WaveCatcher Electronics for ALTO
VHE Gamma-Ray wide-field observatory: From tests to prototypes to implementation possibilities

http://alto-gamma-ray-observatory.org

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--- for the ALTO group ----
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The ALTO project

• Project born in 2014 at Linnaeus University after we received a research grant from the Crafoord Foundation (Sweden)

• A Wide Field-of-View (~ 2 sr) gamma-ray observatory:

  • In the Southern hemisphere → Daily observations of Southern sources
  • At high altitude (~ 5 km) → Low threshold $E \geq 200$ GeV
  • Particle detectors → Observations may be done 24h per day
  • Hybrid detectors → Improved S/B discrimination
  • Excellent timing accuracy → Improved angular resolution (~ $0.1^\circ$ at few TeV)
  • Modular design → Phased construction and easy maintenance
  • Simple to construct → Minimize human intervention at high-altitude
  • Long duration → Should operate for 30 years
  • “Open Observatory” → Distribute data to the community “à la Fermi-LAT”
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**ALTO Science Goals**

**Daily monitoring of Southern targets:**

- Transients and variable sources;
- Active Galactic Nuclei, Gamma-Ray Bursts (if spectra favourable), X-ray binaries;
- Galactic centre and central region;
- Alerts to other observatories;
- Multi-year light-curves;
- High-end of the sources’ spectra;
- Search for Pevatrons;

**Study of extended sources:**

Fermi Bubbles, Vela SNR, AGN radio lobes;

Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory, and Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR)

**Other accessible goals:**

- Search in past data if detections of:
  - gravitational waves or neutrinos;
- Study of the cosmic-ray composition and anisotropy;
- Dark matter searches;
- EBL studies (if threshold low enough);
- Search for Lorentz invariance violation;
- Axion-like particles from distant AGNs.

**H.E.S.S. PKS 2155-304 (blazar) flare**

![Graph showing the Crab flux level over time](image)

**Cen A**

**Crab flux level**
# Current Collaboration

## Sweden
- Department of Physics and Electrical Engineering, Linnaeus University, Växjö
  - PI Yvonne Becherini
  - Post-doc Satyendra Thoudam
  - Two PhD students **just started** (50%)
    - Mohanraj Seniappan: MVA Rejection
    - Tomas Bylund: DAQ & Control
- Industry: TBS Yard AB, Torsås
  - Industrial construction, responsible Lars Tedehammar

## France
- APC Laboratory, IN2P3/CNRS, Paris
  - Michael Punch
  - Contacts with Jean-Christophe Hamilton (discussions about the site)
- Aix-Marseille University
  - Jean-Pierre Ernenwein
- LAL/Orsay
  - Dominique Breton (discussions on electronics)
- CEA/Saclay
  - Eric Delagnes (discussions on electronics)

**Discussions with other parties in Academia/Research Institutes:**
- Los Alamos Laboratory, U.S.
- North-West University, Potchefstroom, South Africa
Key design characteristics of the full array

- Altitude (~ 5km):
  - For Physics goals, as a survey/alert instrument for transients

- Fine-grained array of 1242 units:
  - Smaller WCD (Water Cherenkov Detector) than existing Northern HAWC
  - Low dead-space ("packing factor" ~70%)
  - Improved angular resolution
An ALTO detection unit

• **Water Cherenkov tank:**
  - Contains one Hamamatsu super-bialkali 8” PMT (10 dynodes) plus light-guide “crown”;

• **Muon-detector tank** for background rejection:
  - Liquid scintillator box (LAB+PPO+POPOP) (Scintillator Layer Detector, SLD) with one Hamamatsu standard QE 8” PMT (10 dynodes);
  - Water Cherenkov also a possibility

• **Advanced electronics** for 6-tank “cluster”, WaveCatcher + White Rabbit:
  - Trigger channel precisely time-stamped with “White Rabbit” system (ns precision);
  - Analogue memories + ADCs to measure the waveform of the detector pulses;
  - No cables from central DAQ room, only fibres.
An ALTO “cluster”

Cluster = Group of 6 Units
= 6 x (WCD + SLD)

- WCDs on concrete “table”
- SLDs below “table”, on telescopic rails

Each cluster to have common:

- Electronics readout unit
- Solar panel + battery
- Communication/data to central DAQ room by fibre only
ALTO Electronics

- Readout electronics box, powered by solar panels
- Communications, by fibre-optic connections only, to central DAQ
- Electronics box containing:
  - **SBC**, Single Board Computer (Arduino / BeagleBone ...) or similar
    - For local control and monitoring, autonomy in case of connection loss
    - Analogue I/O for control of PMT active bases, readout of temperatures (e.g. USB LabJack)
- **“WaveCatcher”**
  - 12-channel version, i.e. 16 minus 1 mezzanine
    - Would be well adapted for ALTO
    - BUT, majority trigger logic on all channels
    - Low power consumption (∼20W)
  - Output data
    - Either copper ethernet UDP through switch to SBC
    - Or direct fibre to central DAQ
  - **TiCKS White Rabbit node** (or firmware-modified SPEC)
    - Time-stamping of WaveCatcher Read-out trigger to ns precision
    - Dedicated single-mode 1Gb optical fibre required to central DAQ
      (White Rabbit Switch Stack for time distribution)

