NenuFAR Key Programme Description

Radio Gamma

1 Summary

The radio detection of atmospheric particle showers initiated by ultra-high energy cosmic rays is today a proven technique that allows to reconstruct their properties (direction of arrival, energy, nature). Among the precursors of this method, the CODALEMA experiment installed at the Nançay radio-astronomy Observatory has contributed to several major technological innovations relevant for the radio detection technique (autonomous triggering, hybrid reconstruction, very wide frequency bands) and its high-performance antennas are also used on the NenuFAR radiotelescope in Nançay. We propose to exploit the unique environment of the Nançay Observatory through the CODALEMA experiment and the NenuFAR radio-telescope to explore the possibilities of radio-detection of atmospheric showers initiated by very high energy photons. The central idea is to phase a large set of antennas (several tens) in the direction of known sources emitting gamma (catalogs H.E.S.S., MAGIC, VERITAS, Fermi-LAT ...) to significantly increase the sensitivity of detection and to use the triggering capabilities on ultra fast transients controlled within the framework of CODALEMA. This would make it possible to observe the sources with a useful cycle close to 100%. We will use the time waveforms recorded in the Transient Buffer Boards (TBB) of NenuFAR, triggered by the signal built on the incoherent combination of several mini-arrays. Still in the state of prospective reflection, this approach requires first of all to perform simulations of the radio signals produced by the showers initiated by the gammas in order to set detection limits in energy (thanks to the AIRES and SELFAS codes in particular), but also to correctly define the triggering criteria to be applied according to the expected photon fluxes, the ambient noise level and the instrumental constraints of the systems used. We expect to reach a sensitivity to hundreds of TeV gamma, depending on the number of mini-arrays (MA) involved in the trigger system. The research program will be conducted in two main phases:

- First, observation of cosmic ray diffuse flux, in order to scale the sensitivity to gamma air showers from well-known signals issued from the cosmic rays observed by CODALEMA. The trigger will be issued from CODALEMA and all the TBB will be read on its reception, allowing to compare NenuFAR signals to CODALEMA ones.
- Second, after the required number of MA is determined from the first step, a dedicated trigger board should be built and used in the same way on NenuFAR, the latter being then pointed toward known gamma sources.

2 The team

Coordinator:

Richard Dallier (Assistant Professor IMT Atlantique)
SUBATECH - UMR 6457
IMT Atlantique – CNRS/IN2P3 – Université de Nantes
4 rue Alfred Kastler - B.P. 20722
44307 NANTES CEDEX 3 - FRANCE
Tel: (33) 2 51 85 82 79 – E-mail: richard.dallier@subatech.in2p3.fr
Co-affiliation: Unité Scientifique de Nançay (associated researcher)

Participants:

Lilian Martin (CR CNRS), Didier Charrier (IR CNRS) and Benoit Revenu (DR CNRS), same affiliations
Antony Escudié (post-doctorant), Université Libre de Bruxelles (from October 2019 for 2 years).

3 Scientific rationale and the need for NenuFAR observations

It is probably not necessary to recall here extensively the tremendous growth of gamma astronomy during the last years, with the instrumental development of the H.E.S.S., MAGIC and VERITAS ground telescopes, the Fermi satellite and the flurry of results accompanying them. Gamma astronomy is now reaching a mature stage, and this field offers astronomers and physicists images and spectra, made in a “routine” way, from sources that are more and more numerous and distant, close to what offer instruments working in the visible, radio or infrared. The big project for the future, CTA, is moreover conceived as an observatory open to the community rather than as the project of a collaboration. CTA will allow for the first time a deep study of the gamma sky observed at energies from a few tens of GeV to more than 100 TeV. However, one of the drawbacks of the technique is that the current telescopes which observe the Cerenkov radiation of the showers created by the photons in the atmosphere have a useful operating cycle which is rather reduced compared to the other domains, due to more severe constraints on the necessary observation conditions (no Moon, no clouds ...). Moreover, if CTA should be able to reach or even exceed the energy limit currently held by HAWC (~ 100 TeV), the standard average sensitivity of other telescopes is restricted to a few tens of TeV for the most energetic photons. Until the commissioning of CTA, the field of the most extreme energies remains virgin, only explored — through another type of messengers — by the ultra-high energy cosmic ray observatories (UHECR), of which we know today unfortunately the limits regarding the identification of sources.

