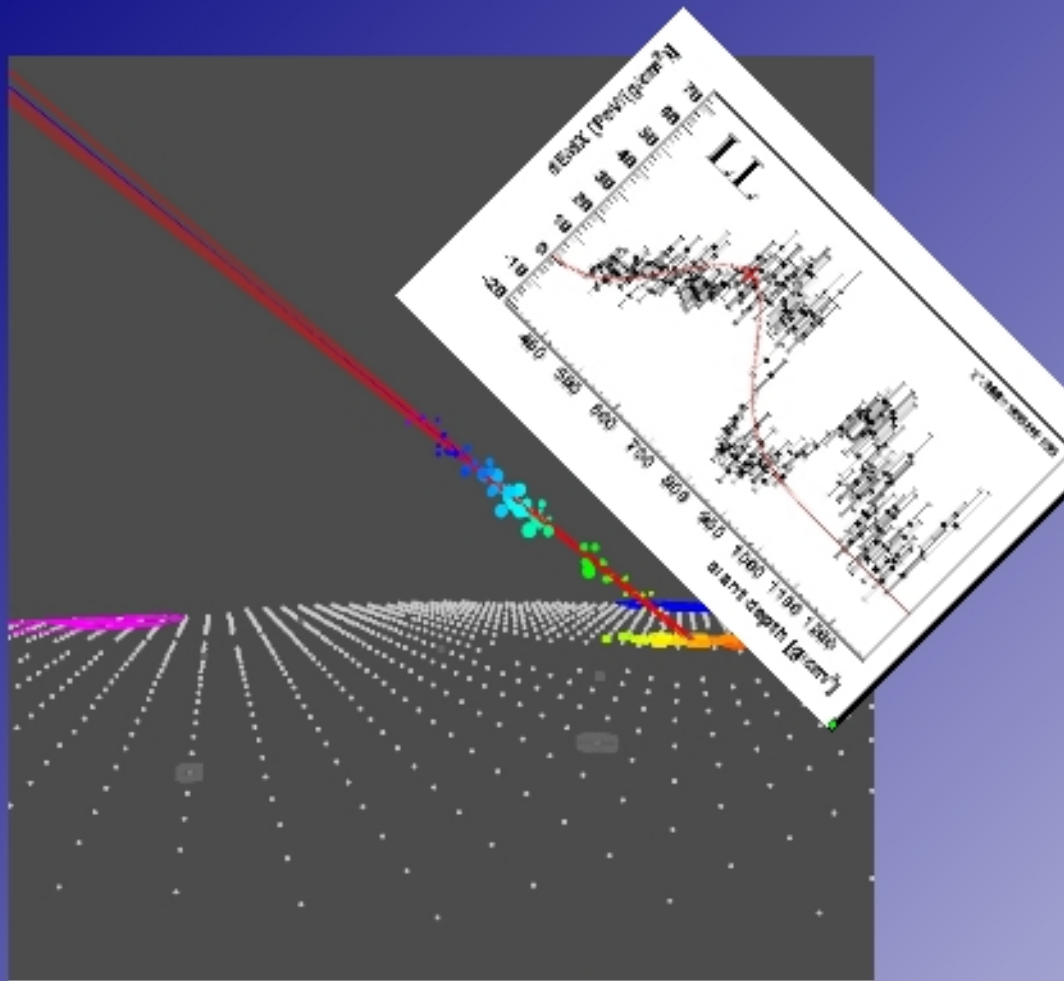
In 5 minutes, LIDARs can perform a scan along the angular shower track detected by the Fluorescence Detectors:

	From	Run	Time	Nanotime	Pixels	dt	Chi2	Kind	Passed
24	LosLeones	4394	802071057	852646229	6	0	0	0 FD	NO
25	LosLeones	4396	802071142	751508669	7	0	0	0 FD	NO
26	Coihueco	4399	802071157	939934181	5	0	0	0 FD	NO
27	Coihueco	4400	802071260	851355490	4	0	0	0 FD	NO
28	LosLeones	4399	802071606	591480290	9	0	0	0 HYBRID	YES
29	Ground Array	1763	802071606	591447000	5	0	0	0 HYBRID	YES
30	Coihueco	4402	802071634	503221130	4	0	0	0 FD	NO
31	LosLeones	4400	802071714	890623091	4	0	0	0 FD	NO
32	Coihueco	4404	802071781	113646791	15	0	0	0 FD	NO