- In **Central DAQ**, 
  - Time stamps reunited with their WaveCatcher data by their event counters
  - Coincidence logic applied to time-stamps in software gives Array Trigger
    (cluster multiplicity/topology)
**ALTO Electronics**

- **Per cluster**
  - 6 (Up) Cherenkov Channels
  - 6 (Down) Muon channels

- **Rates**
  - Expect $< 20$kHz singles rates
  - 20ns hardware coincidence window reasonable
  - 2-fold coincidence rate with 12 channels $\rightarrow$ 1 kHz

- **Coincidence:**
  - Ideally OR of
    - majority 2/6-Up or
    - any pair Up-Down
  - But can live with existing 2/n Majority logic
    - Maybe finer logic in 2$^{nd}$ step by LUT sent to FPGA to reduce data rate?

- **Read-out characteristics:**
  - Few tens of ns (maybe more pre-pulse to have baseline), lower is better for dead-time
  - GHz sampling is probably sufficient (lower would give lower dead-time)
    - Simulations re-analysis to find how coarse to go without degrading angular resolution
  - *(note, full reconstruction and S/B rejection chain needed to close this loop... soon ready)*
ALTO Unit response to single particles

Muon (1 GeV) vs Electron (1 GeV)

Strong signal in scintillator
Weak signal in scintillator

Trigger threshold
ALTO Array response to Air Showers

**Gamma ray**
- More compact
- Regular pattern

**Cosmic-ray proton**
- Clumpy
- Hot spots in the muon detectors far from core
ALTO Pre-prototyping: tests in laboratory

- Many test-benches, all with readout triggered by small (10x20cm) muon-paddles, read by “WaveCatcher”
- All compared with GEANT4 simulations to find reflectivity, absorption, etc.
- Small water tank viewed from above by 8” PMT (next slide), to test
  - blackness of the internal “gel-coat”
  - Effects over time with strong chlorine concentration (bio-growth, leaching)
  - → 20x normal swimming pool concentration OK for now
- “Scintillator rails” read by 2” PMT
  - To test Aluminium material used in lower tank
  - Comparison of measured and expected (from GEANT4 simulations, adjusting reflectivity & polish)
  - → led to redesign using folded 0.5mm Al sheet
  - No welding, much simpler construction
- Large scintillator tank read by 8” PMT
  - To test aluminium material with final PMT immersed in Scintillator
  - Test of re-design → Confirmation of simplicity of construction
  - Result scalable to full-sized tank (factor ~x2 PE from reflections on walls)
- Comparison with a deeper (10cm) tank with Water (not scintillator)
  + Tyvek as reflector to replace scintillator tank, currently running
  - May be able to reduce costs, avoid some radioactivity triggers (see next slides)
Tests in laboratory, small-scale upper tank

Long term test (6 months) to verify the possible interaction of water-black gel coat

50cm x 50cm x 50cm test box with final black gelcoat.

In dark room

- black gelcoat
- water

Only ~1-2 pe seen by the PMT

Muon : ~15000 photons produced in total in the water

Muon detector 1

Cherenkov light

Trigger = 1&2 in 60ns

Muon detector 2

Long term tests:
- wall reflectivity/water transparency
- electronics: Matacq & WaveCatcher
- 2” then 8” PMT

Linnaeus University
Tests in laboratory

\[ \text{Eff} = \frac{N_\mu \text{ in triggers \& water}}{N_\mu \text{ in triggers}} \]

MATACQ 1 GHz (4096 samples) + multiplicity board building a coincidence NIM signal from muon detectors.

WaveCatcher 1.1 GHz (1024 samples), coinc. trigger built from muon detectors.

Chlorine (x20 wrt std concentration)

- Mirror
- Diffuser on mirror
- Water changed
- 2"
- Black walls
- 8" + black walls

Trigger failure

M 1pe 2pe
Test of small-scale bottom tank
(area=area of final tank/10)

Tests of:
Water
(Cherenkov)
and
LAB+PPO+POPOP
(Scintillation)

Reflector in tanks:
aluminium, Tyvek
Collected $p_e = f$(trigger distance from PMT center)

Cherenkov case (Water+Tyvek+super bialkali R5912 Hamamatsu with gain $10^7$)

Threshold $3p_e \rightarrow 98\%$ efficiency and single rate $1.3$ kHz
Results of tests in dark room, next steps

- R5912-SB Hamamatsu @gain $10^7$ + ISEG PHQ 7081SEL_4 + WaveCatcher perfectly suitable for bottom tank in the 2 studied options: water or liquid scintillator.
- The same chain will be used in the top tank (chain is also suitable according to simulations).
- Full test will be done with the Växjö prototype.
- The test setups use Labview+USB (max rate of 1 event/s), and 1024 samples @ 1.07 GHz.
- The Växjö prototype and next steps will use a linux software+UDP (to be developed).

