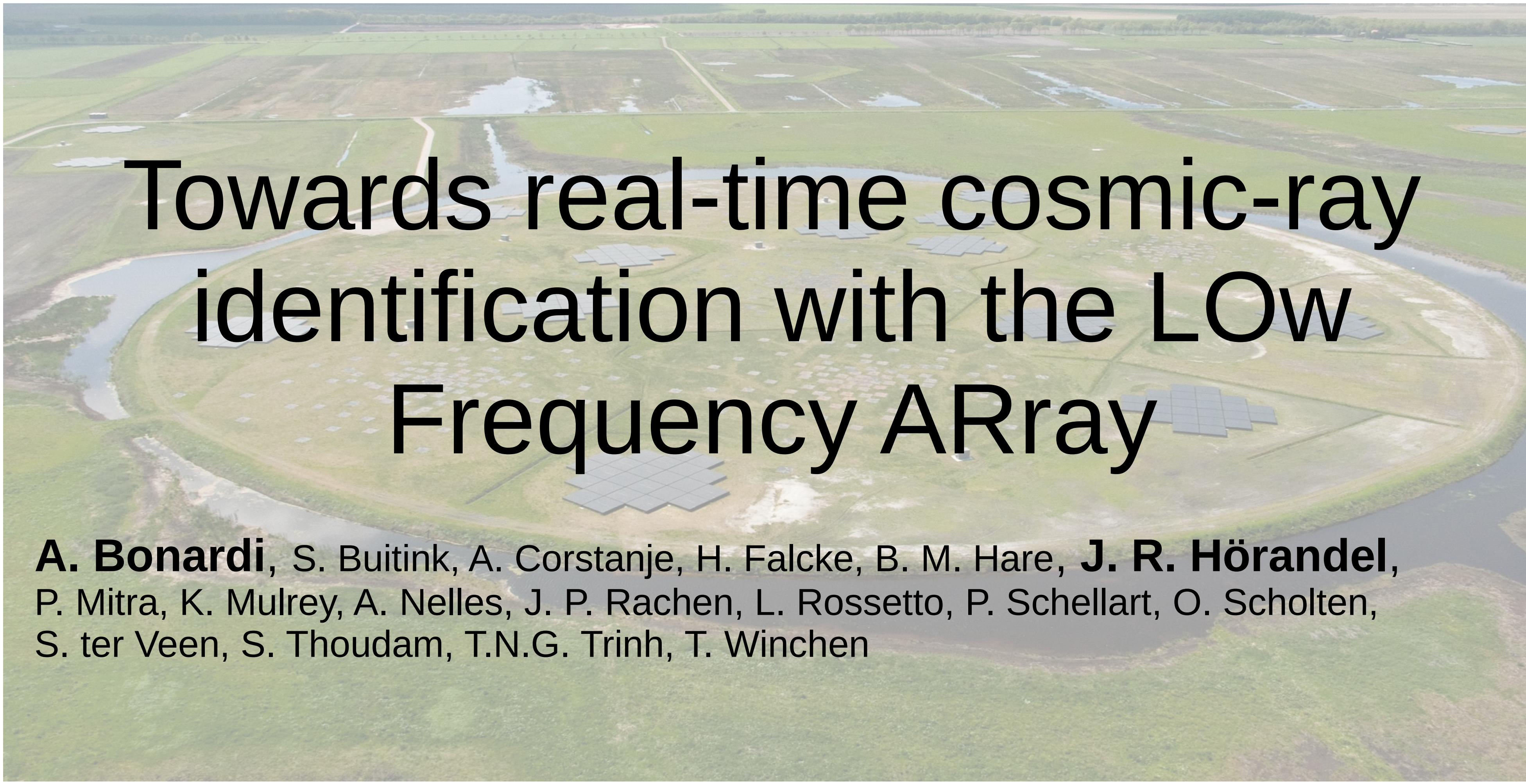
Towards real-time cosmic-ray identification with the Low Frequency ARray

del Sud

Catania, 12th -15th June 2018

Radboud University LOFAR ARENA



Towards real-time cosmic-ray identification with the LOw Frequency ARray

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Acoustic and Radio EeV Neutrino Detection Activities Conference Catania, 15th June 2018

