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Belgian Research Action through Interdisciplinary Networks

PIONEER PROJECTS

SPADE

A FULLY DIGITAL PROTOTYPE OF A PHASED-ARRAY RADIO SOLAR SPECTROGRAPH

CONTRACT - BR/314/PI/SPADE

FINAL REPORT

15/10/2018

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SUMMARY

Context

Monitoring of the solar activity at radio wavelengths is an essential part of our understanding of solar eruptive events, giving access the history of the magnetic field restructuring during the eruption via the radio signatures of accelerated electrons and in some cases to large scale disturbances propagating out in the corona.

To alleviate typical issues in low frequency solar observations (sensitivity, interferences), we have proposed to design and build a small phased array based on Software Defined Radio commercial hardware.

Objectives

The objectives of the project:

- Design and construction of a small array for the observation of the Sun
- Selection and test of SDR commercial hardware for the operations of the instrument
- Design of a control and operating software using of open source libraries

Conclusions

At the end of the project in 2017, a fully finalised hardware set up was delivered. For the software part, many different technical issues were resolved in the different subsystems. The available manpower within the project, even augmented with the invaluable help of different persons, was not sufficient to finalise the control software before the end of the project but is now being continued outside the project funding.

Keywords

Sun, radio waves, phased array, SDR, open source

SAMENVATTING

Context

Het opvolgen van de zonneactiviteit in radiogolflengtes is essentieel voor het begrijpen van zonne-uitbarstingen. Zulke radiowaarnemingen geven namelijk inzicht in het herstructureren van het magneetveld gedurende de uitbarstingen, via de radio-signalen van versnelde electronen, en in sommige gevallen, grootschalige verstoringen die zich voortplanten doorheen de corona.

Om de typische problemen met lage-frekwentie zonnewaarnemingen (gevoeligheid, interferenties) te omzeilen, hebben we voorgesteld om een kleine *phased array* te ontwerpen en te bouwen, gebaseerd op commerciele hardware voor Software Defined Radio.

Doelstellingen

De doelstellingen van het project waren :

- Ontwerp en constructive van een kleine *array* for zonnewaarnemingen.
- Selectie en testen van commerciele SDR hardware voor de bediening van het instrument
- Ontwerp van de controle- en bedieningssoftware met gebruik van *open source libraries*

Besluiten

Op het einde van het project, in 2017, is de volledig afgewerkte hardware opstelling afgeleverd. Voor het software gedeelte zijn veel verschillende zaken in de verschillende onderdelen aangepakt en opgelost. De beschikbare mankracht was binnen het project, zelfs nadat deze aangevuld werd met de zeer geapprecieerde hulp van velen, echter niet voldoende om de controle-software te vervolledigen voor het einde van het project. Deze controle software wordt momenteel afgewerkt op middelen buiten de projectfinanciering.

Trefwoorden

Zon, radio golven, phased array, SDR, open source

RÉSUMÉ

Contexte

La surveillance de l'activité solaire en ondes radio représente une part essentielle de notre connaissance des événements éruptifs solaires. Grâce aux signatures radio d'électrons accélérés ou de structures à large échelles se propageant dans la couronne, elle nous renseigne sur l'historique de la restructuration du champ magnétique pendant les éruptions. Les difficultés caractéristiques affectant les observations radio basses fréquences (sensibilité, interférences) peuvent être atténuées par la conception et la construction d'un petit réseau phasé utilisant des récepteurs commerciaux de type SDR (Software Defined Radio). C'est ce que nous proposons ici.

Objectifs

Les objectifs du projet sont :

- La conception et la construction d'un petit réseau phasé pour l'observation du Soleil
- La sélection et le test de récepteurs commerciaux SDR pour la mise en œuvre de l'instrument
- La conception d'un programme de contrôle basé sur les bibliothèques libres.

Conclusions

À la fin du projet en 2017, la partie purement matérielle de l'instrument a été achevée. Pour la partie logicielle, plusieurs problèmes techniques concrets ont été résolus dans différents sous-systèmes. Par manque de main d'œuvre, et bien que le projet ait bénéficié de l'aide précieuse de plusieurs personnes, il n'a pas été possible de finaliser le programme de contrôle à temps, mais ce développement continue en dehors du cadre du projet.

Mots-clés

Soleil, ondes radio, réseau phasé, SDR, logiciel libre

1. INTRODUCTION

Solar eruptive events like flares or Coronal Mass Ejections (CMEs) are produced by the sudden relaxation of unstable magnetic structures that slowly build up in active regions (associated with sunspots) or along magnetic neutral lines. The level of solar activity varies therefore with the well-known 11-year cycle, but in short time scales of days or hours, it remains essentially unpredictable. Research groups all over the world are actively investigating the conditions that lead to solar eruptive event to take place, and analyse and model the ones that have been observed. Operational activities based on these fundamental research efforts are being set up in Europe, and in particular at the Royal Observatory of Belgium (ROB) which hosts one of the Regional Warning Centre of ISES (International Space Environment Service) as well as the Solar Weather Expert Centre of the Space Situational Awareness program of ESA.

Research and operational activities targeting solar eruptive events are fuelled primarily by remote sensing observations spanning the whole electromagnetic spectrum. Space based instruments cover wavelengths that are not accessible from the ground, like the Ultra-Violet (UV), the Extreme Ultra Violet (EUV), the soft X-rays (SXR) or Hard X-rays and gamma rays. Ground based instruments observe the visible part of the spectrum, the near infrared and the radio part of the spectrum down to the ionospheric cut-off. Altogether, these observations give scientist an access to the whole solar atmosphere from the “cool” layers close the photosphere to the million Kelvin hot corona. In this respect, ROB is one the few European institutes which operate both space based instruments (PROBA2) and ground based ones in the optical domain (USET, in Uccle) and in radio (Humain Radio astronomy station).

