Status of the Lunar Detection Mode for Cosmic Particles of 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
  - 96 Low-Band (10 – 90 MHz) antennas
  - 768 High-Band (110 – 240 MHz) antennas
A Fully Digital Radio Telescope

Conventional radio telescope:
Mechanically point (few) directional antennas into observing direction + combine signals
Observe only one direction at a time

Digital radio telescope:
Many omni-directional antennas digitally combine signals according to direction
Observe multiple directions simultaneously

Nancay Radioheliograph, 2009

LOFAR Core, 2012
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 validate lunar origin

Challenge:
LOFAR designed to integrate flux, user access only to processed signal
- Reconstruct ns time series from processed 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

- Real time
- Trigger within 5s

Requires O(1000GFLOPs) computing power per beam:
Beyond standard LOFAR capabilities

blocks (250 ms) of subband spectra 24x6.2 Gbit/s
DRAGNET Cluster

- Designed for Pulsar searches with LOFAR  
  (J. Hessels et al., Amsterdam)

- 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 PetaFLOP/s

+ Performance of prototype implementation allows full coverage of moon

- Bandwidth limited to processing data of 5 / 24 stations  
  → Implications on Beamshape + Performance
Full Simulation

1. Simulate Physical Detector
   - E-Field Pulse
   - Fold with tile gain-pattern
   - Voltage in Stations

2. Simulate Pre-Processing
   - Voltage in Stations
   - PPF
   - Other Filters
   - Station Beams

3. Online Analysis
   - Station Beam
   - PPF Inversion
   - De Dispersion
   - Analysis Beams on Moon
   - Trigger
Simulated Pulse from Moon Center

Signal trace in 49 Analysis Beams at different points on the moon.

→ Pulse Visible in several beams

Tobias Winchen - Lunar Detection of Cosmic Particles
Simulated Pulse from Horizon (RFI)

Signal trace in 49 Analysis Beams at different points on the moon.

→ RFI Visible in all beams with similar intensity
RFI visible in Data

- 0.14s of TBB Data (not on Moon)
- Processed by Analysis/Simulation pipeline
Threshold Trigger

Limit trigger rate to 1/min to reduce data transfer
Ionospheric Dedispersion

- EM Pulse from Moon pass through Ionosphere
- Frequency dependent dispersion
- Dispersion depends on electron content of ionosphere (STEC)
  \[ \Delta t(\nu) = 1.34 \frac{STEC}{TECU} \left( \frac{\nu}{\text{Hz}} \right)^{-2} \text{s} \]
  1 TECU = $10^{16}$ electrons / m²
- STEC not known exactly → Test as many STEC-Values as possible
DeDispersion – STEC Accuracy

- Simulated STEC varies distributed around 20 TECU with spread 1 TECU
- Always corrected for 20 TECU

- 1 TECU uncertainty on Ionosphere corresponds to roughly factor 2 in E-Field threshold for 100% efficient reconstruction
- The minimum detectable field is not affected that significantly

- We probably can know the STEC better than 1 TECU (~0.1 TECU reported by Zelle et al, 2015.)
Difference to previous values (Bray 2016):
- 5 instead of 24 stations
- Increased bandwidth
- Reduced trigger threshold
- Full detector simulation instead of semi-analytical parametrization

Caution: Still relies on semi-analytical model for pulse escape from moon
Conclusions

- Search Cosmic Particles on ZeV scale via Lunar-Askaryan-Effect with LOFAR (and SKA in future)
  - Full Simulation of Process + Prototype Implementation
    - Analysis + Simulation software ready:
      - PPF Inversion, Dedispersion, Beamforming, Filter
    - Preliminary design choices for station selections, etc.
    - Design of trigger + sensitivity calculation (In progress)
  - Coincidence trigger imposes no upper limit on detectable pulses
  - Including regime with low efficiency reduces energy threshold for limits