The LOw Frequency ARray

50 stations in Northern Europe

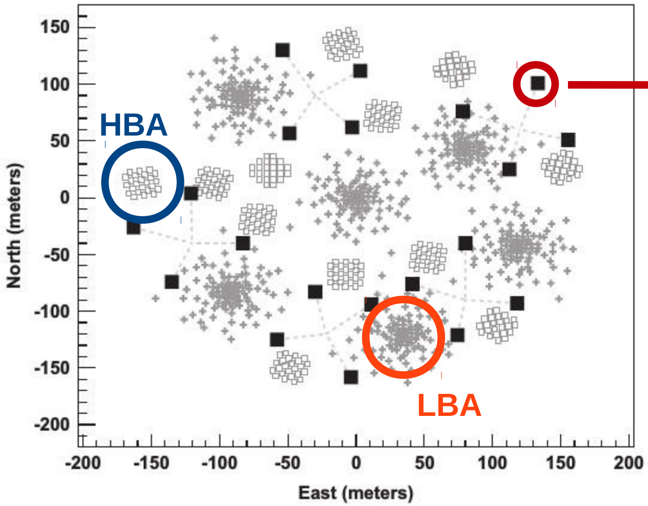
6 stations in the SuperTerp, the densest region

For each station 96 LBA (10-90 MHz) and 96(48) HBA (110-240 MHz)

Observations are driven by astronomical targets (ToOs)

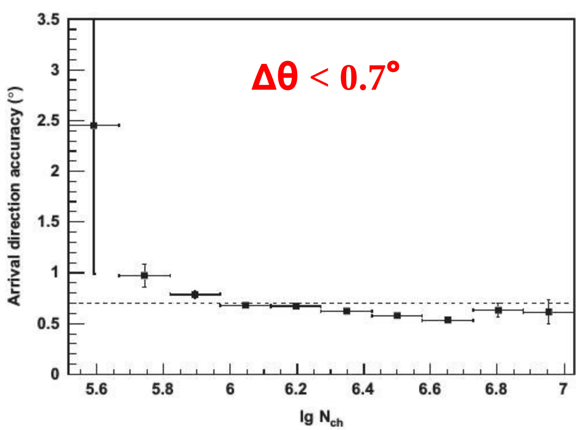
When a CR trigger occurs, the time buffer of the 24 closest stations is downloaded for the off-line analysis

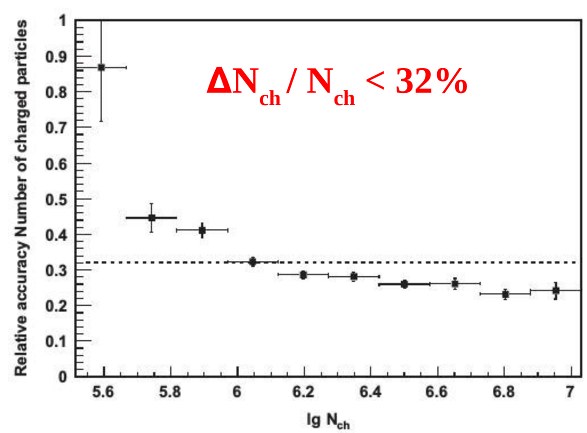
The LOfar Radboud Air Shower Array

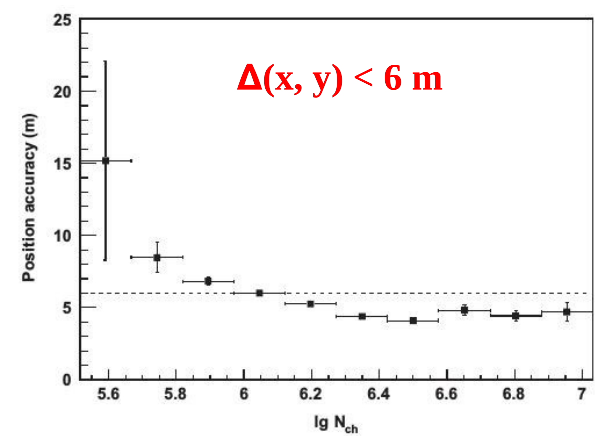


20 scintillator detectors (~ 1 m² each) located in the SuperTerp:

- trigger for LOFAR CR detection
- position and arrival direction measurement
- energy measurement between 10^{16} – 10^{19} eV
- area covered ~ $7 \cdot 10^4$ m^2