If a hybrid or stereo event occurs, the *local* client T3 Listener orders the LIDAR to shoot the shower

Coincidence time window:
0.2 ms for stereo events
0.4 ms for hybrid events

LIDAR network: Shoot-the-Shower mode



15 minutes after the event occurred, a StS scan is written on Lidar PC and can be used to **precisely determine the cloud coverage in the shower-detector plane.**

Cloud effects on shower profiles / 1

SDEvent 3027983

Los Morados - Mirror 2

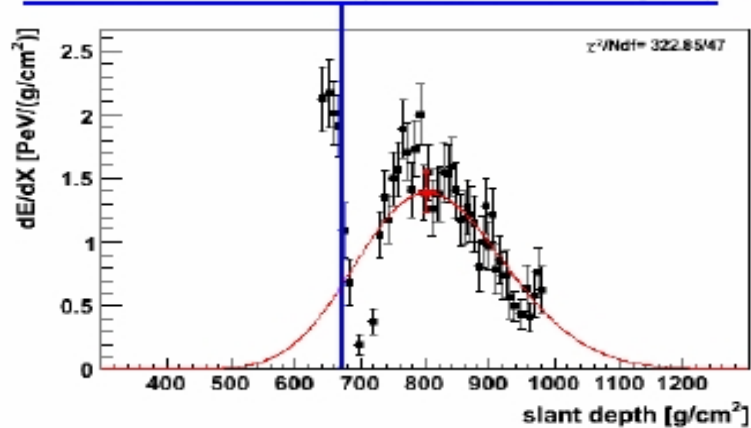
Run 1284 Event 1751

time stamp: 852606254 s 113501109 ns

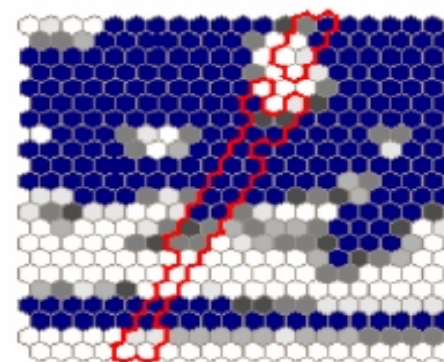
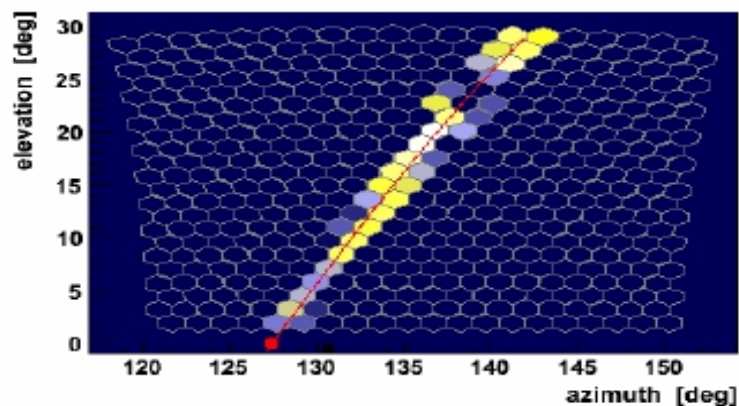
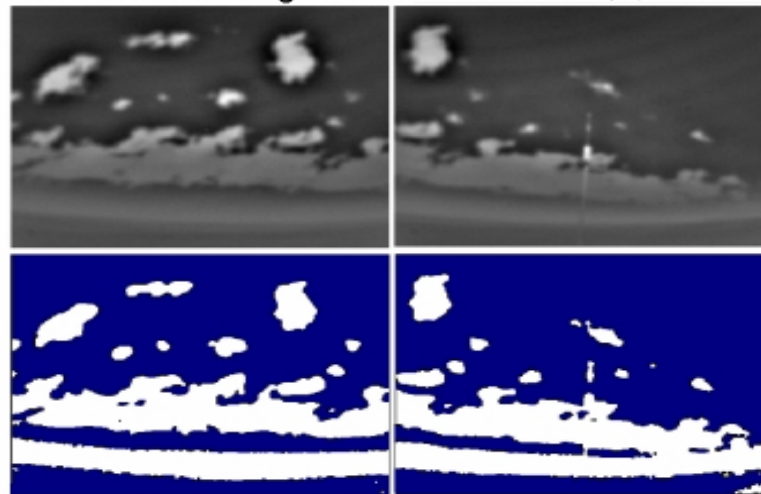
UTC date: 2007/1/12 03:04:00