In parallel with the impressive development of Cerenkov gamma-ray astronomy in the 2000's, this physics of ultra-high energy cosmic rays has also undergone an important evolution, notably with the commissioning of the Pierre Auger observatory in 2004 and the re-birth and the development of a former method of detection and today of observation of atmospheric showers initiated by cosmic rays: the radio detection. The principle is simple: the development of the cascade of charged secondary particles induced in the atmosphere by the arrival of a cosmic ray (atmospheric shower) is accompanied by a brief pulse of electric field (~ 20 ns) which can then be detected by a radio antenna and analyzed at high frequencies (from around 10 MHz to 300 MHz). In fact, the idea of measuring the electric field produced by the secondary particles of the atmospheric showers dates from the early 1960's, following the theoretical approaches of Askar'yan [1], then Kahn and Lerche [2]. All came to the conclusion that the electric field produced during the displacement of the secondary particles should be measurable using antennas working on the first approach in the first hundred MHz. Beyond that, because of the finite longitudinal dimension of the shower of particles (of a thickness of a few meters), the radio signal loses its coherence and therefore its intensity. The first detection experiments took place immediately but, as H.R.~Allan shows in a review that still refers [3], the often contradictory results, the technical difficulties and the progress of the particle detectors contributed to a nearly 30 years *statu quo*. However, thanks to the progress of fast electronics, in the early 2000's the two experiments LOPES (installed at the KASCADE particle detector in Karlsruhe, Germany) [4] and CODALEMA in France [5, 6, 7, 8, 9] have made it possible to renovate the method with convincing successes, notably by relying on new theoretical approaches [10, 11, 12, 13, 14]. Following these precursors, the radiation detection of the atmospheric showers initiated by the UHECR has seen and still sees many flourishing experiments around the world (AERA at Auger, the Cosmic Ray Key program of LOFAR and the Cosmic Ray Focus Group on SKA, Tunka-Rex in Russia, TREND in China, ARA and ARIANNA in Antarctica, etc.), demonstrating the hope and vitality of this community.

As far as the authors are concerned and in a pioneering way, since 2003 the multidisciplinary scientific collaboration CODALEMA — bringing together several laboratories from particle and nuclear physics and astronomy — developed on the Nançay radio observatory site a large collection of detectors, intended to study the properties of the radio emission associated with cosmic showers in the energy range from 10^{16} to 10^{18} eV. In its current version, CODALEMA consists essentially of:

- a square array (0.4 x 0.4 km) of 13 particle scintillator counters (surface detector),
- a set of 57 so-called ``autonomous" crossed dipoles, not interconnected and synchronized by GPS dating (operating between 20 and 200~MHz), distributed over 1 km^2,
- a so-called “Compact Array” of 10 cross-polarized antennas, arranged in a star of 150 m extension and whose signal acquisition (from 20 to 200 MHz) is triggered by the particle detector,
- an array of 7 low-frequency antennas capable of observing the signal below 10 MHz, also triggered by the particle detector.

The autonomous station array is purely self-triggered, meaning that each station is independent. Transients coming from cosmic ray air showers or any other source (noise, planes...) are either stored on a distant disk for off-line analysis or directly sent to a central DAQ able to build on-line the event based on several station signals, respecting several selection criteria, which offers a large noise rejection factor (more than 99 %) and a very good efficiency on cosmic ray air shower transient detection. A crosscheck can be made off-line with the events detected by the particle detector or any of the triggered instruments (Compact Array or Low-Frequency stations).