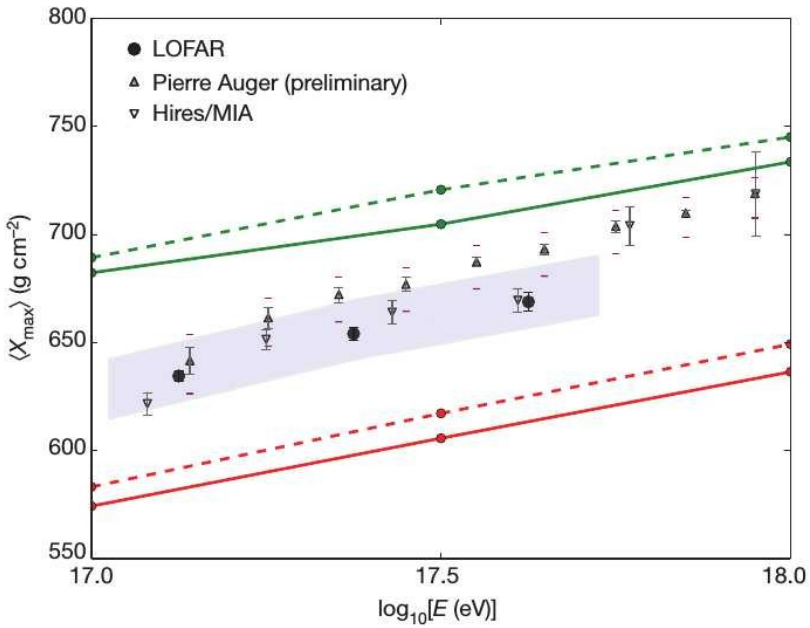


S. Thoudam et al., Nucl. Inst. Meth. A 767, 339, 2014

Self-trigger system - Motivation

1) broadening the LOFAR energy range

LOFAR stations are potentially able to study CRs above 10^{18} eV, but the collecting area is a serious constraint. At the present time only CRs falling within the Superterp are detected. By implementing a self-trigger system on the whole LOFAR array we can increase almost 50 times the collecting area



S. Buitink et al., Nature 531, 70-82, 2016

2) being the precursor for future radio detectors

Implementation of self-trigger system is crucial not only for LOFAR, but for all future radio-based cosmic-ray experiments, which could benefit from LOFAR experience

3) contributing to the survey of other radio transients

LOFAR is carrying out surveys for radio transients (e.g. FRB) and atmospheric phenomena (e.g. electric fields during thunderstorms), which could benefit from a cosmic-ray self-trigger system

Performance requirements

Facts

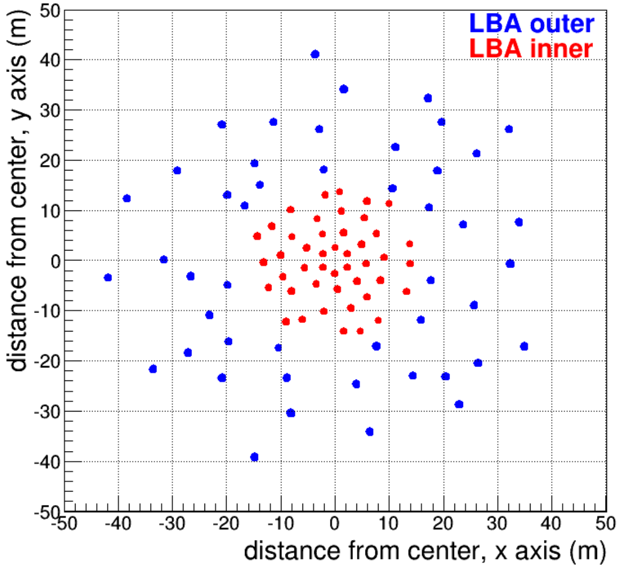
- Cosmic-ray signal is very short (10-100 ns) and very rare
  by assuming an average event rate of ~1 event per hour at E > 10^{16} eV, the time window ratio is about 1 over 10^{11}
- LOFAR is not in a radio-quite area, RFI can mimic CR radio signals
  commercial 88-108 MHz FM emitters can overspill in the 30-80 MHz band, airplanes traffic, electric sparks from close-by electric fences, etc.
- LOFAR capability of downloading the buffer data is limited
  large deadtime is generated every time antennas time-series data are downloaded

Therefore

1) RFI suppression to about 1 fake trigger per hour is crucial
2) High CR selection efficiency for E > 10^{17} eV is very important
3) Trigger algorithm has to fit with current LOFAR hardware and software architecture

The developed self-trigger algorithm

Self-trigger scheme:



- Since HBAs have a limited field of view (~15 deg), only LBAs are considered
- Both "LBA outer" and "LBA inner" configuration have been considered for developing the self-trigger algorithm
- Each LOFAR station is independently investigated, no correlation between neighboring stations is used. Anyhow, one triggered station in the Superterp will trigger all other Superterp stations
- In order to generate a trigger on one station, radio pulses must pass at first a selection phase, and then a rejection phase which is aimed at discarding RFI pulses

The developed self-trigger algorithm

Radio-pulse selection criteria:

- for each antenna the two polarizations are evaluated independently
- At least 23 antennas along one polarization over a given threshold, within a waiting time window of 30 (LBA outer) or 20 (LBA inner) ns

RFI rejection criteria:

- signal time length on the whole station must be shorter than 300 (LBA outer) or 75 (LBA inner) ns. The signal time length is defined as the time interval during which at least 3 antennas are above the threshold
- radio pulse arrival elevation angle must be larger than 30°
- if two consecutive pulses are identified within 5 μs, both pulses are rejected