$E = (4.53 \pm 0.41 \pm 4.47) \times 10^{17}$ eV
 $X_{\max} = 803 \pm 11$ g/cm²
 $dEdX_{\max} = 1.39 \pm 0.16$ PeV/(g/cm²)
 $(\lambda, X_0) = (14 \pm 8, -150 \pm 426)$ g/cm²
Cherenkov-fraction = 14%
 $(\theta, \phi) = (29.9 \pm 0.4, 60.7 \pm 1.0)$ deg
 $(x, y) = (57.08 \pm 0.02, 39.32 \pm 0.04)$ km
dca to Eye = 5.26 ± 0.03 km

Mie attenuation: measured ($h < 4.8$ km $X_{\text{slant}} > 673$ g/cm²)



Cloud camera images recorded at UTC 2007/1/12 03:05



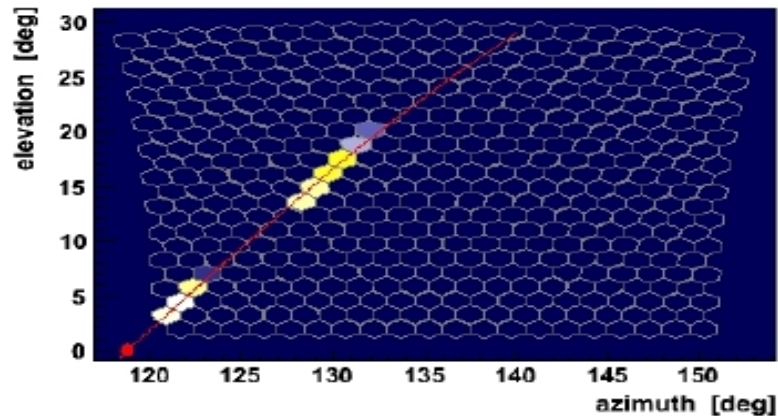
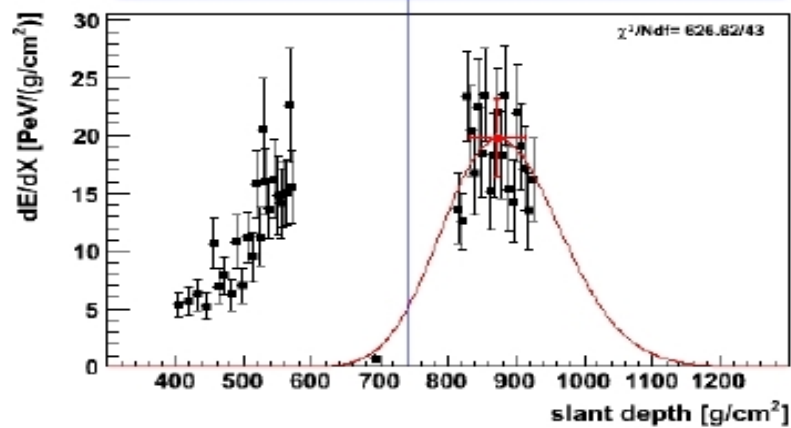
Los Morados - Mirror 2

