ASTRON

Netherlands Institute for Radio Astronomy

10 YEARS **OF LOFAR HIGHLIGHTS**

12 JUNE 2020

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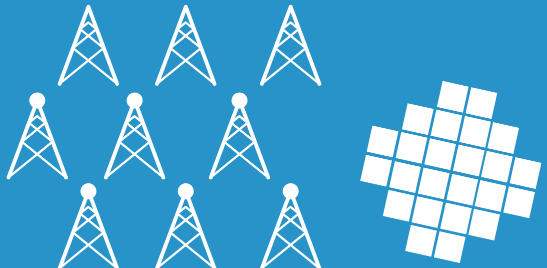
On 12 June 2020, LOFAR celebrated its tenth anniversary. The radio telescope is the world’s largest low frequency instrument and is one of the pathfinders of the Square Kilometre Array (SKA), which is currently being developed. Throughout its ten years of operation, LOFAR has made some amazing discoveries. It has been a key part of groundbreaking research, both in astronomy and engineering. Here we feature some – but definitely not all – of these past highlights, as well as some highlights we look forward to with LOFAR 2.0.



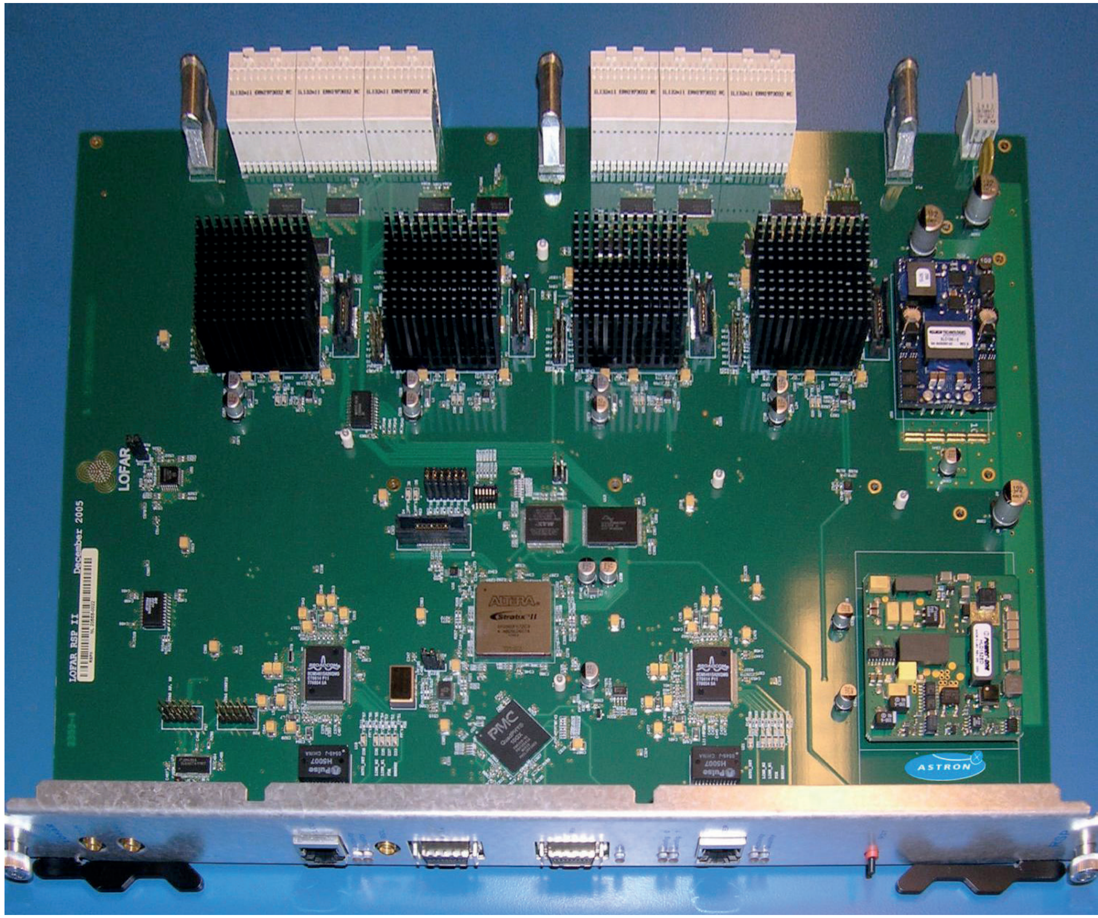
RSP boards make sure beamforming is possible

LOFAR is the first radio telescope of its size, wherein tens of thousands of small antenna elements are used instead of a few big dishes, as was more common in radio astronomy. All these antennas generate enormous amounts of data 24/7.