Testing the self-trigger algorithm

Method 1 – raw-data downloaded following a LORA trigger:

- When LORA generates a trigger, the time-series of all the antennas in the central stations are downloaded. The time window is ~2.2 ms, centered on LORA trigger time
- Good for evaluating CR selection efficiency
- Evaluation of RFI-rejection efficiency is limited by the total length of the downloaded time O(10 s)

Method 2 – self-trigger acquisition run without RFI rejection:

- Trigger is generated internally for each individual station, ~500 μs time-series is downloaded
- No RFI-rejection → dataset is made almost exclusively by RFI pulses
- Test run length O(24 h) → best method for evaluating RFI-rejection efficiency

Testing the self-trigger – method 1

Stations configuration: LBA outer
Total independent real time: 8.9 s   Total real time: 118.7 s

THR = 3 RMS
total number of stations triggered by CR signal = **1520**

THR = 4 RMS
total number of stations triggered by CR signal = **898**

THR = 5 RMS
total number of stations triggered by CR signal = **598**

THR = 10 RMS
total number of stations triggered by CR signal = **191**

Note: LBA inner is not shown but results are similar

Testing the self-trigger – method 1

Stations configuration: LBA outer
Total independent real time: 8.9 s   Total real time: 118.7 s

THR = 3 RMS
total number of stations triggered by CR signal = **1520**
fraction of stations triggered by CR signal and vetoed = 182 / 1520 = **12%**

THR = 4 RMS
total number of stations triggered by CR signal = **898**
fraction of stations triggered by CR signal and vetoed = 41 / 898 = **5%**

THR = 5 RMS
total number of stations triggered by CR signal = **598**
fraction of stations triggered by CR signal and vetoed = 17 / 598 = **3%**

THR = 10 RMS
total number of stations triggered by CR signal = **191**
fraction of stations triggered by CR signal and vetoed = 3 / 191 = **2%**

Note: LBA inner is not shown but results are similar

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Stations configuration: LBA outer
Total independent real time: 8.9 s   Total real time: 118.7 s

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Events with at least one RFI signal triggered after RFI rejection= **5**

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THR = 10 RMS
total number of stations triggered by CR signal = **191**
fraction of stations triggered by CR signal and vetoed = 3 / 191 = **2%**
Events with at least one RFI signal triggered after RFI rejection= **2**

Note: LBA inner is not shown but results are similar

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Thunderstorm condition

THR = 5 RMS
total number of stations triggered by CR signal = **598**
fraction of stations triggered by CR signal and vetoed = 17 / 598 = **3%**
Events with at least one RFI signal triggered after RFI rejection= **4**

