Proposal for a Giant Radio Array for Neutrino Detection

Olivier Martineau
KICP @ U Chicago, December 15, 2015
• Goal: search for cosmic neutrinos
• Detection principle:
  ▫ $\nu$-induced tau decay in atmosphere generates ~horizontal extensive air showers.
  ▫ Subsequent EAS radio-detection
EAS radio emission

- Production mechanism: geomagnetic effect (+ charge excess)

- Transient (<100ns), beamed emission, coherent in 10-200MHz.
- Flat wavefront, amplitude scales linearly with energy.

Selfas simulation (V. Marin)  
CoREAS simulation (Huege)
(Very) inclined EAS radio detection

30-80MHz Efield computation
ZHAireS simulation code

$2 \times 10^{17}\text{eV}$ tau decay @ origin
Subsequent shower:

$E = 1.4 \times 10^{17}\text{eV}$

$\theta = 89.5^\circ$
EAS radio detection

- Radio antennas are basic detectors, benefiting from extensive technical developments (large band & large field of view).
- Fast electronics (>100MHz) easily available.
- Atmosphere transparent to radio waves.
- Short waves prevent detection below 25MHz.
- Sky noise level: \( \text{rms} \sim 15 \mu\text{V/m} \) for 30-100MHz.

- Radio antennas well suited to very large arrays.
- E-field emitted by horizontal EAS still in detection range after 100km+ for \( E > 2 \times 10^{17} \text{eV} \).

\( \Rightarrow \) Radio antennas well suited for \( \nu \)-induced EAS!

[Brusova et al. <0708.3834>]
GRAND project genesis

- **TREND** proposed in 2008 with P. Lautridou & D. Ardouin (Nantes) (Ardouin et al. <1007.4359>)
- 1st goal: autonomous EAS radio detection & identification.
- Small team: NAOC (Wu XiangPing + 2), IHEP (1), OM (@Beijing, 2009-2013) & V. Niess

Zhao Meng, Wu XiangPing, P. Lautridou, D. Charrier & D. Ardouin
Nantes, April 2008

TREND site, October 2008
TREND-50 (2011-2014)

- Site: Ulastai, XinJiang province, China (site of the 21CMA radio-interferometer)
- 50 monopolar antennas deployed over 1.5km²
- DAQ allowing ~200Hz trigger/antenna

TREND: 465 EAS candidates selected in 317 live days from offline analysis of radio data. Distribution as expected for EAS ⇒ **TREND goal reached:** autonomous EAS detection & identification with radio antennas is possible.
EAS radio detection unit

Waveform captures...

- Least distorted waveform
- Allows frequency studies
- High time and amplitude resolution
- Apparent simplicity of electronics
- But... High data flux & power consumption, Technologic traps

Can be also a trigger technics!

- Bandpass (high order)
- Multiplier $V(t)V'(t)$
- Low-pass (few MHz)
- Low freq. waveform
- ADC

- Perfectly mastered
- Indestructible data flux (1 word/evt !)
- High integration
- Cheaper technology

P. Lautridou
GHz workshop, Clermont-Ferrand
January 2011

Toward a second generation of stations:
fully based on mainstream technologies

- Consumpt. <2.5 W (5V*0.5A)
- WIFI/3G...
- Processing
- Storage > 16Go
- Cost <200E

Power source: 10W
(12V)
Surface 40*25cm
Cost <60E

ADC
+ Trigger
+ GPS dating

Cost objective < 800 E/station
Consumption < 5 W
Mecanics < 10 kg, no civil engineering

All in radiator head
Let’s not be shy... and go for a GIANT array!
GRAND check list

• How about a (really) GIANT array?
  ▫ Expected performances?
**Preliminary study:** 60000km²

- MC down to τ decay ($E_\nu$ in $10^{17} - 10^{21}$ eV, $\theta$ in [85-95°])
- Simplified criteria for subsequent shower detection:
  - Antenna fired if:
    - in direct view of shower
    - in a light cone of few degress ($\Omega=f(E), [0.5-3°]$)
    - Tau decay point distant by [14-120] kms.
  - Shower detected if one cluster of 8+ antennas fired.
- Simulation array = ~90000 antennas over 220x270~60000 km² in Tianshan mountains (800m step size).
GRAND $\nu$ sensitivity study - Results

- 60'000km² simulation setup
- single flavor flux $\phi(E) = \phi_0 E^{-2}$
  - no candidate in 3 years
  $\Rightarrow$ 90% CL integral limit:
  $\phi_0 < 8 \times 10^{-10} - 2 \times 10^{-9}$ GeV/cm²/sr/s

- Sensitivities > 0 for zenith values = $\pm 4^\circ$ around horizontal $\Rightarrow$ Earth-skimming trajectories only.
- Mountains are sizable targets (~40% of total).
- Earth becomes opaque at higher energies
GRAND $\nu$ sensitivity study - Results

- **Field of view**
- **Energy reconstruction**
  - ... is not possible
  - But at least we know $E_\nu > E_{sh}$
  - Do better thanks to $E_\nu$ correlation with $\tau$ time of flight (?)
- **Angular resolution**
  - Computed analytically for all detected showers in simulation from Ardouin et al., arxiv/1007.4359, assuming 3ns trigger timing precision.
  - Mean = 0.05°: full benefit of extended trigger zone.