The radio part of the spectrum provides a wealth of information on the energy release that takes place during eruptive events. In the HF to UHF bands (~30 to ~3000 MHz), the dominant emission mechanism during eruptive events is plasma emission, a collective process involving non-thermal electrons accelerated during the energy release of the eruption. Below ~1000 MHz, dynamical spectral observations (where the radio spectrum of the sun is monitored continuously) have shown the existence of different characteristic spectral signatures of particle acceleration: electrons travelling at 1/3 of the speed of light along open magnetic field lines (type III bursts), or electrons accelerated by shock waves linked to flares or CMEs (type II bursts), or energized electrons trapped in post-flare loops (type IV bursts). Before the space age, these radio signatures were often the only reliable source of information about eruptions. Still today, they remain an almost real-time source of information, and complement nicely space based or other ground based observations.

The lower part of the spectrum (below $\sim$ 100 MHz) is particularly interesting because it corresponds to intermediate altitudes in the solar corona between the ones covered by EUV instruments and the ones that are observable with white light coronagraphs.
Basic observations can be performed in that frequency range with relatively modest infrastructures, but the growing occupation of the radio spectrum by civilian and military technologies makes wide band radio astronomy a challenge in some parts of the world like Europe.
The rise of consumer grade digital techniques like Software Defined Radio (SDR) receivers provides an opportunity to address this issue. It brings indeed an important flexibility in implementing what used to be hardware based: frequency band definition, filtering, addition, mixers, etc.
To further improve the quality of low frequency observations, multiple antenna systems represent an obvious solution. In use since the late 1960s, phased arrays allow to virtually steer a network of identical antenna in a given direction in the sky, alleviating the need for mechanical moving parts and motors that are prone to fail. Until the development of recent phase arrays for radioastronomy like LOFAR, the phasing and pointing operations were made in an analog way using physical delay lines. The SPADE project is a small phase array which promises to perform all these operations entirely digitally. Its small size (eight antenna) allows to use consumer grade digital equipment to do so. The relatively low-cost as compared to full grade, multi-purposed instruments makes it an ideal pathfinder for the set-up of a radio network of low frequency solar observatories.

2. METHODOLOGY AND RESULTS

Design of the array

Over most the radio spectrum, the Sun is the strongest radio source, in competition with galactic emission and jovian ones. Radio bursts linked to solar eruptive events are among the strongest natural radio emissions (see Figure 1).