THR = 10 RMS
total number of stations triggered by CR signal = **191**
fraction of stations triggered by CR signal and vetoed = 3 / 191 = **2%**
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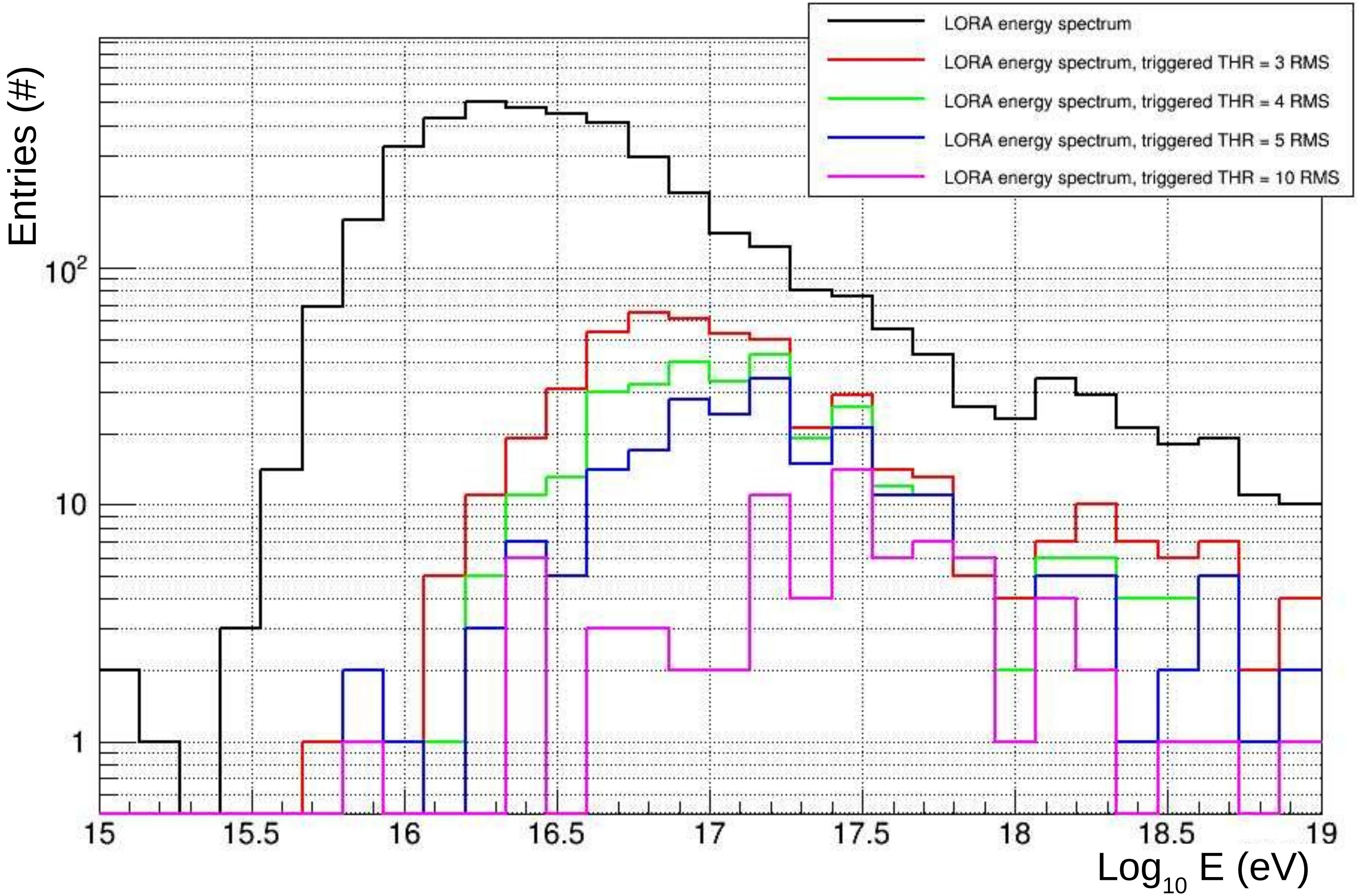
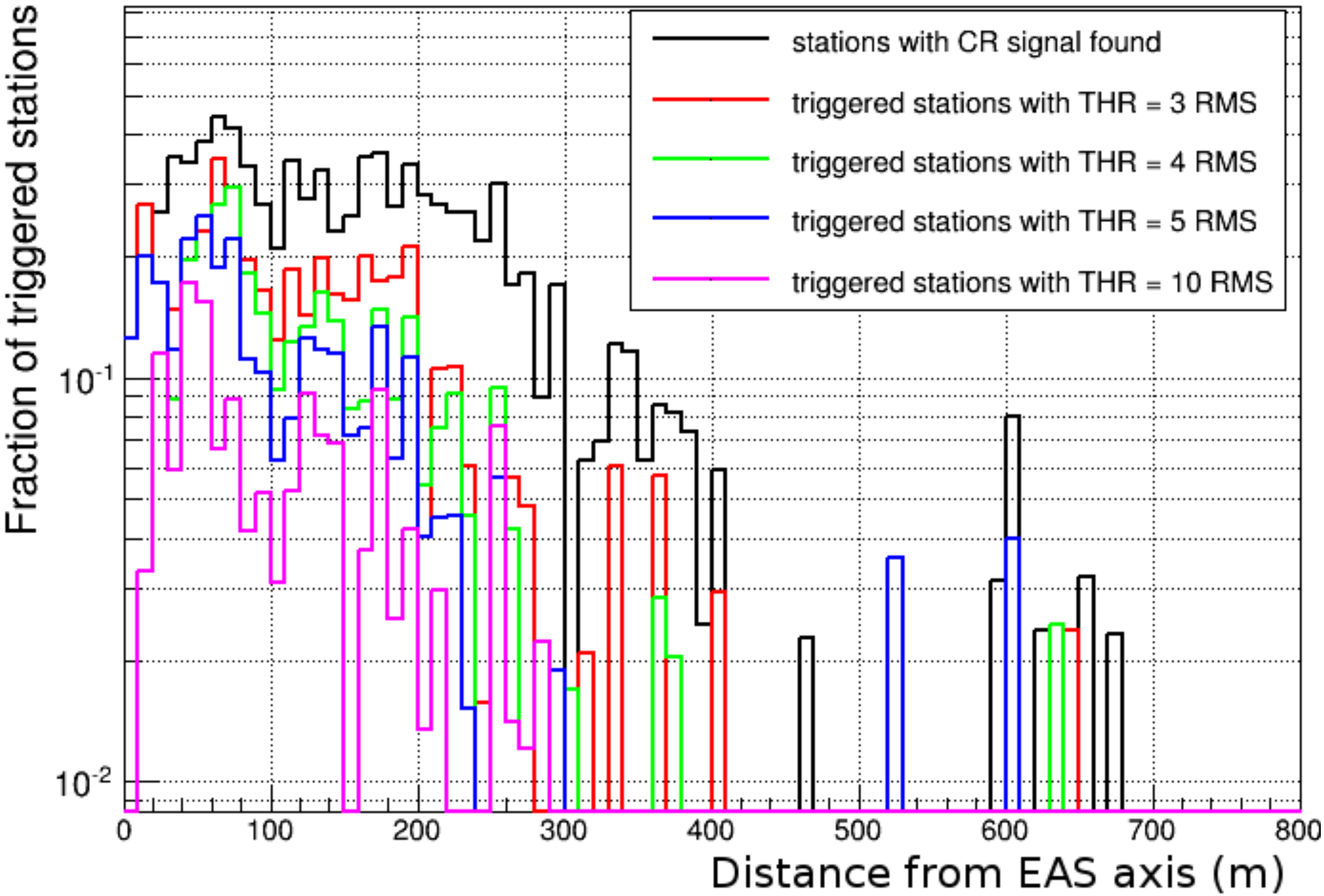
Note: LBA inner is not shown but results are similar