Median = 0.02°
Mean = 0.05°
f($\Delta\theta > 1°$) = 0.2%
... thanks to mountains!
GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case?
**Cosmogenic neutrinos**

- GZK neutrinos above $10^{19.5}\text{eV}$:

  $$\text{p} + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \pi^+ + \text{n}$$

  Guaranteed flux.

  Great tool to study UHECRs.

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**AUGER composition**

**Output of GRAND 1st workshop (LPNHE, Feb. 2015):**

GRAND should GUARANTEE detection of cosmogenic neutrinos (and rate of several tens/year for reasonable models).
GRAND $\nu$ sensitivity study

- Target sensitivity: $\phi_0 = 5 \times 10^{-11}$ GeV/cm$^2$/sr/s
  ($\sim$10 times better than 60000km$^2$)
- Driver: go for hotspots! Then 200000km$^2$ may be enough to reach target sensitivity
- Giant simulation area (1’500’000 antennas over 1’000’000 km$^2$?) to identify hotspots.

Hotspot with favorable topology
$\Rightarrow$ enhanced detection rate!
$x \times 10$ in sensitivity for $x \times 3$ in surface(?)
Neutrino astronomy

- Study of populations, transient or individual violent sources (AGNs, GRBs, pulsars, etc.)
- Possible if GRAND expected sensitivity & angular resolution is reached.

Murase., astro-ph/0707.1140

Fang et al., astro-ph/1311.2044
Trans-GZK UHECRs

- Significant stat achievable thanks to huge detection area (AUGER x 60)... very valuable if competitive composition measurement
GRAND science case

• Help find & study sources of violent phenomena in the Universe through HE cosmic particle detection.
  ▫ Cosmogenic neutrinos
  ▫ Neutrino astronomy
  ▫ Trans-GZK UHECRs

• Other topics
  ▫ Epoch of Reionization
  ▫ Fast Radio Bursts
  ▫ Extreme electromagnetic atmosphere events (Elfs, Sprites, etc.)

GRAND could be a great tool for HE astrophysics (if ...), it already generates significant excitement in the community.

«White paper» to be written within 1.5 years.
GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation: on the way
    - Background rejection: GRANDproto
    - Technological challenges: leads to explore
GRAND people

- GRAND study initiated (2012-2014) with very limited resources (OM+ V. Niess for ν sensitivity study, K. Kotera for science case)
- Seminal ILP workshop @ LPNHE (Feb. 09-11, 2015)
  - 38 participants (AUGER, IceCube, ANITA, ARA, ...)
  - Define GRAND strategy: ambitious VHE neutrino astronomy + post-AUGER program
  - Interest raised, individuals getting involved.
- Work getting organised!

---

1. Markus Ahlers, University of Wisconsin, Madison
2. Keith Dziewonski, University of Wisconsin, Madison
3. Mauro Noa Bustamante Ramirez, Ohio State University
4. James Cronin, Kavli Institute for Cosmological Physics
5. Peter Denton, Fermilab/University of Chicago
6. Ke Fang, University of Maryland
7. Toshikazu Fujii, Kavli Institute for Cosmological Physics
8. Jordin Hanson, Ohio State University
10. Olivier Martineau, LPNHE Paris
11. Fotini Oikonomou, Penn State Department of Physics
12. Angela Olinto, Kavli Institute for Cosmological Physics
13. Pietro Paolo, Kavli Institute for Cosmological Physics
14. Andres Romero-Wolf, JPL
15. Albert Stubbins, Fermilab
16. Alfred Veerla, Kavli Institute for Cosmological Physics
17. Xiang-Ping Wu, National Astronomical Observatories, Chinese Academy of Sciences
(Tentative) timeline

2007 08 09 10 11 12 13 14 15 16 17 18 19 20 2022

TREND: EAS autonomous radiodetection
TREND15
TREND50 run
Data analysis

GRANDproto: study of EAS bckgd rejection
GRANDproto development
GRANDproto run

GRAND: giant array for neutrinos
GRAND preliminar study
GRAND design study
GRAND engineering array
GRAND