The first stage of combining all that data and reducing it for subsequent stages is done by the Remote Station Processing (RSP) board. A complex board equipped with 5 high-end Field Programmable Gate Arrays (FPGA) at the time of installation. The processing load of each Dutch station was distributed over 12 of these boards. These boards were all serialized to each other, each board processing its partial sum. The last board in the chain calculated the final station output product. The RSP boards resulted in the first large scale beamformer systems applied in radio astronomy.

The main cost driver of the RSP boards were the FPGAs, which were tendered after the prototype design was complete. We had to completely re-factor the RSP board because the competitor vendor was awarded for the tender. The consequence was a re-design of the board and porting the existing firmware to the FPGA type of the awarded vendor.

During the RSP board design one of the ambitions was to be able to off-load all incoming data for later use. Unfortunately at that time the cost impact did not justify the "nice to have" functionality. As a consequence, LOFAR functionality added to LOFAR later, like AARTFAAC, costed extra design effort to realize. However, in LOFAR2.0 all of the incoming data can potentially be offloaded because the selected hardware (UniBoard^2) has much more IO capability.



Prototype of RSP board with the Altera FPGA, which was later replaced by a Xilinx FPGA. (Credit: ASTRON)

Why lightning often strikes twice

Although the saying goes ‘lightning never strikes the same place twice’, in fact it often does. Why it does so however, has long remained a mystery, but in 2019 a team of scientists led by the University of Groningen (RUG) used LOFAR to shed light on this matter. The radio telescope was able to chart lightning flashes in unprecedented detail, showing structures in the lightning channels the researchers dubbed needles. Through these needles, a negative charge may cause a repeated discharge to the ground.