One of the specificities of UHECR detection is that it is impossible to know *a priori* in which direction to "look", and therefore the detection systems, whatever they are, must have maximum angular acceptance and availability in order to cover all directions of arrival. The UHECR radio detection arrays are no exception to this rule. However, another specificity related this time to the antennas themselves is to be able to phase the signals of several antennas in a given direction, and to combine them *a priori* or *a posteriori* in order to gain in sensitivity of detection: it is the principle of interferometers, widely used on past and current generations of so-called "digital" radio telescopes. Our idea is therefore to combine the ability to detect atmospheric showers by antennas with the ability of these antennas to be phased towards a source to detect the radio signal of the atmospheric showers generated by gamma rays of very high energy from known sources, according to a process identical to that of UHECR. Unlike the case of UHECR, we then know where the signal should come from. The immediate advantage is the gain in detection sensitivity, which varies in direct proportion to the square root of the number of antennas involved. The other advantage is the possibility of reaching a useful observation cycle close to 100 %, since the day/night alternation and the weather have no influence on the detection itself (except in case of large local atmospheric electric fields during thunderstorms). Based on our experience of ultrafast radio transient detection and on the context of the Nançay radio astronomy station for the expertise in radio interferometry, we propose to explore the possibilities offered by this idea and to try for the first time to detect the radio signal produced by an ultra-high energy gamma photon from an identified astrophysical source. We are not talking here about the observation of the radio signal emitted by the source of gamma photons or the radio cartography of this source, already carried out in a complementary way of the imaging made by the Cerenkov telescopes, but of the detection of the signal emitted into the atmosphere by the shower initiated by the gamma. Given the energy threshold of detection found for the UHECR on observations with individual antennas (of the order of few 10^{16} eV), it is likely that this method applied to gamma photons, if it can work, will concern energies beyond the usual limits reached by current and future Cerenkov telescopes, from a few hundred TeV to a few tens PeV — if astrophysical sources can produce gammas at such energies. But we think that this new detection principle deserves to be explored, because all the technical elements seem to be united to make it "explorable": NenuFAR and LOFAR606 are completely surrounded by the 57 radio detection stations of CODALEMA. This environment provides a unique opportunity to test and improve techniques for cosmic ray radio detection, and could act as a pathfinder for air shower detection with the SKA [15, 16, 17, 18] (besides the fact that NenuFAR has already been officially recognized as a SKA pathfinder for regular astronomical observations).

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4 The need for a Key Programme

Still in the state of prospective reflection, this approach requires first of all to perform simulations of the radio signals produced by the showers initiated by the gammas in order to set detection limits in energy (thanks to the AIRES and SELFAS codes in particular), but also to correctly define the triggering criteria to be applied according to the expected photon fluxes, the ambient noise level and the instrumental constraints of the systems used. We expect to reach a sensitivity to hundreds of TeV gamma, depending on the number of mini-arrays (MA) involved in the trigger system. The research program will be conducted in two main phases:

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This progressive observation strategy elaboration suits well with a 2 years key programme and fits in the Early Science phase. In case of success, dedicated observations of gamma sources could be continued during the subsequent regular functioning of NenuFAR.

5 Observational strategy

NenuFAR as an UHECR detector
During the NenuFAR preliminary design phase, the CODALEMA collaboration was asked to give hints for the potential use of NenuFAR as UHECR radio detector. At that time, we considered that stationary analog beam-forming was unfavourable for cosmic ray detection. A dedicated acquisition channel has thus been implemented to extract the signal from one single antenna (the central one) of each of the 96 MA_{19} before beam-forming. An external — either “hard” or “soft” —trigger input on the TBB is available to trigger NenuFAR by CODALEMA during regular astronomical operation (either from the particle detector or from the whole array of autonomous stations, through its central DAQ). This was intended to offer a high antenna density (96 antennas in 0.125 km^2), though

less than the one of LOFAR but large enough to sample the electric field profile in the same way and compare it to the one obtained with the surrounding and included standalone stations of CODALEMA. This is the first way NenuFAR can be used as a cosmic ray detector.

The second way to use the TBB for the observation of cosmic ray air shower signals does not interact neither with the regular astronomical observations. It consists in, simply, reading the TBB of the whole, analogically phased MA_{19} at the reception of a CODALEMA trigger. The main drawback is that the mini-arrays could be pointed in any direction not necessarily compatible with the direction of arrival of the cosmic ray shower, thus lowering the sensitivity. However, this should increase the number of events detected and, through gain simulations of the MA19 in their pointing direction, this should allow to scale the MA_{19} signals with respect to the regular CODALEMA antennas ones. This mode should be the main observing mode in the first stage of the current key programme.