07/07: meeting with Wu XP
02/15: GRAND workshop
GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list
    - Ground reflexion?
GROUND reflexion

- Perfectly conducting ground: \( \sigma = +\infty \Rightarrow E_{\text{plane}} = 0 \) for \( \theta = 90^\circ \)
- BUT:
  - Mountain slopes: wave rarely parallel to ground.
  - In reality \( \sigma \neq +\infty \) (☆ full mapping of \( \sigma(x) \) ???)
  - Dedicated antenna design (large h)?
GRAND check list

- How about a (really) GIANT array?
  - Expected performances?... are promising
  - Science case?... is exciting
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation
GRAND ν sensitivity study - To Do (1)

- Set-up end-to-end MC simulation code
  - Include radio simulation:
    - ZHAireS (J. Alvarez-Muniz + W. Carvalho, Santiago di Compostella)
    - EVA (K. de Vries, UV Brussels)
    - Analytical model (J. Hansen)
  - Check very inclined showers for EVA (in progress, TREND data for x-check)
  - Implement interactions with ground (reflexion & obstacles) & antenna characteristics.
  - Full-band simulation (Cerenkov ring)
  - Transition radiation

\[ \Theta = 78^\circ, \]
EVA2015

\[ \Theta = 78^\circ, \]
EVA2014


70° shower
GRAND ν sensitivity study - To Do (2)

- Giant simulation area (1,500,000 antennas over 1,000,000 km²?)

- CPU request:
  1h/antenna * 100 antennas * 7 θ values * 8 φ values * 1000 core values = 8000 CPU x month
GRAND check list

- How about a (really) GIANT array?
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    - Rigorous simulation: on the way
    - Background rejection?
Neutrino cosmic background

Sensitivity limit for 0 candidates within 3 years...
=> Background rejection is a major challenge.

- «Cosmic» background sources:
  - Atmospheric $\nu$ and $\mu$ fluxes negligible beyond $10^{16}$eV.
  - UHECRs wrongly reconstructed below the horizon
    - «Old» showers
      ⇒ larger $X_{\text{max}}$
      ⇒ larger footprint at ground
    - Cut on reconstructed zenith angle $\theta$> horizon - $1^\circ$ kills large fraction of background thanks to angular resolution.
**Terrestrial background**

- **GRAND bckgd event rate estimation:**

  
  
  TREND50:
  ~30kEvents/day/km²
  (~1.5 \(10^7\) coincs in 317 DAQ days)

  
  **TREND50 \(\rightarrow\) GRAND:**
  Area x40000 but antenna density /25
  ⇨ Trig density /2000 (safe estimate)
  Large step size helps kill background!

  
  GRAND:
  <15 events/day/km²
  (safe estimate)
  \(3 \times 10^8\) evts/year over full array

  
  
  **TREND 2011-2012 data**
  
  [Image: TREND antenna, Reconstructed source position, HV transformer]

  
  Lesson learnt from TREND: even in remote sites, many background transient signals of various origin (HV, trains, planes, thunderstorms, etc.)

  
  Expected v event rate:
  0-100 events/year
Terrestrial background rejection

- EAS signatures
  - Trigger pattern at ground (beamed emission with flat wavefront & lateral drop)
  - Cerenkov cone
  - Polarization: $\perp B_{\text{geo}}$ & $\perp v$ at 1st order on all antennas

30-80MHz Efield computation
ZHAireS simulation code

Tau decay @ origin
Subsequent shower:
$E = 1.4 \times 10^{17}$ eV
$\theta = 89.5^\circ$

How well would polarization measurements allow background rejection?
\( \Rightarrow \text{GRANDproto} \)
(+ proposal to AERA)
Polarization measurement

- Assume that for every wave detected, the polarisation expected under EAS hypothesis can be computed within 15° for every triggered antenna.

- Then probability that a wave with random polar has an « EAS-compatible » polar is \( p = 0.02 \ldots \) For 5-antennas: \( p = 0.02^5 = 1.4 \times 10^{-9} \).

... Promising!
GRAND-proto

- Hybrid setup composed of 35 3-polar antennas + 21(+3) scintilator array
- Deployed at the noisiest location of TREND array, aiming at showers coming from North.
For all trig’d antennas, compute expected \( \eta \) and \( \beta \) from simulated voltage, assuming signal due to EAS.