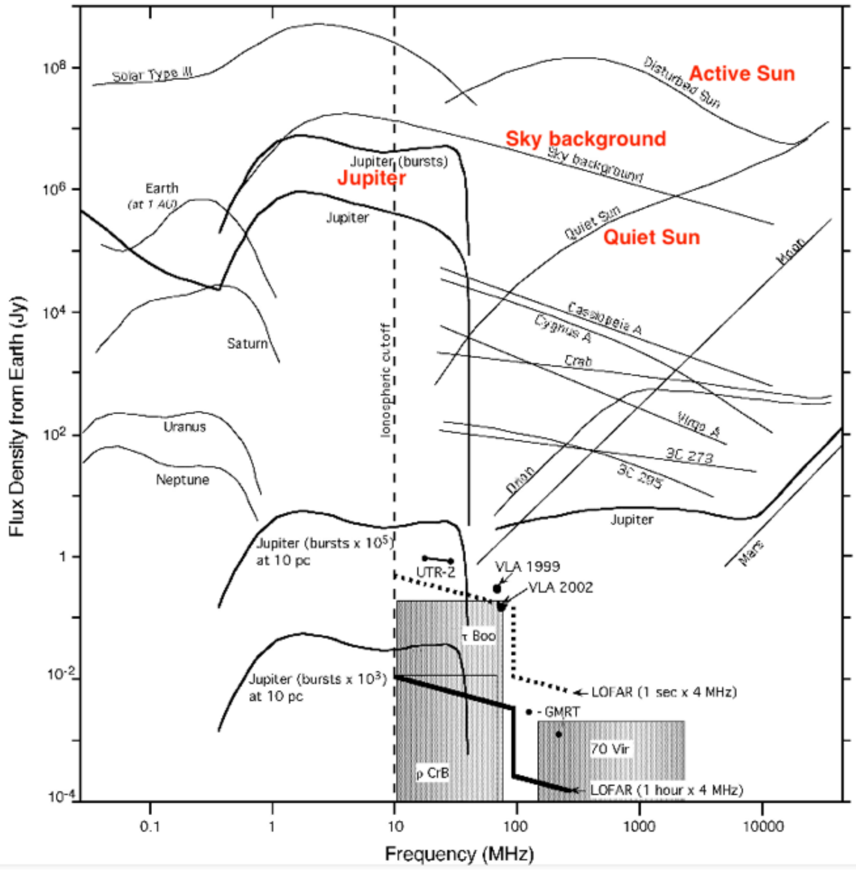


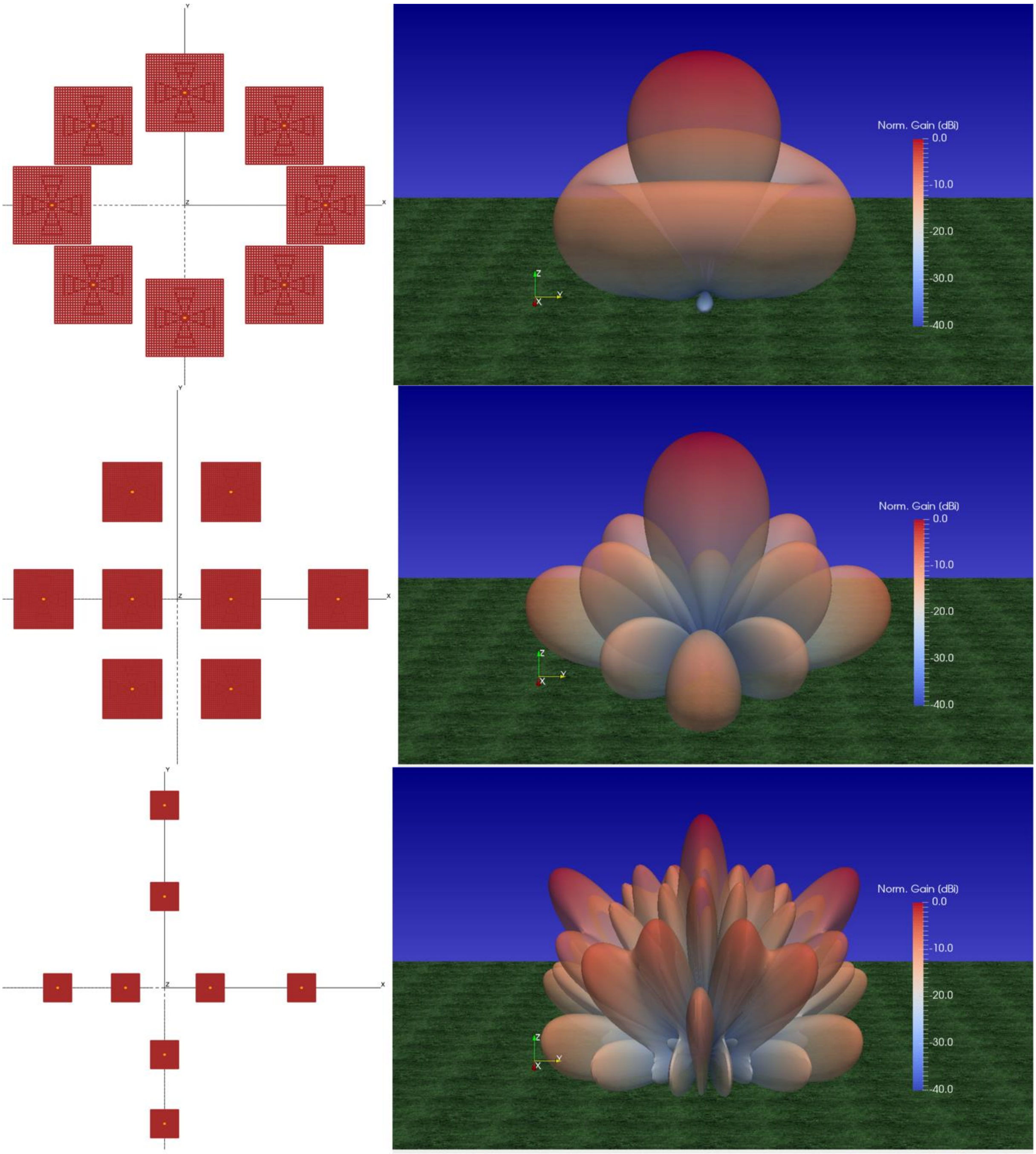
Figure 1 Spectrum of different radio sources (adapted from Zarka, 2005)

In balance with budget constraints (in particular the expected cost of the electronics), this drove the concept of an 8-antenna array, being able to observe solar radio bursts as well as the sky background and strongest jovian bursts.

The design the optimal shape of the array was evaluated using an open source “method-of-moments” antenna simulator called NEC. Individual antennas are modelled as a collection of small segments or wires, in which the net flowing currents and resulting electric fields induced by a radio wave are calculated. Prior to the start of the project, only two types of antenna were considered: the ones used in the Low Band Array of LOFAR, and the ones from the Long Wave-length Array. It appeared quickly that the LOFAR antenna would not be available during the time of the project, and therefore the calculations were done with the LWA-type of antenna (more details on this will be given later on).

Several configurations have been tested and discussed with our consultant, Pr. Christophe Craeye from UCL.

The different tested designs are shown in Figure 2, for a frequency of 50 MHz.



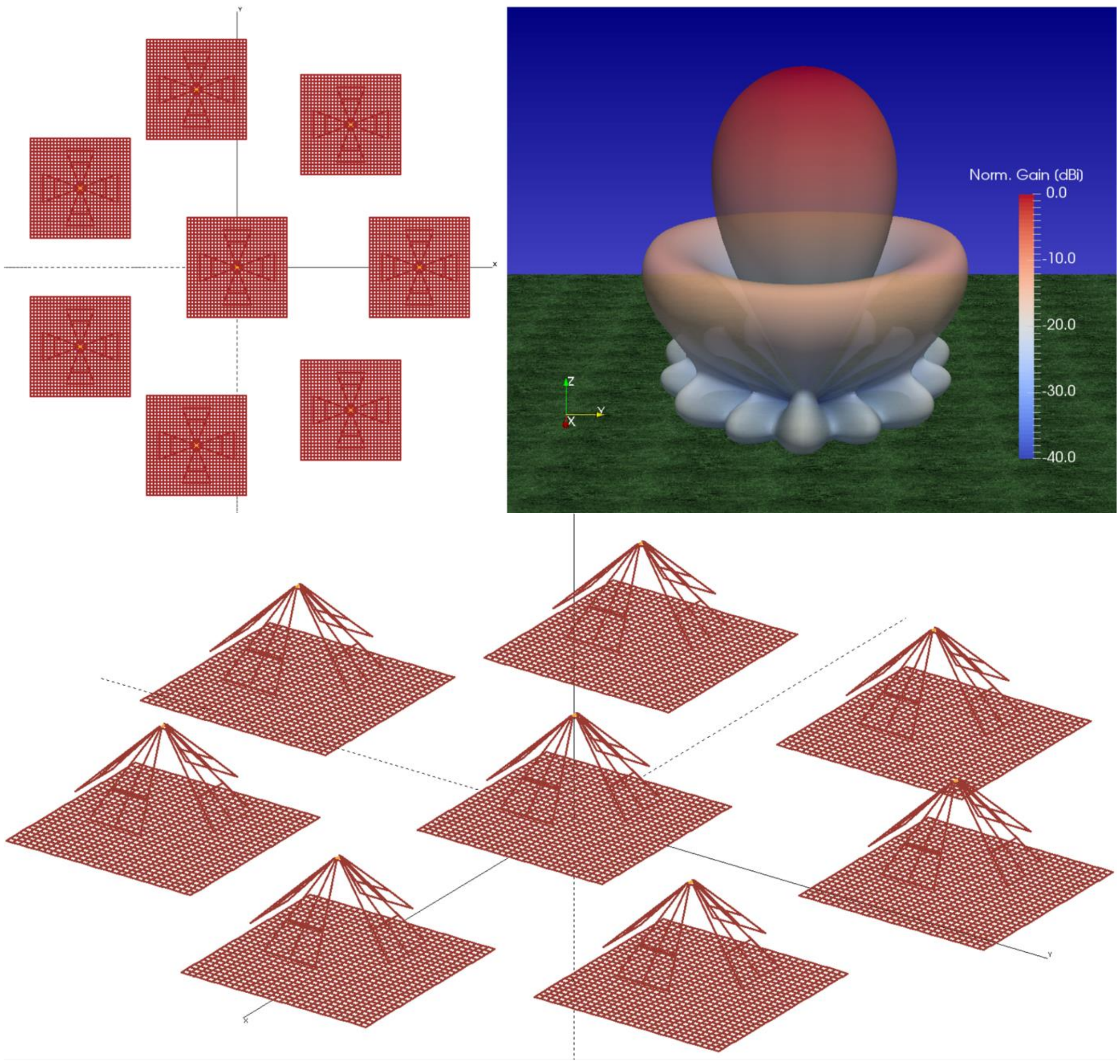


Figure 2 Different test designs for the SPADE array. The last one (shown also in perspective) is the one that has been chosen