- Outlook
  - Implementation of Online System in progress
  - First commissioning data (1 min) taken (analysis ongoing)
  - Further commissioning runs + integration of software in LOFAR systems in Summer 2018
  - Proposal for observation runs 2018/2019 (LOFAR cycle 11+)

PhD + PostDoc positions open in Brussels
Backup
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)
Inversion of Polyphase Filter

- Filter to decompose signal into subbands
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF
  + avoids frequency smearing
  - Reduces time resolution from 5 ns to ~5 us
- Inversion with small error possible, but computationally intensive:
  \[ O(1000) \text{ GFLOP / s / beam} \]
- As much computing power as possible needed for dedispersion + trigger

**Not available on regular system, requires additional computing power**
- Use DRAGNET, CPU/GPU cluster for pulsar searches
Polyphase Filter

N Samples | N Samples | N Samples | N Samples | N Samples | ... |

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 squares (LSMR)

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

Input: White Noise + Pulses

Reconstructed Signal
Dedispersion

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

- Available bandwidth to DRAGNET limited to ~ 5 stations
- Choose FULL stations as grating lobes have only weak influence on analysis beams

Preliminary set:
CS003, CS013, CS030, CS031, CS301
Analysis Beams
**LOFAR Network**

<table>
<thead>
<tr>
<th>Core Station 1</th>
<th>10 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Core Station 24</td>
<td>10 Gbit/s</td>
</tr>
</tbody>
</table>

Data rate of each station: 6.2 Gbit/s

Bandwidth Limited: 24 x 6.2 Gbit/s >> 56 Gbit/s

Consequences:
- Can use only data of 5 stations (maybe more with preprocessing)
- Select stations → Beam properties?
- Beamforming on dragnet
- Distribute data among nodes
Online System: Data Broadcast

- Serial: $O(N)$
- Binary tree: $O(\log_2 N)$
- Hardware Multicast: $O(1)$

Prototype for online system in progress
Performance Prototype Pipeline

- Beamforming: CPU
- PPF Synthesis: GPU (160% Realtime)
- Dedispersion: GPU
RFI Suppression: (‘Anti - Coincidence’)
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**Signal:**
- Pulse from random* position on Moon
- + 20 +/- 1 TECU DeDispersion
- + TBB background (no RFI)

**Background:**
- Strong pulse from horizon
- + DeDispersion 20 TECU
- + TBB background (no RFI)

Strong signals might trigger all beams

* isotropically in solid angle covered by Moon – pdf of possible impact angles not included!
Trigger in Every Beam

Good signal / background separation for strong signals
→ Anti-coincidence does not limit energy range!
Angular Resolution of Lunar Mode

- Limit observations to rim
- Possible Incident angles yield \(\sim 5^\circ\) resolution
- Explicit reconstruction should do better

Cosmic Ray Excess at 15\(^\circ\) scales


James, 2016
Challenge HBA Calibration

- Analog Beamforming of HBA Antennas to Tile
  - Gain pattern (of tile) varies between events (beam direction) and stations (orientation of tiles)

![Gain pattern diagrams for CS003, CS013, CS501]

- Beam direction 20°, 20°
- Beam direction 45°, 120°
Calibration

→ Frequency dependency of same order of uncertainty
→ Use average value independent on frequency to simplify procedure

Next step: Investigate directional dependency using constant value for electronic noise
Differences between Stations

Calibration constant varies between stations by +/- 18%

\[ \Delta C = \frac{c_i - c_j}{\frac{1}{2}(c_i + c_j)} \]
Directional Consistency

Color = Calibration value for event in direction

There is some directional structure in calibration constants
→ Look at variation between nearby beam directions
Directional Consistency

- Exclude values from celestial pole
- Histogram difference between calibration constant of events as function of angular distance

Some events with large discrepancy,
**Most close-by calibration constants within +/- 8% of each other**
Conclusion: HBA calibration

- HBA Calibration on Event-Event basis
- Uncertainty of calibration +/- 36 % (in Power)
  - +/- 30% from frequency dependency
  - +/- 18% from difference between stations
  - +/- 10% based on variation of similar directions