- If experimental values matches computed ones: **EAS tag**
- Off-line validation of EAS candidates with scintillator array (requires known efficiency for scintillator array)

\[ \Rightarrow \text{Quantitative evaluation of EAS identification} \]
Principle of EAS polarization measurement in GRAND-proto

- How good do we have to be? A very rough estimate.
  If we allow 15° tolerance on reconstructed polarization angle:
  - Random polar may be tagged as valid for one antenna with $p=0.02$
  - $p=0.025 = 1.4 \times 10^{-9}$ for 5-antennas events
    (7 $10^{-15}$ for 8-antennas events)

- How GRANDproto can be instrumental for GRAND?
  - Valid dataset $\Leftrightarrow$ event for which EAS nature can be cross checked
    - Events from below horizon / known bckgrd sources (check bckgrd rejection)
    - Events with $(E,\theta,\phi)$ for which $\epsilon_{\text{scint}} > 90\%$
      (check signal validation)
  - Expected event rate?
    - Background: 50Hz event rate $\Rightarrow$ 1 year live to reach total stat of $1.5 \times 10^9$ events.
    - Signal: $\sim 0.5$ event/day with $E>2 \times 10^{17}\text{eV}$ for $45<\theta<70^\circ$ & $\phi$ in $\pm 20^\circ$ around North.

Q. Gou et al., GRANDproto, ICRC proceedings
GRANDproto status

- Array fully funded by NAOC & IHEP.
- 6 antennas & 6 scintillators deployed in summer 2015 to test hardware, DAQ and recons. To be completed in summer 2016.
- Radio array electronics developed @ LPNHE. Now under test, to be validated on site March 2016.
- Data taking \(\Rightarrow\) 2019.
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    - Technological challenges?
GRAND FE electronics

- GRANDproto electronics as base for developments for GRAND detection unit:
  - Pre-trigger on (filtered) antenna signal
  - Enveloppe detection by power detector
  - "Slow" sampling (100 -> 60MS/s)
GRAND trigger

- Enhanced signal processing @ FPGA level:
  - Very little done on the topic so far...
  - Could be improved because we KNOW expected signal (simulations) AND background (data).
  - Adaptative filter
  - Signal correlation
  ⇒ 2\textsuperscript{nd} level trigger @ FPGA level
  ⇒ better threshold, better background rejection

\[ d(n) = s(n) + n(n) \]
\[ y(n) = w_n x(n) \]
\[ w_{n+1} = w_n + 0.01 e(n)x(n) \]
GRAND data format & transfer

- Save minimal info: $5 \times 16 = 80$ bits per trigger
  - Trig time ($2 \times 16$ bits $\Rightarrow$ 4s)
  - Amplitude (16 bits)
  - Polarization info
    - (2 angles: $2 \times 8$ bits)
  - Others (ID, monitoring...)
- Assuming trig rate = 10Hz (☆ safe estimate?)
- 800 bits/antenna/s $\Rightarrow$ 20MBy/s data rate for full array
- Solution for data transfer? Many development in recent years for commercial applications may be useball/usefull.
  - Smart Mesh + Wireless HART
  - Wifi (802.11xx), WiMax
  - GSM
  - ...

5 GHz Commercial Wireless COMMS

- 20 dBi 90° sector antenna + Ubiquity 5 GHz Rocket M access point
- Stations: 30 dBi parabolic dish antenna + Ubiquity 5 GHz Bullet M subscriber unit

C. Timmermans @ GRAND workshop

For 150 subscribers: two 40 MHz channels in 5 GHz band gives 2 Mbps per station, required ~0.5 Mbps
The GRAND array: 200k antennas over 200’000km²?

Huge technological challenge, but not unrealistic:
- Radio-antennas as simple, robust & stable detectors.
- Keep it as basic as possible.
- Rely on industrial and validated technologies (GPS, data transfer).
- Engineering array (~1000 antennas) to validate concept & technology (CR physics)
- Lots of R&D ahead.

- Caution: science case directly impacts technical aspects.

<table>
<thead>
<tr>
<th>Neutrinos</th>
<th>UHECRs</th>
<th>FRBs, EoR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna max amplitude &amp; trig time</td>
<td>+ Waveform? + Frequency spectrum? + Large antenna aperture</td>
<td>+ ~ms-long waveforms + Higher frequencies</td>
</tr>
</tbody>
</table>
GRAND check list

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    • Background rejection: GRANDproto
    • Technological challenges: leads to explore
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  - 38 participants (AUGER, IceCube, ANITA, ARA, ...)
  - Define GRAND strategy: ambitious VHE neutrino astronomy + post-AUGER program
  - Interest raised, individuals getting involved.
- Work getting organised!
(Tentative) timeline

- **2007**
  - 07/07: meeting with Wu XP

- **2008**
  - TREND15

- **2009**
  - TREND: EAS autonomous radiodetection
  - TREND50 run
  - Data analysis

- **2010**
  - GRANDproto: study of EAS bckgd rejection
  - GRANDproto development
  - GRANDproto run