In the simulations shown here, the array is pointing towards zenith. The configuration that seems to minimize the best the side lobes while providing the best primary beam spatial resolution is the last one (shown also in perspective). It consists of 7 antennas located evenly on a circle centred on the eighth one. It has one symmetry along the North-South axis. Further discussions and simulations showed that a single grid underlying the whole array would improve the gain even more at a cost of asymmetrical side lobes. Figure 3 shows cross-sections in the North-South and East-West planes of the final antenna distribution with individual ground planes and a single, large one. The gain is improved by ~ 5 dB, and the side lobes reduced in most directions.

To summarize, the final configuration is as followed: Eight antennas, with seven on a circle of 5.5 m radius; One symmetry axis in the North-South direction; A unique ground plane, square, 20 x 20 m, with a mesh grid of 0.15 x 0.15 m.

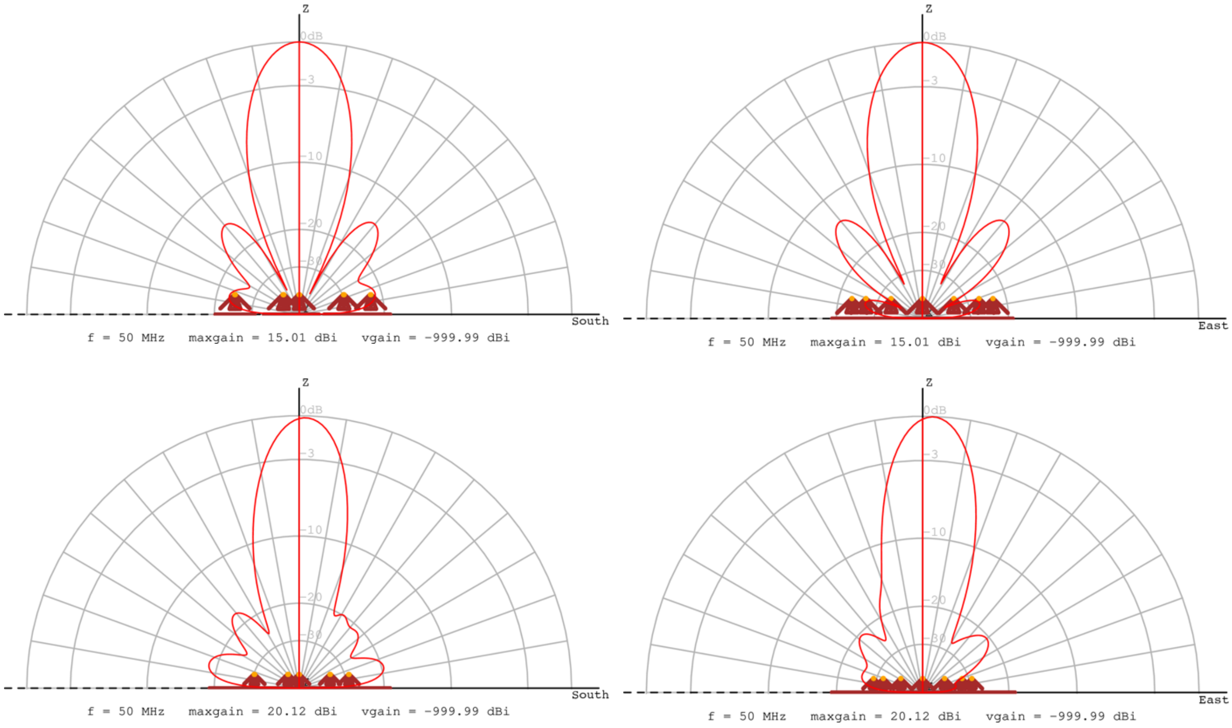


Figure 3 Top row: Antenna pattern cross-section in EW and NS planes of the final configuration with individual ground planes. Bottom: the same with an extended ground plane

Antenna selection

As briefly mentioned earlier, LWA antenna were preferred over other possible designs. These antennas have been designed and built for the Long Wavelength Array in the USA (Hicks et al., 2012). They consist of two orthogonal fat dipoles covering the band 10 to 80 MHz and are active antenna, with a broadband balun and an amplifier. We have been in contact with the Paris Observatory who is using the same kind of antenna for the NenuFAR project (Zarka et al., 2012) at the Nançay radioastronomie station. The NenuFAR antennas (Girard et al., 2012) are essentially LWA antennas fitted with a special active electronics designed by the Subatech engineering school (Charrier, 2014) in collaboration with CNRS. The main characteristics of this electronics is the very low noise amplifier (LONAMOS, see
Figure 4).