Cloud effects on shower profiles / 2

SDEvent 3027949
Los Morados - Mirror 2

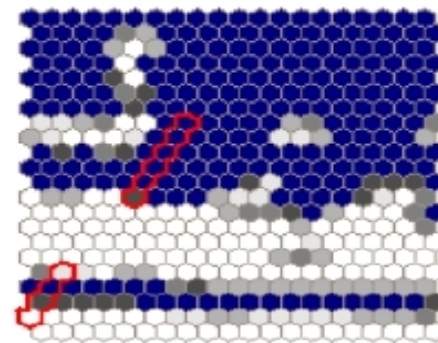
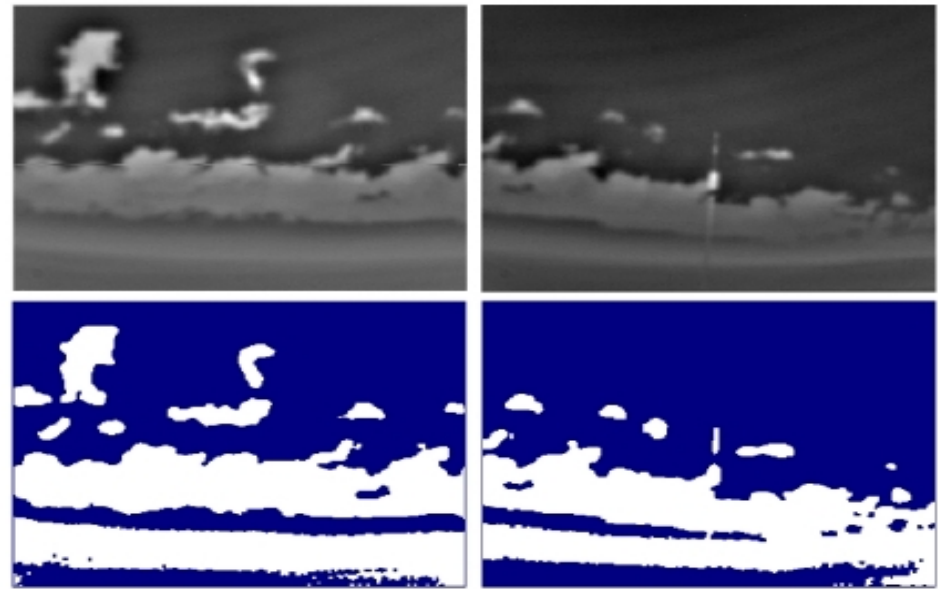
Run 1284 Event 1375
time stamp: 852605638 ± 495786933 ns
UTC date: 2007/1/12 0253

Mie attenuation: measured ($h < 13.2$ km $X_{slant} > 209$ g/cm²)
Co LIDAR lowest cloud height = 2458m, 739 g/cm²



$E = (4.73 \pm 1.22 \pm 0.42) \times 10^{10}$ eV
 $X_{max} = 874 \pm 40$ g/cm²
 $dEdX_{max} = 19.73 \pm 3.37$ PeV/(g/cm²)
 $(\lambda, X_0) = (10 \pm 0, 129 \pm 310)$ g/cm²
Cherenkov-fraction = 3%
 $(\theta, \phi) = (33.1 \pm 0.9, 27.6 \pm 0.5)$ deg
 $(x, y) = (48.63 \pm 0.09, 51.88 \pm 0.07)$ km
dca to Eye = 20.58 ± 0.06 km