- **2011**
  - GRAND: giant array for neutrinos
  - GRAND preliminar study

- **2012**
  - GRAND design study

- **2013**
  - GRAND engineering array

- **2014**
  - GRAND

- **2015**
  - 02/15: GRAND workshop
Backup
TREND
RADIO PERFORMANCES:
DIRECTION RECONSTRUCTION

- **Plane track**

- 3037 events in 4 minutes
- $\Theta > 60^\circ$
- Max multiplicity: 40

**Point source recons**
- mult $\geq 22$ antennas
- $\sigma = 0.7^\circ$

**Total angular resolution** $< 1.5^\circ$ on the track
(and improves with smaller zenithal angle)

Estimated antenna trigger timing error: $\pm 10$ns
TREND trigger performances

- To rate <100Hz for 90% of the time on all antennas.
- DAQ efficiency ~ 70%.
- Large trigger rate variations at all time scales on all antennas: «noise bursts»
- Noise is correlated between antennas: common (physical) origin.
- Time delay between consecutive events & point reconstruction points dominantly towards HV sources.

2011-2012 data:
317 DAQ days analyzed
3.7 $10^9$ triggers recorded
2.4 $10^8$ coincidences
~10Hz average coinc rate over whole array

(see EAS/GRAND)
Absolute calibration (under development)

Use load measurement

- $\text{PSD}_{\text{load}}$: power spectrum density with input = 75Ω load.
- $\text{PSD}_{\text{ref}}$ with input = antenna right after load.
- $\text{PSD}_{\text{current}}$ with input = antenna at time $t$.

$$G_{\text{dB}}(t) = \text{PSD}_{\text{load}} + \text{PSD}_{\text{current}}(t) - \text{PSD}_{\text{ref}}$$
TREND issues

- «You get what you pay for»: system reliability questionable
  - Sudden drops in gain [not solved]
  - Aging (antennas, amplifiers, optical system, computers...)

- Significant maintenance effort required
- Reduced detection efficiency
- Monitoring of efficiency & absolute calibration (very) challenging
• Azimuth distribution (2011-2012 data)
**Discriminating parameters**

- Spherical wave recons: point source reconstruction of backgrd sources close to array, EAS more distant.

- Signal shape: prompt signal for EAS

---

**Data:**

R > 3000m

- 66% killed

**Simulated EAS:**

R > 3000m

- 92% pass

---

**Data:**

R > 3000m

- 45% killed

**Simu:**

R > 3000m

- 100% pass
Discriminating parameters

- Array trigger pattern should be continuous for EAS
  (E-field linear polarization at 1st order, random for background)

Simulated EAS
$E = 5 \times 10^{17}$ eV
85% pass

Continuous trig zone

Limited array size + monopolar antennas
(Assembly difficulties, etc.)
Environment cuts

- Bckgd events strongly correlated in time & space

Consecutive coincs: reject EAS candidate if 1+ coinc with 4+ antennas in common within 30s.

Same direction events: reject EAS candidate if 1+ coinc with 2+ antennas in common and $|\Delta \varphi| < 10^\circ$ within 10 minutes.
Cut efficiency:
from $2.4 \times 10^8$ to 465 events

<table>
<thead>
<tr>
<th>Cut</th>
<th>% survival</th>
<th>$N_{\text{coincs final}}$</th>
<th>Simu % survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>« 50Hz » cut</td>
<td>24%</td>
<td>$5.9 \times 10^7$</td>
<td>To be determined</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>56%</td>
<td>$3.3 \times 10^7$</td>
<td>100%</td>
</tr>
<tr>
<td>Multiplicity &gt; 4</td>
<td>57%</td>
<td>$1.9 \times 10^7$</td>
<td>-</td>
</tr>
<tr>
<td>Valid direction reconstruction</td>
<td>79%</td>
<td>$1.5 \times 10^7$</td>
<td>100%</td>
</tr>
<tr>
<td>Radius &gt; 3000m</td>
<td>33%</td>
<td>$5 \times 10^6$</td>
<td>92%</td>
</tr>
<tr>
<td>$\Theta &lt; 80^\circ$</td>
<td>14%</td>
<td>$7 \times 10^5$</td>
<td>/</td>
</tr>
<tr>
<td>Trigger pattern/Extension</td>
<td>15%</td>
<td>$10^5$</td>
<td>85%</td>
</tr>
<tr>
<td>Neighbourgs (direction)</td>
<td>3%</td>
<td>2600</td>
<td>To be determined</td>
</tr>
<tr>
<td>Neighbourgs</td>
<td>18%</td>
<td>465</td>
<td>To be determined</td>
</tr>
</tbody>
</table>

No cut is related to wave (absolute) arrival direction.
Possible causes for much fewer candidates:
- Array maintenance degraded (>30% antennas off)
- Bckgd noise significantly higher, affects DAQ duty cycle & acceptance (environment cuts)
TREND early days (2009-10)

- **2009:** 6 log periodic antennas: reconstruction algorithm development + autonomous trigger proof of principle.