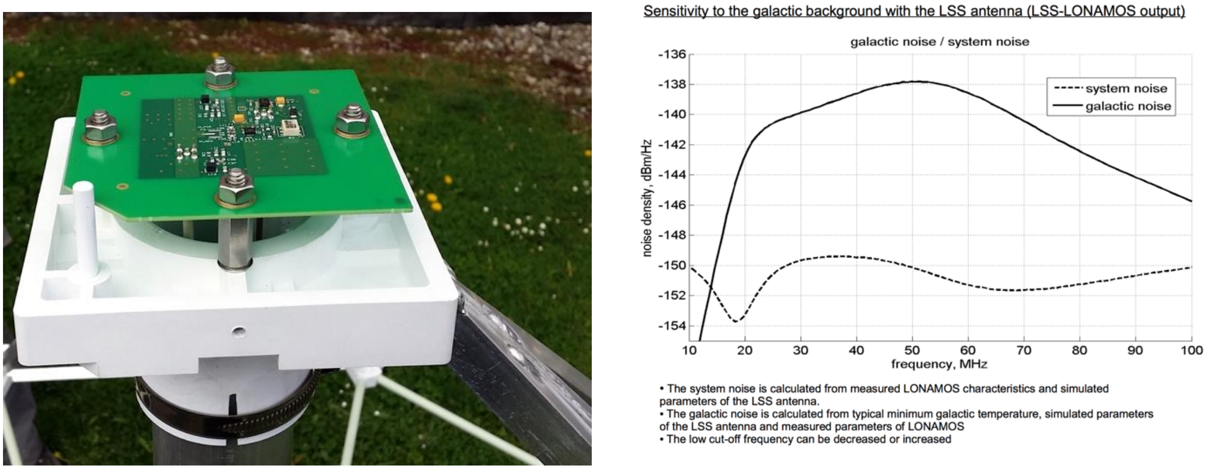


Figure 4 Left: LONAMOS board mounted on one of the antenna during a test at ROB, in Uccle – Right: Performance plot of the LWA-LONAMOS system (From Charlier, 2013)

Eight NenuFAR/LWA antennas were bought from the NenuFAR team at the Paris Observatory – Nançay Radioastronomy Station. The purchase was made after formal approval of our request by the executive board of the Paris Observatory.

Set up on site

Choice of the location in the Humain station

One requirement for locating SPADE on site was a flat area close to facilities with power and internet connection to host the receivers and control PC, and provide power to the active electronics of each antenna. Figure 5 shows a bird view of the Humain station in 2017 (from the WalOnMap website). The flattest part on the station was unfortunately the most remote one, near the tip of the north branch of the old solar interferometer. We choose, from on-site measurements of the declivity, a place next to the 6-m solar radio telescope currently operated. It has the advantage to be close to a cabin with the required access to electricity and internet.
We applied for an internal extra source of funding to build the basement of the array: a mix of gravel and sand was poured to provide a relatively flat terrain over an area of 20 x 20 m.

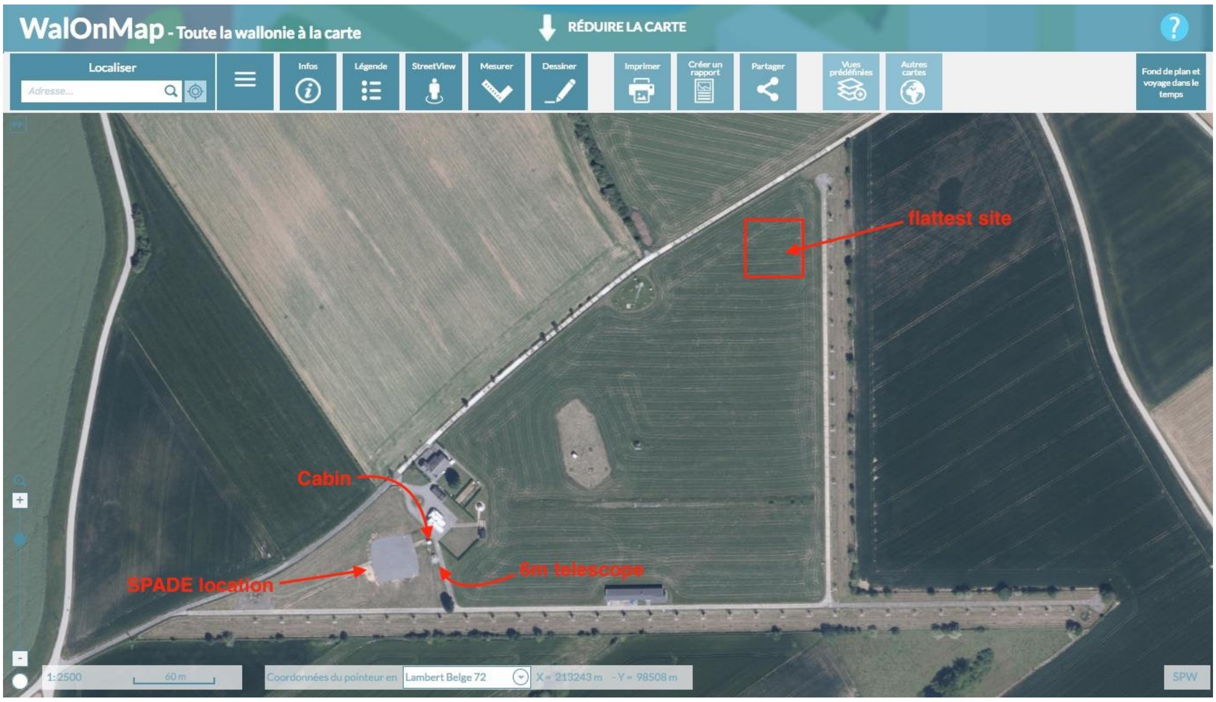


Figure 5 Bird view of the Humain station showing the SPADE array foundations

Array construction

Prior to the construction of the foundations, the position of the array and of each antenna was measured on site with a special GPS device borrowed from the seismology department of the Observatory. The device essentially combines information from GPS and GSM networks to achieve a precision of a few centimetres. Figure 6 shows the on-site measurement campaign of the antenna positions.

Trenches and pipes were buried with the help of the technical service of the observatory (
Figure 7), and a company was selected for the construction of the flat platform (Figure 8).