Another cosmic ray observation mode being implemented, though in a dedicated mode not compatible with simultaneous astronomical observations, is to set each MA_{19} on a different direction in the sky, in a kind of “radio fly's eye” mode, thus covering the 2 π sr with 96 beams. In that respect, NenuFAR will act as the LOFAR Superterp in cosmic ray mode, but with a sensitivity $\sqrt{19}$ times higher than the one reached with single antennas. Moreover, it has been shown that NenuFAR single antennas have a better sensitivity than LOFAR's ones, on a much wider frequency band. We expect a observing gain on both sides of the energy range, with the ability to observe as well low energy showers triggering the particle detector that would not have passed the threshold of a CODALEMA station, as high energy showers falling far away from the center of the instrument. The quite large field of view of each MA_{19} (10 to 50° from 10 to 85 MHz) ensure an overlap between adjacent beams and thus detection likely by several MA_{19}.

These observing modes, based on the reading of a small part (10 µs over 5 s) of the TBB on the reception of a triggering signal coming from CODALEMA, are currently being implemented on NenuFAR and should be tested in summer 2019. We thus envision to test at first the cosmic ray observation modes of NenuFAR to calibrate the signal of the latter on well-known cosmic ray event signals recorded by CODALEMA, in order to determine the way the gamma-ray trigger should be built.

NenuFAR as a gamma ray detector

As already mentioned, the specificity of the gamma-ray sources is that we know their position in the sky, thus the arrival direction of the high-energy photon, contrarily to the UHECR case. It is therefore possible to use one or several mini-arrays phased together in the direction of the source and use them as a trigger on transient events. As for the cosmic ray observation modes, we can take benefit of the TBB of the remaining MA_{19}, which would be triggered by the trigger arrays, to roll-back in time and find the transient in their memories. Each MA_{19} would then be a sampling point of the shower footprint at ground, exactly as it is done in UHECR radio detection arrays with single antennas. This would allow knowing the electric field distribution and use it to recover the properties of the primary photon, notably its energy thanks to simulations.

In principle, to reach the maximal sensitivity of detection and lower the detection threshold in energy, we could use all the available mini-arrays analogically phased individually on the source to build the trigger, provided it is possible to read their signals in real time and decide whether or not there has been a transient in the phased combination of all the signals. This however is at that time out of reach, due to the huge amount of data to be processed online: indeed, each MA_{19} delivers 400 MB/s per polarization, which should be taken at the level of the TBB, where the raw waveforms are still recorded and should be read and then combined again to sum all the signals. Otherwise, in the regular astronomical observation channels where digital phasing is made online, data flows are split in sub-bands of 200 kHz, leading to much less data volume but with only 5 µs of time resolution, far from being enough for the observation of transients lasting a few tens of ns. Furthermore, the TBB have to be triggered (which in that case can be done externally by a periodic clock system) to read their 5 s memory, *i.e* 2 GB per polarization per mini-array. The dead time between two readout of one TBB could be large, lowering the duty cycle, adding to that the online processing that has to be made to phase the current 56 signals (and later 96).

We then chose a different approach, based on the experience gained on CODALEMA. It is possible to split the signal from individual MA_{19} before they enter the acquisition chain, but after analog phasing at the level of one MA_{19}. Each polarization thus behaves as the signal of a single antenna, and can feed one input channel of a dedicated electronics able to combine several of them. A classical but dedicated electronics board of NenuFAR, accepting 8 channels as input, can then be used to make digital phasing online and produce a trigger on a simple threshold level, the latter being subsequently used to trigger the TBB of all the MA_{19}. This would reduce the trigger sensitivity, since at most 8 MA_{19} can participate on one polarization, but this would at first be the most efficient and elegant way to proceed. Another option would be to build a dedicated analog trigger board similar to the one of CODALEMA, but accepting more than two input channels. At that time both solutions are under study, the first stage being to determine how many MA_{19} are necessary to reach a sub-PeV sensitivity on detection.

In order to do that, the first test that have been done was to split the signal of a single MA_{19} and to feed one of the input channels of the trigger board of a nearby CODALEMA station. In that respect, one of the polarization of the regular Butterfly antenna of the station is replaced by one polarization of the MA_{19}, increasing the signal amplitude by a factor of 19 and the signal to noise ratio (or detection sensitivity) by a factor of $\sqrt{19}$. This station is still included in the regular CODALEMA acquisition, which will allow comparisons between the signal of a Butterfly and the one of the MA_{19} on the same cosmic ray events. Provided that the latter's energy is reconstructible, an estimate of the gain in sensitivity detection and a first attempt of an energy calibration of the signal of a mini-array can be made and extrapolated to the expected energy of a gamma photon.