- **2010:** 15 log-periodic antennas + 3 scintillators: independent trigger & analysis of scint data (EAS) &

Reconstruction of 3-fold scintillator coincidences $\equiv$ EAS

Selection of radio EAS candidates with dedicated algorithm

Some radio EAS candidates are coincident with scintillator coincidences + direction recon match!

<table>
<thead>
<tr>
<th>$N_{\text{ants}}$</th>
<th>$\theta_{\text{radio}}$</th>
<th>$\phi_{\text{radio}}$</th>
<th>$\theta_{\text{scint}}$</th>
<th>$\phi_{\text{scint}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$61 \pm 3$</td>
<td>$359 \pm 2$</td>
<td>$67 \pm 5$</td>
<td>$3 \pm 4$</td>
</tr>
<tr>
<td>4</td>
<td>$52 \pm 1$</td>
<td>$195 \pm 2$</td>
<td>$49 \pm 3$</td>
<td>$191 \pm 4$</td>
</tr>
<tr>
<td>5</td>
<td>$42 \pm 1$</td>
<td>$55 \pm 4$</td>
<td>$36 \pm 3$</td>
<td>$56 \pm 5$</td>
</tr>
<tr>
<td>4</td>
<td>$45 \pm 1$</td>
<td>$12 \pm 1$</td>
<td>$49 \pm 3$</td>
<td>$10 \pm 5$</td>
</tr>
<tr>
<td>7</td>
<td>$56 \pm 2$</td>
<td>$33 \pm 4$</td>
<td>$53 \pm 4$</td>
<td>$323 \pm 2$</td>
</tr>
</tbody>
</table>

First EAS identification with autonomous radio array

- Combining $8.10^{16} \& 10^{17}$ eV simulated data sets.
- Comparable zenithal, azim and multiplicity distributions (except for very inclined showers: reflexion issues or cuts?)
- Expected nb of events for threshold = $10^{17}$ eV: ~6000 in 317 days before analysis cuts. 465 observed...

Detection efficiency < 10%
ToDo: full MC simulation

- Simulate EAS events with proper distributions in flux, direction, core positions & energies.
- Generate expected antenna response to these EAS events at fixed random times.
- If 5+ triggers, insert these simulated events in experimental data (after experimental EAS candidates have been removed).
- Process these data through standard analysis chain.
- Produce simulated maps & compare to data
  - Background rejection performances
  - Detection threshold
  - Detection efficiency
The neutrino simulation ingredients

• \( \nu \) Deep Inelastic Scattering (DIS) in the rocks:
  - Integrated cross sections from Gandhi et al. (CTEQ4-DIS), but inelasticity randomised with Pythia CTEQ5d pdf.
  - The neutrino is tracked until a CC interaction occurs, its energy falls below a threshold (1 PeV typically) or it escapes the simulation volume.

• \( \tau \) propagation in rocks (energy loss+proper time):
  - **Detailed studies** of the \( \tau \) energy loss in rocks with GEANT4 simulations for various \( \tau \) initial energies. The \( \tau \) photonuclear interactions, dominant energy loss process at UHE, have been coded in GEANT4 following Dutta et al.
  - **Parameterisation** of the \( \tau \) energy loss and of the proper time spectrums according to the distance \( d \) (0-60 km) and the initial energy, \( E_0 \).
  - For the simulation, use an **hybrid Monte-Carlo scheme** for the \( \tau \) propagation in rocks (energy loss, decay) according to the parameterisations derived from GEANT4.

• \( \tau \) decays:
  - Simulated with Pythia+TAUOLA.
  - The decay daughters are logged to a file which would be served as input to the shower simulation. The daughter \( \nu_\tau \) is further simulated.
Parametrisation of $\tau$ energy loss and proper time in Standard rocks

$E = E_0 \exp(-L_E)$

$t_0 = \frac{d}{c_0 \gamma_0} \exp(L_T)$

$L_E$ and $L_T$ are $\gamma(a, b)$ distributed with a correlation factor $\sim 0.9$

$\Rightarrow$ Parameterise the $\gamma$ distribution parameters $a$ and $b$ as functions of $E_0, d$
GRAND shower parametrization