Figure 6 Campaign of on-site measurements of antenna positions (marked by the white sticks)

Figure 7 Excavation made for the pipes

Figure 8 Construction of the foundations of SPADE

After the end of the earthwork, the position of each antenna location was measured again. Displacements have been noticed and will be taken into account during the operations of the instrument. The final positions are listed below (Figure 9):

Antenna	Longitude (º ' ")	Latitude (º ' ")
0	5º 15' 10.05697362"	50º 11' 30.69922570"
1	5º 15' 10.05743279"	50º 11' 30.52184082"
2	5º 15' 09.84477293"	50º 11' 30.58752160"
3	5º 15' 09.78572203"	50º 11' 30.73669150"
4	5º 15' 09.92899861"	50º 11' 30.85513697"
5	5º 15' 10.18045294"	50º 11' 30.85866689"
6	5º 15' 10.32975617"	50º 11' 30.73142842"
7	5º 15' 10.27669808"	50º 11' 30.58862724"

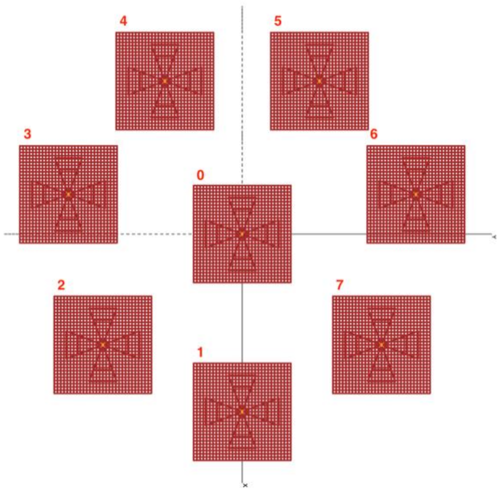


Figure 9 Position and theoretical layout of the antennas

RF cables connecting the antennas to the receivers are classically of type RG213: they are suitable (i.e. low attenuation) for the frequency range of SPADE. Both LONAMOS boards and receivers use SMA connectors which are small compared to the diameter of the cable. To avoid RF adaptors that create loss and reflections, special SMA connectors with a large connection area were purchased and mounted directly on the cables. Considering the distance from the array to the cabin, 8 rolls of 100 m of cables were purchased.

Each antenna electronics needs to be powered via the RF cable. To save money we reused the power supply of the old interferometer array still in perfect conditions. Bias-Tee devices allowing to inject the 12 V needed for the electronic operation are installed for each cable in the cab-in and connected to the power supply via an in-house set-up. The whole system is protected via a stabilized voltage UPS kindly provided by the Observatory technical service (
Figure 10).

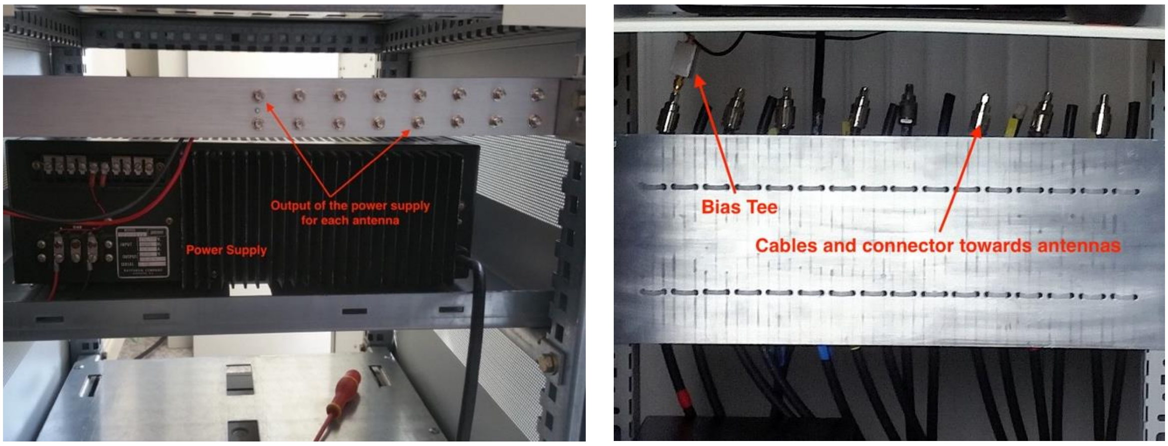


Figure 10 Left: Back of the power supply with the output for each antenna. Right: RF cables towards the antennas, with the special connectors and one bias tee installed

Choice of the hardware

Receivers

The initial idea was to rely on off-the-shelf Software Defined Radio receivers that are essentially used to digitize the radio signal and flag in time the different samples. The signal is then processed on the control PC connected to the receiver. Several options from the same vendor, all compatible with the well-known open source library Gnuradio have been investigated.
The first one is based on N210 receivers from Ettus Research (National Instruments). This was the idea suggested during the writing of the proposal. Eight receivers would be needed to operate the full array in two polarizations. An external clock sharing a reference in time and phase would be necessary to synchronize the eight receivers. The main issue we have encountered with this option is the clock speed at which the FPGA of each receiver runs. At 100 Ms/s, and with the interface boards compatible with the frequency range of SPADE, aliasing would occur for the higher part of the band (50 – 80 MHz). Several solutions were discussed including de-scoping the project to narrow down the overall bandwidth or down converting part of the band to stay below the Nyquist limit. These solutions were deemed too complicated, and out of reach in terms of manpower or budget.

Higher grade receivers from the same vendor, the X300 series, runs FPGA at 200 Ms/s and can accommodate the frequency range of SPADE without aliasing problems. Low pass filters are still needed to limit the input bandwidth (essentially above the FM band), but besides that, for a given polarization no extra front-end is needed. These receivers are more expensive than the other ones and only 2 can fit in the budget envelope, but up to 4 receiving ports can be set up per receiver. Moreover, only one receiver needs a clock and phase reference (via a GPS chip) and can share this reference with other receivers, which means that no external clock is anymore needed. With this option, and given the budget allowable for hardware, only one polarization can be monitored at a time. However, the benefit is such that this solution was preferred: switching from one polarization to the next in an external simplified frontend is easy to implement and can be triggered directly from the receivers, and in the future, extra funding may allow the purchase of two extra receivers.

At a certain point in the project, rules to purchase expensive equipment were modified. It was suddenly not clear if the X300 option would be feasible. We therefore investigated the use of a third category of (cheaper) receivers (USRP B210) from the same company, with 2 receiving ports each and built-in frequency conversion (alleviating the issue of aliasing). A home-made frequency conversion would still be needed to match the input frequency band of the receivers, but only four receivers would be needed (for one polarization). After weeks of investigations, it was not obvious if coherent operations would be up to the requirements needed for the project. After new accounting rules were put in place we decided to go for the X300 series.

