Search for Cosmic Particles With the Moon and LOFAR

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The LOw Frequency ARray

- Fully digital radio telescope
- 48 Stations throughout Europe
- Dense core of 24 stations in the Netherlands
The LOw Frequency ARray

- 24 Core stations
  - 96 Low-Band (10 – 90 MHz) antennas
  - 768 High-Band (110 – 240 MHz) antennas

LBA antennas

HBA tiles of 4x4 antennas
Observation Strategy

- HBA Antennas have optimal frequency range
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to check lunar origin

Challenges

- Data rate 0.8 GiB/s per station/beam
  → Trigger required
- LOFAR designed to integrate flux
  - Reconstruct time series from filtered signal for trigger
  - Use buffered traces for analysis
Online Data Analysis

Station
- HBA Antennas
- ADC
- Polyphase Filter
- Station Beamformer
- Select Subbands
- Dump Buffers

Computing Cluster
- Tied Array Beam
- Invert Poly. Filter
- Ion. Dedispersion
- Trigger Logic

Requirements:
- Real time
- Trigger within 5s

blocks of subband spectra 24x6.2 Gbit/s
Signal Filtering @ LOFAR

- Decompose signal into subbands
- Example signal 16,184 samples
  - White noise
  - Transmitter: 123.42 MHz
  - Sampling freq. 200MHz
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF
  + avoids smearing
  - Reduces time resolution from 5 ns to ~5 us
Polyphase Filter

1. Matrix product
\[ Hx = y \]

2. Fourier transformation
\[ \mathcal{F}(y) = \tilde{y} \]
Inverse Polyphase Filter (PPF\(^{-1}\))

\[
\mathcal{F}^{-1}(\tilde{y}) = y
\]

- Direct inversion of FIR filter
  \[
  H^{-1}y = \hat{x}
  \]

  Inverse does not exists as H is not square

- Approximate inverse
  \[
  Gy \approx \hat{x} \quad GH \approx I
  \]

  Supposed to be numerically unstable / produces artifacts (spikes)

- Robust approach: Solve linear system
  \[
  H\hat{x} = y
  \]

  using iterative least least squares (LSMR)

  \[
  \min_{\hat{x}} \|H\hat{x} - y\|
  \]
PPF⁻¹ Example

Input: White Noise + Pulses

Reconstructed Signal
Accuracy of PPF Inversion

→ Almost perfect inversion of PPF possible:
  Numeric noise with spikes at ~ 30% of noise level
  Uncorrelated with pulse position

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Performance Prototype Pipeline

- Beamforming << Realtime (CPU)
- Dedispersion << Realtime (GPU)
- PPF Synthesis 160% Realtime (GPU)

Prototype implementation on Nijmegen cluster
CPU: Xeon-2660 (2012)
GPU: M2090
DRAGNET Cluster

- **Designed for Pulsar searches** (J. Hessels et al.)
  - 23 worker nodes
    - 16 CPU cores (2x Xeon E5-2630v3 (2014))
    - 128 GiB ram
    - 4x TitanX GPU
    - 56 Gbit/s Infiniband connection to LOFAR
  - = 92 High-End GPUs + CPUs ; 0.5 PetaFLOPs

- **Estimate based on prototype implementation:**
  - 2 beams per node,
  - Computing power allows 46 beams total:
    - Full coverage of the moon with .1 deg beams possible
Sensitivity Optimization

COSMIC RAYS

$E^2 J(E) \text{ [km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}]$

7d LOFAR
Auger 2015
Telescope Array 2013

NEUTRINOS

$E^2 J(E) \text{ [km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}]$

Auger 2015
IceCube 2013
Anita 2012
WSRT 2014
LOFAR

PRELIMINARY
Sensitivity Optimization

**COSMIC RAYS**

- **Energy Threshold:**
  - Number of Stations
  - Shape of beams
  - ...

- **Sensitivity:**
  - Number of Beams
  - Observation Time
  - ...

**NEUTRINOS**

- **Energy Threshold:**
  - Number of Stations
  - Shape of beams
  - ...

- **Sensitivity:**
  - Number of Beams
  - Observation Time
  - ...

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![Graphs showing sensitivity of cosmic rays and neutrinos](image.png)
Conclusions

- LOFAR High-Band antennas optimal for lunar Askaryan
- Online analysis requires inversion of polyphase filter
  - Inverse almost perfect: Regular spikes at ~30% noise level
  - Computationally expensive
- DRAGNET GPU/CPU cluster available
- First test-run in preparation
- Next talk by Sander ter Veen:
  - Trigger strategies, TEC measurements, offline processing, ...
Backup
LOFAR Network

Core Station 1
... 10 Gbit/s
Core Station 24

10 Gbit/s

10 Gbit/s

COBALT

Infiniband 56 Gbit/s

Ethernet 10 Gbit/s

DRAGNET

Infiniband 56 Gbit/s

Ethernet 10 Gbit/s

Worker Node 1
Worker Node ...
Worker Node 23

Port 1 Gbit/s

Process. Node

Head Node

Portal
2 Step Online Processing

- COBALT Cluster
  - Tied Array Beam
  - ~5 `Proto' Beams
  - Full-Moon
  - 31 Gbit/s

- DRAGNET Cluster
  - 46 Tied Array Beams
  - PPF Synthesis
  - Ion. Dedispersion
  - Trigger Logic

Requirements:
- Real time
- Latency < 5s

blocks of subband spectra 24x6.2 Gbit/s
Pulse Reflected at High Frequencies

- Radiation emitted in Cherenkov cone
- Cherenkov angle == Angle of total reflection
- Upgoing shower required / rely on surface roughness
Pulse Escapes at Low Frequencies

- Cherenkov cone is broader at low frequencies
- Also downgoing showers detectable
- Optimum in 100 - 200 MHz range (Scholten et al. 2006)
Dispersion

- Frequency dependent time delay of pulse due to free electrons in ionosphere

\[ \Delta t(\nu) = 1.34 \frac{STEC}{TECU} \left( \frac{\nu}{\text{Hz}} \right)^{-2} \text{ s} \]

STEC: Standard electr. content

1 TECU = $10^{16}$ electrons / m$^2$

- Typical values 5 - 100 TECU
  > 500 ns delay between 100 MHz and 200 MHz
Dedispersion

Recovery of 99% of amplitude possible
PPF results in 30% fluctuations with small TEC values → need to scan multiple TEC values