- Conical parametrization
- ONE simulated shower \( (E = 10^{17}\text{eV}) \), amplitude scaling with \( E \)

\[
E = 9.6 \times 10^{16}\text{eV}
\]

\[
E_{\text{th}} = 30\mu\text{V/m}
\]

\[
E = 7 \times 10^{17}\text{eV}
\]
ZHAireS shower profile
Detection parametrization

- **Agressive:**
  - Detection if Efield > 30µV/m
  - $\alpha = \min(1.4^\circ, \text{cone half angle})$
  - Distance to decay point in [14, 50->120] km

- **Conservative**
  - Detection if Efield > 100µV/m
  - $\alpha = \text{cone half angle}$
  - Distance to decay point in [14, 50->120] km
Simulation results
TREND EAS detection criterium(1):

- Consider **shadowing effect** (only antennas in direct view of showers)
- Discard isolated antennas ($d_{\text{closest}}>2\text{km}$)
- Request 1+ cluster with 5 antennas at least.
GRAND EAS detection criterium (2): minimum distance to shower

Minimum shower distance:
- Shower has to be distant enough to develop and produce enough $e^+/e^-$ to generate sizeable electromagnetic field.
- **5 km** seems reasonable.

@ 2000 m asl: $\rho = 0.1 \text{ g/cm}^3$

atm depth [g/cm$^2$] $\leftrightarrow$ 0.1xlength [m]
TRENDS EAS detection criterion (3): maximum distance to shower

- **Experimental situation**
  
  - **ANITA**
    - Balloon-borne experiment above the Antarctic.
    - Detection of 16 EAS (14 reflected on the ice surface) with \(<E>=1.5 \times 10^{19}\) eV, \(<d>\approx 100\) km from reflection point.

  - **CODALEMA**
    
    - Array of radio antennas on ground
    - Detection of \(10^{17}\) eV showers (with \(\varepsilon=85\%\)) \(~ 300\) m away from axis.
    - \(\varepsilon(d) = k\varepsilon_0 \exp(-d/d_0)\) and \(\varepsilon \propto E\)
GRAND ν sensitivity study - Parameters

- « Detection cone » inside which antennas trigger.
- CODALEMA:
  \[ \tan \alpha(10^{17} \text{eV}) = \frac{250}{7000 \text{m}} = 3^\circ \]
- Linear scaling of Efield with EAS energy
  \[ \varepsilon(d) = \varepsilon_o \exp(-d/d_o) \]
  \[ \varepsilon(d_{th}) = kE \exp(-\tan \alpha_{th} / \tau) \text{ with } \tau = d_o/L \]
  \[ \tan \alpha_{th} = \tau \ln \left( \frac{E}{10^{17}} \right) + \tan \alpha_{th}^{17} \]
- ANITA: radio triggers @ ~10^{19} \text{eV}
  at distances > 200kms
**TREND detection criterium (3)**

- $\alpha_{th}^{17}?$
  - CODALEMA showers:
    - $d_{max} \sim 300\text{m (CODALEMA)}$
    - $X_{max} \sim 630\text{g/cm}^2 \ @ \ 10^{17}\text{eV}$
    - And $<\theta>=30^\circ$ L~6000m
      - $\alpha_{th}^{17} = \tan(d_{max}/L) \sim 3^\circ$

- $\tau?$
  - $d_o$ in [100,400m for L~6000m] (CODALEMA)
    - $\tau = d_o/L$ in [0.017, 0.067]
TREND EAS detection criterium (4): minimum shower energy

- $E_{\text{threshold}}$?
  - CODALEMA: $\varepsilon=85\% \ @ \ 10^{17}\text{eV}$.
  - For ~horizontal showers & East-West+North-South measurements, geomagnetic effect should be more efficient.
  - Beamed emission + low attenuation: threshold should not be affected by distance to shower.

$E_{\text{th}}$ in $[3 \times 10^{16}, 3 \times 10^{17}] \text{eV}$
GRAND expected resolution

Cut out events with max deniv<100m
(2% of events)

num: 16424 mean: 0.0524 median: 0.0228
Stefan Jensen, PhD thesis (in preparation)

Table 7.2: Overview of systematic uncertainties of the average depth of shower maximum as a function of bin energy in the selected high quality data set.

<table>
<thead>
<tr>
<th>$\log_{10}[E/\text{eV}]$</th>
<th>17.9</th>
<th>18.1</th>
<th>18.3</th>
<th>18.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>gain calibration [g cm$^{-2}$]</td>
<td>4.5</td>
<td>4.2</td>
<td>3.7</td>
<td>3.4</td>
</tr>
<tr>
<td>parameterization [g cm$^{-2}$]</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>total [g cm$^{-2}$]</td>
<td>20.5</td>
<td>20.4</td>
<td>20.3</td>
<td>20.3</td>
</tr>
</tbody>
</table>

In addition, it is compared with the average $X_{\text{max}}$ as a function of energy produced by three different interaction models for showers with proton and iron primaries. The statistical uncertainty of the average value can be estimated by calculating the standard error of the average, and is represented in the plot by the error bars.