For expected 2-fold coincidence rate with 12 channels is 1 kHz (assuming 20kHz single rate and 20ns window). ing → Basic tests with labview+UDP and 48 samples @ 2GHz on 8 channels work up to ~3000 evts/s.
ALTO prototype at Linnaeus University in Växjö, Sweden

- Construction stared January 9\textsuperscript{th} 2018
- Several PMT solutions will be tested; along with comparison scintillator/water for the lower tank.
- Fully funded: construction of two full ALTO units, with 4-tank concrete layer
- The empty slots will be equipped with (smaller) additional scintillator boxes

Additional scintillator layers recycled from an on-board air-shower array used for ANTARES calibration purposes
ALTO prototype setup in Växjö

Water Tank
(25 m³, 500kg empty)

Carbon fiber
(black "gel-coat" painted inside)

Scintillator Tank
(0.33 m³)
Aluminum
(reflective inside)

concrete
ALTO prototype setup in Växjö
We received the building permit
Currently the water tanks (carbon fibre and PVC foam) being produced in Torsås by TBS Yard AB
Bottom Aluminium tank to start when design is finalized (see “tests in lab”)
Ground preparation completed, using existing pipe for fibres/poser
Next step will be the installation of tanks
Tests...
ALTO prototype construction at Linnaeus University: Status

Concrete table construction (is completed now)

Upper tanks completed, will be moved from factory to Växjö in 4 weeks.

PMT housing: plexigass tube (housing PMT, active base). Sealing with Wacker potting. Will be placed in the center of the tank floor.
Project timeline & Next steps

- 2018 - Validation of prototype design;
  - At LnU campus, with “Antares Surface Array”

- 2019 - If design & funding requests successful:
  - Installation of one or more ALTO clusters at the site in the Southern hemisphere;
  - Flat-pack construction ("IKEA-type") assembly by local crew or "base camp"

<table>
<thead>
<tr>
<th>2018-Q1</th>
<th>2018-Q2-Q4</th>
<th>2019?</th>
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<tbody>
<tr>
<td>Prototype construction</td>
<td>Prototype validation and operation</td>
<td>Installation of one or more clusters at the final site for further validation</td>
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• Presence of water nearby is a key factor, to lower the costs
• In order to simplify and be quick, we are aiming for the installation of 2-3 full ALTO clusters behind the site of QUBIC/LLAMA in Argentina, at an altitude of 4850 m
  • Synergies within APC lab which is working on QUBIC
• We should be in the back lobe of QUBIC in order not to disturb the QUBIC experiment data taking
• There might also be the possibility to share infrastructure, power, network, roads
• The 2-3 cluster installation will allow us
  • To further test the construction feasibility at high altitude
  • To acquire further experience on singles and coincidence rates
  • To build partnerships with local industries
Conclusions

- ALTO is a new project, financially supported primarily by Linnaeus University and Swedish private Foundations for now;
- The project’s aim:
  → to build a wide FoV VHE gamma-ray observatory with enhanced sensitivity with respect to current WCDA technology;
- Simple design:
  → limits costs of construction in full production phase; Prototype costs higher;
- Collaboration between Academia and Industry:
  → cost-effective solutions;
  → knowledge transfer benefiting both parties;
- Possible location of the observatory:
  → Argentina, near QUBIC/LLAMA;
- Aimed investment cost for full deployment
  → ~ 20M€ excluding salaries;
- Expansion of collaboration:
  → to cover costs, expertise in readout electronics:
    WaveCatcher, expertise in DAQ, design optimisation
- Status of the project with further information can be found at the website:
  → http://alto-gamma-ray-observatory.org/

For enquiries about the project, please contact yvonne.becherini@lnu.se
Feedback on WaveCatcher

- We are **very happy** with the WaveCatcher performance
- **Responsiveness** of Dominique and Jihane very good

We would need:
- For 16 (→ 12) channel wavecatcher, to have majority logic over all channels
- Operation with Linux (Python would be nice)
- ~200 WaveCatchers, if we get funding for full array!

We would like:
- Quieter fans (only for versions in lab, in the field no problem)
- Possibility to connect to heat-pipes for cooling (thin atmosphere at 5km)
- Some more complex combinatorial logic to reject some events
  - Pre-trigger, to lower dead-time or
  - Post-trigger, for lower data rate
- Separate “Read-out” and “Busy” triggers and counters, with corresponding outputs to go to White Rabbit node (to ensure counters stay in sync)

- Mode where only triggered channels data(discussed here), could interest us... need to look at MCs...
Backups
Exploded view of Water Tank
Exploded view of Scintillator Tank