Figure 11 One of the 2 receivers chosen for the project with 2 input cards (each with 2 ports) before integration

Control PC

The choice for the new kind of receivers also put some constrain on the choice of the control PC: the receiver outputs are two 10 Gb/s Ethernet ports, which means we selected a computer able to handle up to four 10Gb/s extra Ethernet ports. The high data rate is of course an issue, not so much for writing as pre-processing occurs before that step, which significantly diminishes the amount of data but simply for the near real-time handling of the data.

Software development

We were not able to build up, within the time frame, a working software for the control of the array, but instead we tested different technical options for the different subsystems.
As stated before, we choose to go with an open source library for the programming of the receiver. Gnuradio is not tight to one receiver brand and can handle different kinds of hardware. It has a broad user base and an active online community.

How to access the data flow?

As often in open source projects, the lack of proper documentation is a problem that can trigger delays. We give in the following a simple example.
Gnuradio is based on the concept of data flow between a source (the receiver) and a “sink” that is usually a graphical interface (a window displaying a spectrum for example) or a file which contains the raw output of the receiver. In between, are different blocks or modules that perform operation (filtering, throttling, Fourier analysis, etc.). To actually access the data flow to perform specific operations requires either to write a specific module: it is possible to do so, either in Python or C++ but for real-time processing only C++ was fast enough. None of the persons involved in the project were skilful enough in this programming language. The other possibility is to access, externally, the data flow for further data processing in Python with buffer mechanisms. After some research, one communication protocol was found adequate (Zeromq), and access to the data flow was possible. There is however no clear description of the data flow structure (how the data and metadata are entangled) and we had basically to reverse engineer byte by byte the stream of data. This process took many weeks if not months of work, but as a positive note, the outcome, which is the ability to handle the data flow processing strictly outside the framework of Gnuradio, can readily be (and is) reused for the other solar radio astronomy projects of ROB.

Data management

One of the reasons we wanted to access directly the data flow is linked to the frequency switch. The band monitored by SPADE is about 70 MHz wide, and might need to be accessed in separated narrower bands. Each retuning of the receiver at a desired frequency requires a certain amount of time (typically a few ms): the local oscillator will take some time to stabilize at a new frequency. However, in the meantime samples are still streamed from the device. We need therefore to count and discard a certain number of FFT samples before we can take them into account. This “waiting” time has basically to be measured in laboratory. We devised simple programs to do so, applicable to different kind of receivers.
One key aspect of the data management is the selection of the correct data format. Typically, dynamic spectra such as the ones that will be produced by SPADE are stored as FITS files, a standard in astronomy. This data format has however some drawbacks: for dynamic spectra (representing time/frequency pseudo images), time and frequency need to be stored in different “sections” of the file. Moreover, there is no standard definition of file structures for datasets such as dynamic spectra.

We choose instead to rely on HDF data format, which defines a hierarchy within the files, to store data and their metadata in a self-documented way. For example, we can store metadata such as the temperature of the receiver, the GPS lock, in a separate internal “directory”, beside a data “directory” containing the data itself, the time and frequency arrays. Moreover, there exists a way to write HDF files that guarantees that the file won’t be corrupted if a program crash occurs. Being able to write in a specific data format was also one of the reasons we wanted to access the data flow directly: we currently have 2 small spectrometers operated with Gnuradio and we produce FITS files from intermediate data files in Gnuradio format, which is cumbersome.
The generation of HDF files has been tested and put in operation with another radio receiver for solar flux monitoring (SAFIRE) and gives satisfaction. We are therefore confident we have chosen here the correct approach.

Preliminary results

Electrical tests of individual antenna have been performed in 2018 (after the official end of the project). We wanted to sanity check the powering of the array, and the fact that the RF cables were properly connected. With the low solar activity, no meaningful solar observations could be done during the tests. We focused instead on observations of meteors: the BRAMS project operates a beacon at the Dourbes station at $\sim$50 MHz, in the middle of the SPADE band. When a meteor occurs in the high atmosphere, its ionization trail can reflect the wave emitted by the beacon and be detected by an antenna (forward-scattering mode). We made such observations with three different receivers: a spectrum analyzer, an analog receiver, and a small SDR. Figure 12, left, shows the dynamic spectrum with the beacon signal, a meteor and planes signatures. The right-hand plot shows profiles measured with a spectrum analyser with 3kHz bandwidth.

The background level is around -100 dBm, in accordance with the specifications (taking into account the bandwidth) of a NenuFAR antenna shown in
Figure 4. As expected, we are limited by the galactic background level.

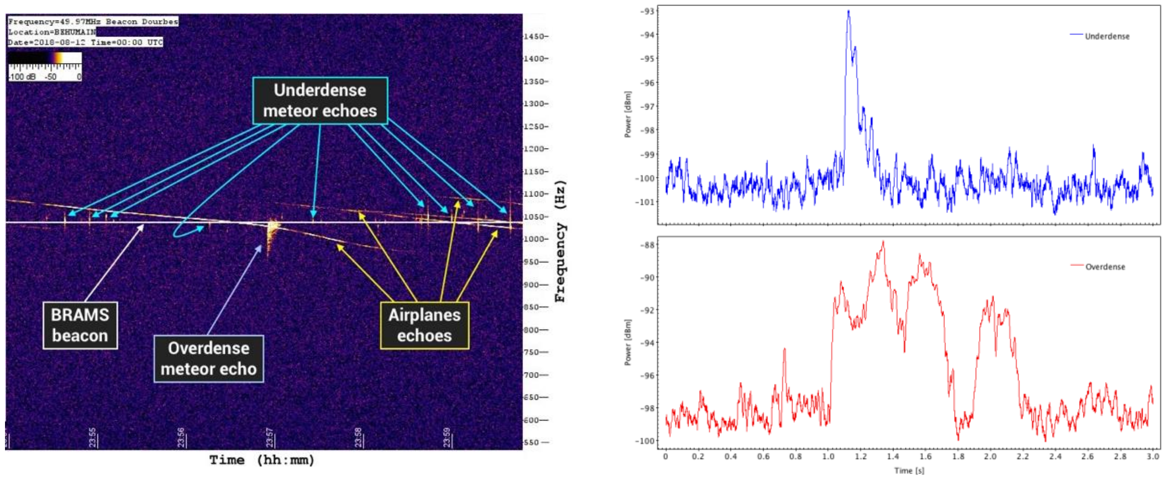


Figure 12 Meteor observation with one of the SPADE antennas. Left, dynamic spectrum; right, profile recorded with a spectrum analyzer (from Martinez & Marqué, 2018 in prep)