See the summary table hereafter for Observation Configuration, Observational Constraints and Local storage / Data processing / Data transfer details.

6 Strategy for data analysis

Data will be transferred from NenuFARB0, the computer that will receive the external trigger signal from CODALEMA and extract the TBB interest zone, directly to a CODALEMA dedicated computer. Analysis will then be conducted offline from Nantes through the regular CODALEMA and a dedicated analysis pipelines.

7 Publication strategy

A paper describing the proposed observing mode is in preparation, and a poster communication has been accepted by the 36th ICRC conference in July 2019 (the largest Astroparticle conference cycle, every two years). As soon as the first results on cosmic rays will be obtained, the subsequent publications will follow the rules of the NenuFAR Scientific Committee.

8 Public outreach plan

None at present.

Summary of NenuFAR Key Programme Description
v.3

General information	
Name of program	Radio Gamma
Short description of programme	Detecting and measuring high energy gamma air shower radio emission, as it is usually done for cosmic ray air showers with the nearby CODALEMA experiment. Sources: known high-energy gamma sources (> TeV)
Target of Opportunity ?	No
Links with other key programmes? (if any)	None
Relevance to the preparation of SKA ? (if any)	We hope so!
Contact person:	richard.dallier@subatech.in2p3.fr
Team: (please mention any PhD or postdocs)?	Richard Dallier (Subatech, Nantes) Lilian Martin (same) Didier Charrier (same) Benoit Revenu (same) Antony Escudié (post-doc, Bruxelles)
Targets & sensitivity	
Number of sources/fields	Stage 1: no source (cosmic ray diffuse flux, triggered by CODALEMA) Stage 2: Crab, few gamma sources to be selected in TeVCat2 catalog
Low DEC sources?	Not below 20°
Requested sensitivity (mJy)	Not relevant
Required calibrators ?	None
- Primary flux calibrator	
- Phase calibrator (imaging)	
- Polarization calibrator (when available)	
Observation configuration	
Total requested time (hr) up to end 2021	Stage 1: all-time piggy-tail (including default zenith pointing) through the use of TBB Stage 2: to be determined according to the sensitivity estimated in stage 1 (pointing and tracking modes)
Pilot or test program ?	Test
Type of observation: *imaging, beamformed, TBB*	TBB
Nature of pointing: *tracking, transit*	Default (zenith), tracking
Required NenuFAR receiver	TBB
Type of data product: *Vis, DynSpec …*	TBB
Number of beams per observation block	1
Bandwidth per beam (MHz)	Full
Frequency coverage (in 10-88 MHz)	High pass 25 MHz ([25 – 85] MHz)
Contiguous or splitted bands ?	Not relevant (full band)
Frequency resolution (kHz)	Not relevant (time waveforms)
Time resolution (sec)	Not relevant

Observation block duration (min)	Source tracking duration
Preliminary Observing strategy / schedule ?	2 stages: from TBB mode availability + 6 months (stage 1), up to end of early phase (stage 2)
Observational constraints	
Required night observation ?	No
Required specific time of year ?	No
Allow fractioning observing time ?	Yes
Can the observation be stopped by observatory?	Yes
Allow rescheduling by observatory ? (without consultation)	Yes
Joint observation with other telescopes/facilities?	Yes (CODALEMA)
Local storage / Data processing / Data transfer	
What strategy for data analysis? *e.g. transfer raw/preprocessed data to your home institute, or reduce on the spot, or need local assistance with data reduction…*	TBB data transferred to dedicated local computer, then analysis at distant institute
Estimated volume for Early Science (2019-2021) (GB, TB)	Not relevant (distant storage)
Required local data storage?	Temporarily, before transfer to local dedicated computer
- How much TB?	Very few…
Request local computing resources?	No
- How many nodes?	
Estimated time for completion of analysis at CDN (freeing computing resources…) ?	Not relevant
Need for technical support?	
- For setting up observation ?	Yes, probably at the beginning
- For preprocessing (Flag + t/f rebins) ?	-
- For calibration ?	-
- For imaging ?	-