Cloud camera images taken at UTC 2007/1/12 0255



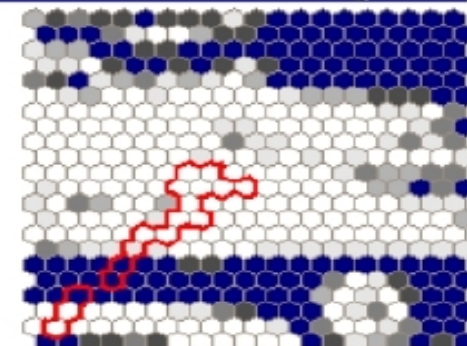
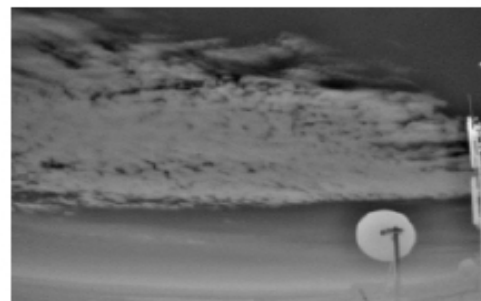
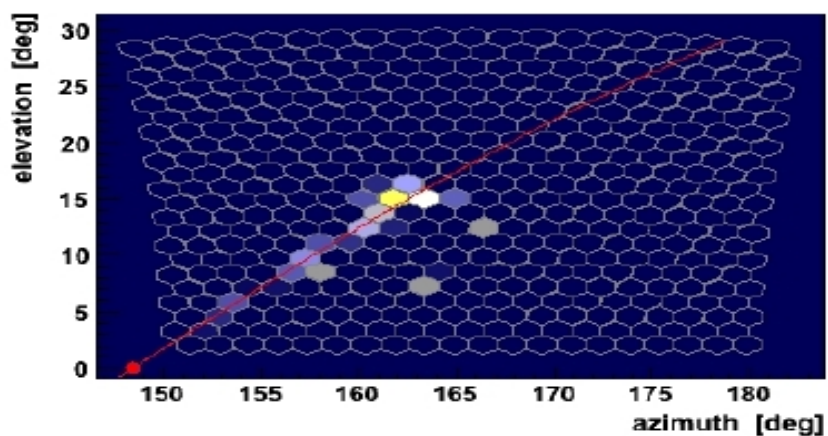
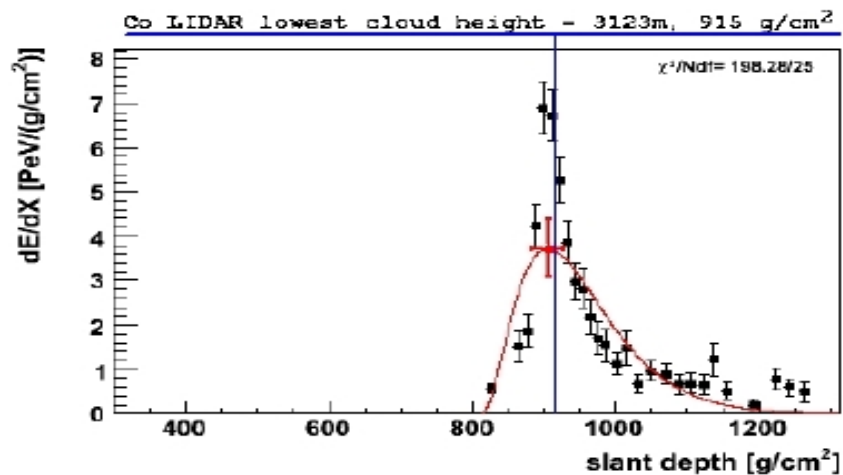
Los Morados - Mirror 2

Cloud effects on shower profiles / 3

SDEvent 3050385
Coihueco - Mirror 1

Run 1946 Event 5275
time stamp: 853141567 s 79952098 ns
UTC date: 2007/1/18 16:15:53

$E = (6.97 \pm 0.72) \times 10^{17}$ eV
 $X_{\max} = 906 \pm 23$ g/cm²
 $dEdX_{\max} = 3.72 \pm 0.65$ PeV/(g/cm²)
 $(\lambda, X_0) = (43 \pm 23, 813 \pm 28)$ g/cm²
Cherenkov-fraction = 18%
 $(\theta, \phi) = (51.7 \pm 0.7, 228.8 \pm 0.5)$ deg
 $(x, y) = (6.43 \pm 0.07, 45.19 \pm 0.07)$ km
dca to Eye = 7.51 ± 0.05 km



Coihueco - Mirror 1

Cloud effects on showers: conclusions

Clouds can impact significantly the quantities measured by Fluorescence detectors:

- can bias the hybrid flux (reducing the effective aperture)
- can bias Energy measurements
- can bias Xmax measurements

Standalone determination of cloud coverage with FD is not feasible

IR Cloud Cameras can provide a 2D coverage map for each pixel every 5 min

IR Cloud Cameras cannot measure cloud height and multiple layers

LIDARs can complement Cloud Cameras with height and layer information

but outside the field of view of the FD's

Shoot-the-shower: a full LIDAR scan on shower-detector plane is done when very interesting events are observed