Lesson learned

To conclude this section, we wish to draw a series of conclusions about the project. We did not deliver an instrument in working conditions within the 2-year time frame of the project, and we believe the following reasons could be put forward:

- We clearly underestimated the amount of work needed for all practical aspects related to the building of the instruments (earthwork, cabling, power supply, antenna positioning on ground, soldering, selection of hardware).
- The manpower needed for all the tasks was also underestimated. One of us (C. Marqué) is involved in development of multiples radio instruments which is time consuming. On the other hand, the selection of compatible hardware and similar control software library helped as common problems occurred and were resolved between the projects.
- The use of open-source library is both positive and negative: the lack of proper documentation is only partially compensated by online resources (mailing list discussions…)
- The complexity of some administrative rules for the purchase of expensive goods has been an issue at a critical time of the project
- It might be fair to say that the format of the BRAIN Pioneer framework was not adequate in terms of duration, budget (for manpower and hardware): we relied on internal funding for some work or equipment (cabling, earthwork). The scope of such a project might be better suited for a BRAIN network framework.

3. DISSEMINATION AND VALORISATION

The progress of the project has been advertised in several conferences by Antonio Martínez Picar:

- A. Martínez Picar, C. Marqué, "*Using a small phase array for meteor observations*", talk given at the International Meteor Conference 2017 - Petnica, Serbia, September 2017
- A. Martínez Picar, C. Marqué, "*Building SPADE – Status Update*", poster given at the International Workshop on Solar, Heliospheric and Magnetospheric Radioastronomy - Meudon, France, November 2017
- A. Martínez Picar, C. Marqué, J. Magdalenić, "*SPADE: Small Phased Array Demonstrator for Solar Radio Astronomy Observations*", poster given at the CESRA 2016 meeting – Orléans, France, June 2016

The antennas used in the SPADE project appeared in one news items on the Solar Terrestrial Center of Excellence website: http://www.stce.be/news/387/welcome.html
SPADE has been shown to the whole ROB staff in May 2018 during a team building day in Humain and Rochefort (http://www.stce.be/news/425/welcome.html).

4. PERSPECTIVES

After December 2017, the project continues with non-dedicated financial resources. It is integrated in the wider development plan of the Humain Radioastronomy Station whose objective is to provide the solar physics department and the operational space-weather service of ROB with a broad radio coverage of the solar activity. Figure 13 provides an overview of the existing instruments and the ones in development. Except the CALLISTO instrument, which is based on an analog hardware, all other mentioned instruments are based on SDR devices from the same vendor. They are not identical, but share the same development library that makes development and maintenance easier. The two projects being in a development or in a commissioning stage are SPADE and SAFIRE. SAFIRE is a solar flux monitoring instrument at a series of discrete individual frequencies between 1 and 5 GHz. Some key-elements of the software development of SAFIRE (data streaming out of the receiver, time management while retuning, and phase stability between the two input channels) can be readily reuse in SPADE. ARCAS and HSRS share a common and somehow older control software that will be updated when SPADE and SAFIRE are deemed operational.

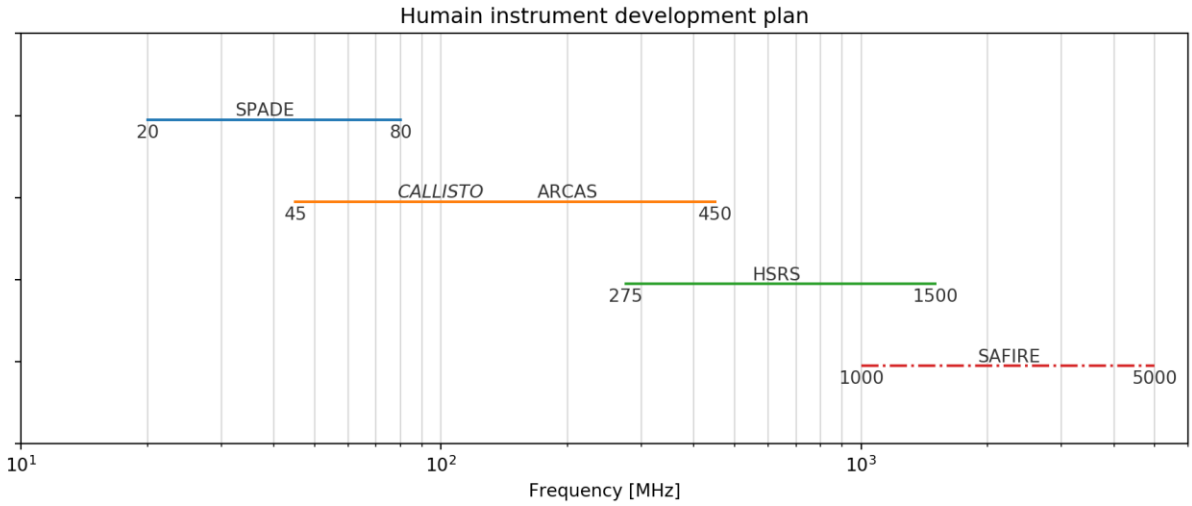


Figure 13 List of the different solar instruments at the Humain Radioastronomy Station

The development of SPADE will therefore carry on and be focused on the software part and the calibration of the antennas on site, with the use of a drone equipped with a radio emitter.

SPADE (and other radio instruments in Humain) have been discussed in March 2018, during a meeting at the Paris-Meudon Observatory: the PI team of the *Radio and Plasma Waves* (RPW) instrument on board Solar Orbiter organized a discussion about synergies with ground based radio instruments and RPW. It appeared that SPADE could become in the future a prime source of solar data between 20 and 80 MHz, as the NDA instrument in Nançay, covering the same band, is more and more used for jovian observations for support of the Juno mission.

5. PUBLICATIONS

- A. Martínez Picar, C. Marqué, "*Using a small phase array for meteor observations*", Proceedings of the International Meteor Conference 2017 - Petnica, Serbia, September 2017, In press

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ANNEXES

N/A