Testing the self-trigger – method 1



- Energy threshold varies accordingly to the single antenna trigger threshold
- Full efficiency between 10^{17} and $10^{17.5}$ eV according to the set threshold

Testing the self-trigger – method 1



- Within 200 m from CR shower axis, ~20% trigger probability is achievable. That is comparable to present off-line detection efficiency

Testing the self-trigger – method 2

Stations considered: Superterp (i.e. CS002-7)
Stations configuration: LBA outer
Run length: 24 h   Total real time after deadtime correction: ~12 h

THR = 3 RMS

total number triggers = 639

THR = 4 RMS

total number triggers = 620

THR = 5 RMS

total number triggers = 593

THR = 10 RMS

total number triggers = 268

Testing the self-trigger – method 2

Stations considered: Superterp (i.e. CS002-7)
Stations configuration: LBA outer
Run length: 24 h Total real time after deadtime correction: ~12 h

THR = 3 RMS

total number triggers = 639
triggers after RFI rejection= **3** (Note: value affected by acquisition threshold)

THR = 4 RMS

total number triggers = 620
triggers after RFI rejection= **10**

THR = 5 RMS

total number triggers = 593
triggers after RFI rejection= **10**

THR = 10 RMS

total number triggers = 268
triggers after RFI rejection= **10**

Testing the self-trigger – method 2

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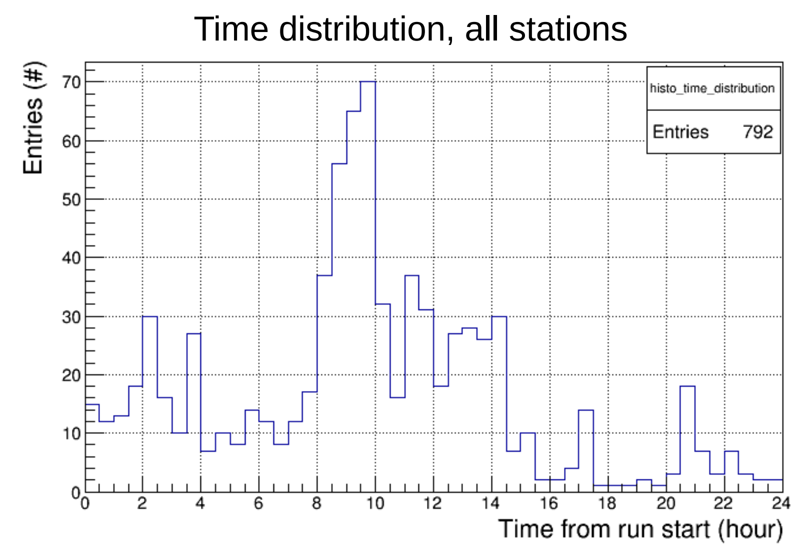
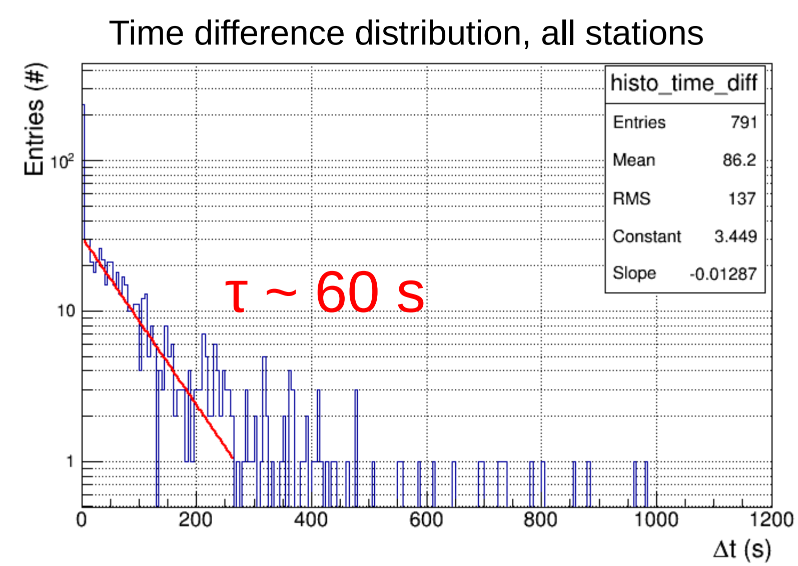
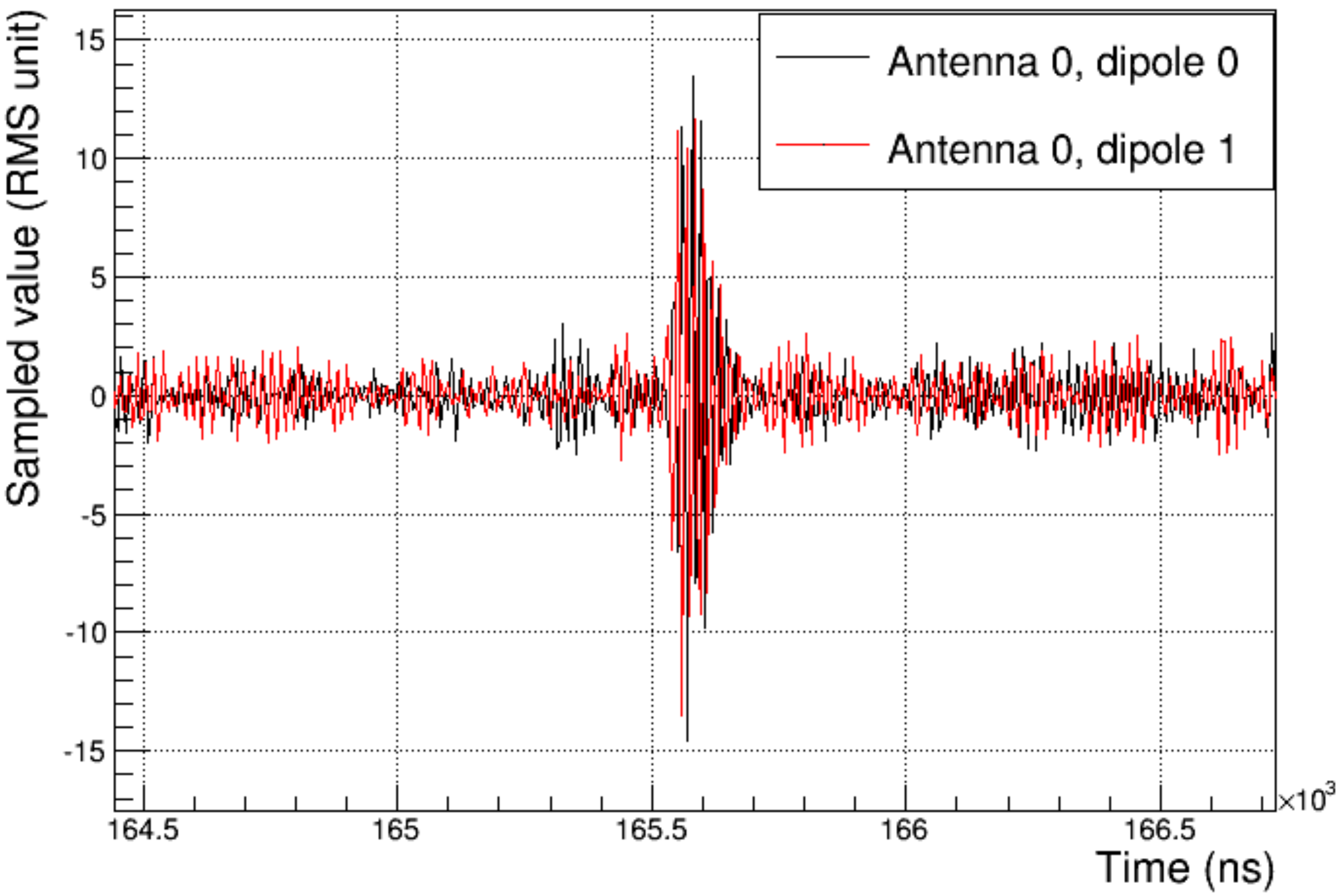