Figure 7.28: Average depth of shower maximum as function of cosmic ray energy as measured by AERA using the spectral index compared with the fluorescence measurements from the Pierre Auger observatory. The error bars of the AERA data points represent the standard error of the average. The colored band indicates the systematic uncertainty. Predictions of the depth of shower maximum of iron and proton primaries from three different interaction models are plotted as lines.

The average depth of shower maximum as a function of energy as measured with AERA using the parameterization of the spectral index of the radio pulse is compatible with the mea-
Expected minimal distance to shower for GRAND antennas

θ ~90°

1km

Expected minimal distance to shower for GRANDproto antennas

40°<θ<70°

400m

Most often antenna signal below threshold For d>700m
Tech aspects
Spectrum up to 230MHz with the Butterfly antenna at Augers Radio (CLF)

Wide spectrum(1-230MHz) achieved with a FSH3 spectrum analyser

• Galactic background visible up to 170MHz
• Very Quiet area !: strongest transmitters are only 25dB over galactic background
  ⇒ No intermodulation
• Good symmetry between North-South and East-West polarization
• 16 dipole antennas and 3 Butterfly antennas are in operation on the field for the CODALEMA experiment (Nançay, Cher, France) since 6 years.

• 3 Butterfly antennas with autonomous station are in operation on the field at Augers Radio (Malargüe, Argentina) since one month.

• Both antennas are fat active dipole.
• The CODALEMA dipole antenna is mono polarization.
• The Butterfly antenna is a Dual polarization.
Didier Charrier ARE NA 2010, June 29 – July 2, Université de Nantes

### LNA board characteristics

<table>
<thead>
<tr>
<th>Input type</th>
<th>Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input resistance</td>
<td>300Ω</td>
</tr>
<tr>
<td>Input reactance</td>
<td>6pF // 1uH</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>A=26dB</td>
</tr>
<tr>
<td>1dB compression point</td>
<td>OCP=7dBm</td>
</tr>
<tr>
<td></td>
<td>ICP=8.8mV on 300Ω</td>
</tr>
<tr>
<td>Out reflection coefficient</td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>6V to 15V by signal</td>
</tr>
<tr>
<td>Consumption</td>
<td>2 x 52mA, 625mW</td>
</tr>
<tr>
<td>Gain temperature drift</td>
<td>-0.026 dB/°C</td>
</tr>
</tbody>
</table>
Evolution from the CODALEMA active dipole to the Butterfly antenna

- The radio background can’t be used at DC-20MHz and 88-108MHz band
- Cosmic rays detection is supposed to be better with low frequencies
  ⇒ Frequency range of the butterfly is maximized for the 25-90MHz band
- Butterfly sensitivity is much better for this frequency range
Beverage antennas
GRAND antennas

- Broadband & sensitive — active antennas (*a la SUBATECH*)
- Signal expected around horizon: limit lobe to few (~20?) degrees in zenith to improve signal/noise ratio & optimize threshold.
## Budget for the detection unit

<table>
<thead>
<tr>
<th>Element</th>
<th>Power consumption</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>-</td>
<td>10$</td>
</tr>
<tr>
<td>LNA</td>
<td>~500mW</td>
<td>&lt;10$ x3</td>
</tr>
<tr>
<td>Filter</td>
<td>-</td>
<td>&lt;20$ x3</td>
</tr>
<tr>
<td>Signal detection (shape selection &amp; trigger)</td>
<td>negligable</td>
<td>~10$x3</td>
</tr>
<tr>
<td>ADC+FPGA</td>
<td>~150mW</td>
<td>~50$</td>
</tr>
<tr>
<td>GPS</td>
<td>~100mW</td>
<td>&lt;50$</td>
</tr>
<tr>
<td>Com.</td>
<td>~100mW</td>
<td>10$ or ?</td>
</tr>
<tr>
<td>Power generator: solar pannel (or wind mill?)</td>
<td>-</td>
<td>~50$</td>
</tr>
<tr>
<td>Mechanics</td>
<td>-</td>
<td>100$</td>
</tr>
<tr>
<td>Cables, connectors &amp; PCB</td>
<td>-</td>
<td>100$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 1W</td>
<td><strong>490$</strong></td>
</tr>
</tbody>
</table>

Should remain below 2W & ~500$/unit.
GRANDproto FE electronics

- Analog card: noise level @ nominal perfs + signals observed onsite.
- Numerical card tests under way since November.