A most-likely airplane RFI trigger



Testing the self-trigger – method 2

- After correcting for the dead-time, we have found one trigger per hour
  - ➔ we met our goal!
- Trigger time distribution is not homogeneous during the 24 hours
  - ➔ Airplane traffic, atmospheric effects?
- We found no signal in coincidence with LORA, nor CR candidates
  - ➔ 20 collected LORA triggers, but only one above 10^{17} eV arriving from South which is the most unfavorable arrival direction (v x B effect)
  - ➔ given the circumstances, it is reasonable we didn't find any CR candidate
  - ➔ an additional longer observation has been requested

Conclusions and outlook

- We developed a self-trigger algorithm for individual LOFAR stations, based on the single antenna baseline fluctuations, on the pulse arrival direction, and on its duration
- The algorithm shows good CR efficiency (up to 30% within 200 m) and very good RFI-trigger rejection (less than 1 event per hour)
- It is possible to implement the new self-trigger algorithm without any change to the current LOFAR instrumentation
- A more advanced self-trigger algorithm with frequency-spectrum analysis has been developed, but it requires hardware modification → postponed to LOFAR 2.0

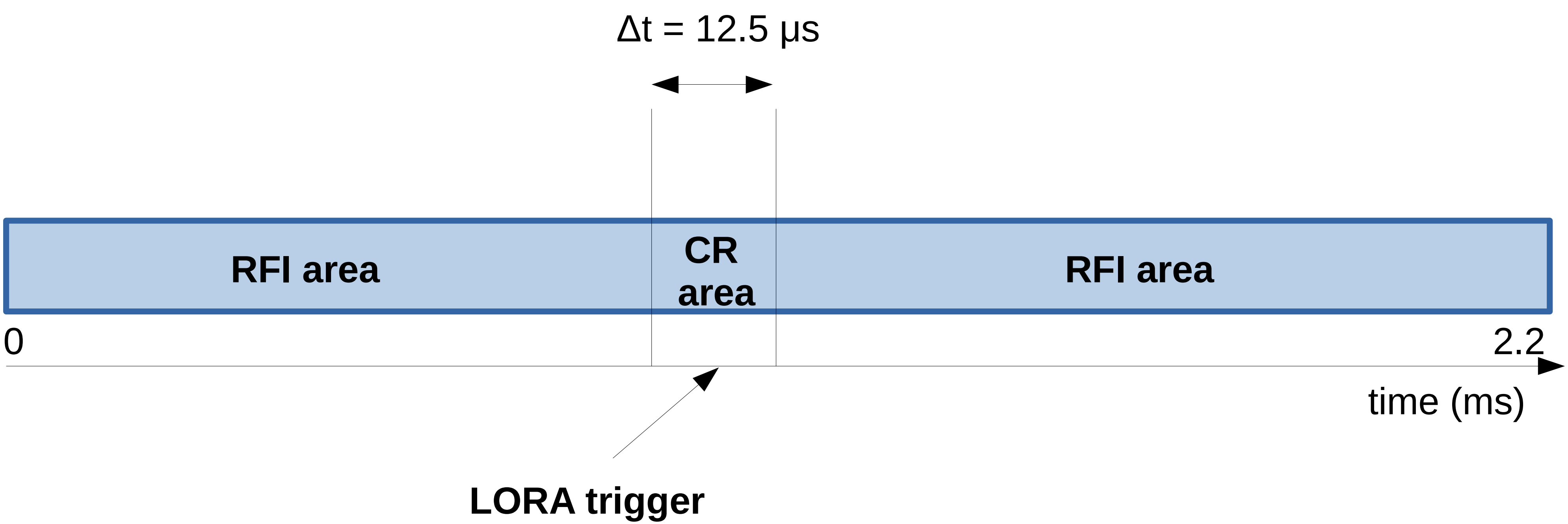
Future plans

- ➔ implementing in coordination with ASTRON the self-trigger algorithm on LOFAR hardware at the station CPU level
- ➔ Studying LOFAR CR performances in Single-station mode for extending LOFAR collecting area to all LOFAR stations

Spare Slides

Method 1 – Disentangling CR - RFI triggers

Time window of the downloaded data-series following a LORA trigger



- Radio pulses falling in the CR area are considered as generated by the CR cascade
- Radio pulses falling in the RFI areas are considered due to RFI spurious signals

The present LOFAR self-trigger system

A very rough trigger algorithm is currently installed, and has been used for long-run test runs for estimate RFI-rejection efficiency

Trigger criteria:

- for each antenna the two dipoles are evaluated independently
- majority of *N* dipoles over a given threshold, on a coincidence time window *T* (computed from the first threshold overpassing)

RFI rejection criterion:

- radio pulse arrival direction must be within the elevation range *E*

Performances:

- trigger rate spanning between 0.01 and 1 Hz, accordingly to *N*, *T*, and *E*
  - ➔ trigger population dominated by RFI pulses
  - ➔ very low effective duty-cycle because of the data downloading time