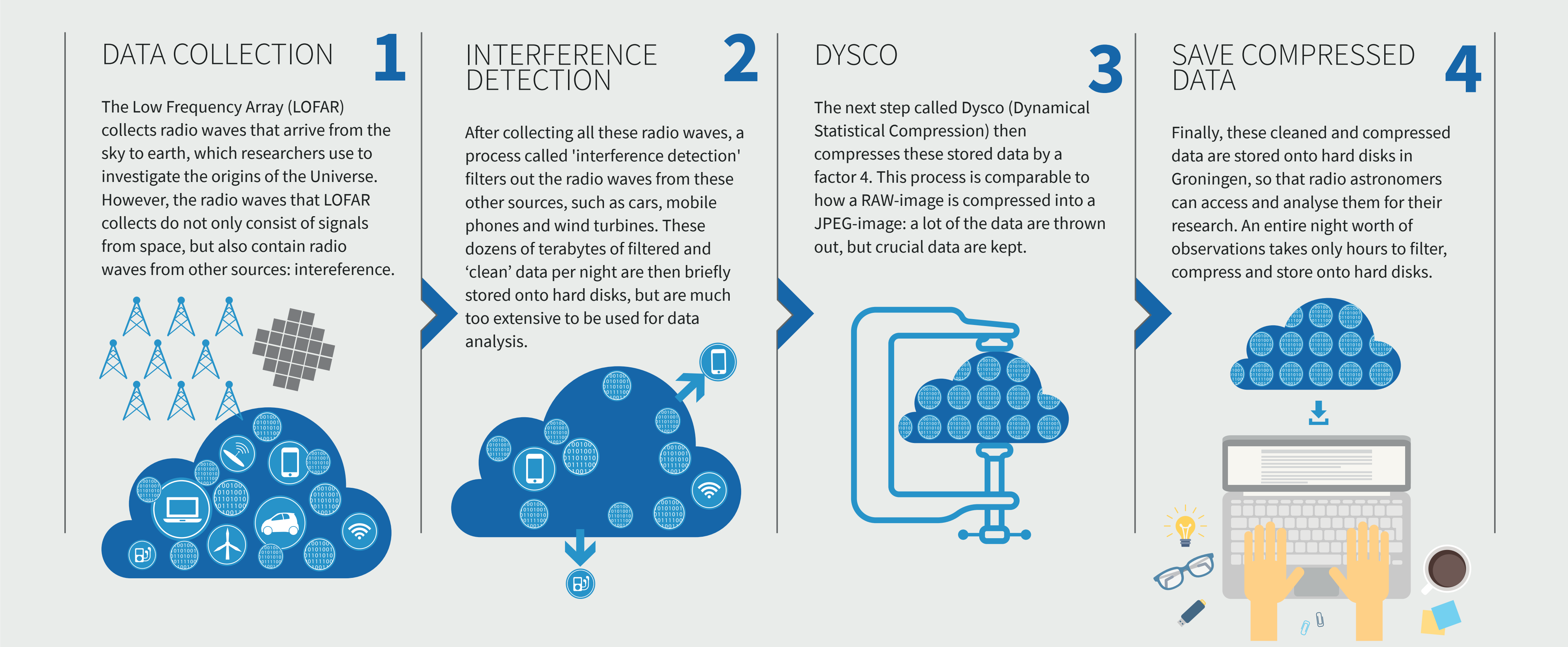
Lightning occurs when strong updrafts generate a kind of static electricity in large cumulonimbus clouds. Parts of the cloud become positively charged, others negatively. Once this charge separation is large enough, a violent discharge occurs: lightning. Such a discharge starts with a plasma, a small area of ionized air hot enough to be electrically conductive. This small area grows into a forked plasma channel that can reach lengths of several kilometres. The positive tips of the plasma channel collect negative charges from the cloud, which pass through the channel to the negative tip, where the charge is discharged. Lightning produces a large amount of VHF (very high frequency) radio bursts at the growing tips of the negative channels, while the positive channels show emissions only along the channel, not at the tip. Since LOFAR can detect signals in the VHF radio band, it is able to detect lightning propagation at an unprecedented scale and to ‘look’ inside a thundercloud, where most of the lightning resides.

The LOFAR study revealed the occurrence of a break in the discharge channel at a location where needles are formed. These needles appear to discharge negative charges from the main channel, which subsequently re-enter the cloud. The reduction of charges in the channel causes the break. However, once the charge in the cloud becomes high enough again, the flow through the channel is restored, leading to a second discharge of lightning. By this mechanism, lightning will strike in the same area repeatedly. The researchers published their results in the science journal Nature on April 18th.

The reason why the needles have never been seen before lies in the ‘supreme capabilities’ of LOFAR, says Dr Brian Hare, first author of the paper: ‘These needles can have a length of 100 metres and a diameter of less than five metres, and are too small and too short-lived for other lightning detections systems.’
Although LOFAR is developed primarily for radio astronomy observations, this discovery proves that it is also very suited for lightning research.

Lightning above the central part of LOFAR. (Credit: Danielle Futselaar)

Infographic: Interference detection and Dysco



DATA COLLECTION 1

The Low Frequency Array (LOFAR) collects radio waves that arrive from the sky to earth, which researchers use to investigate the origins of the Universe. However, the radio waves that LOFAR collects do not only consist of signals from space, but also contain radio waves from other sources: intereference.

INTERFERENCE DETECTION 2

After collecting all these radio waves, a process called 'interference detection' filters out the radio waves from these other sources, such as cars, mobile phones and wind turbines. These dozens of terabytes of filtered and ‘clean’ data per night are then briefly stored onto hard disks, but are much too extensive to be used for data analysis.

DYSCO 3

The next step called Dysco (Dynamical Statistical Compression) then compresses these stored data by a factor 4. This process is comparable to how a RAW-image is compressed into a JPEG-image: a lot of the data are thrown out, but crucial data are kept.

SAVE COMPRESSED DATA 4

Finally, these cleaned and compressed data are stored onto hard disks in Groningen, so that radio astronomers can access and analyse them for their research. An entire night worth of observations takes only hours to filter, compress and store onto hard disks.

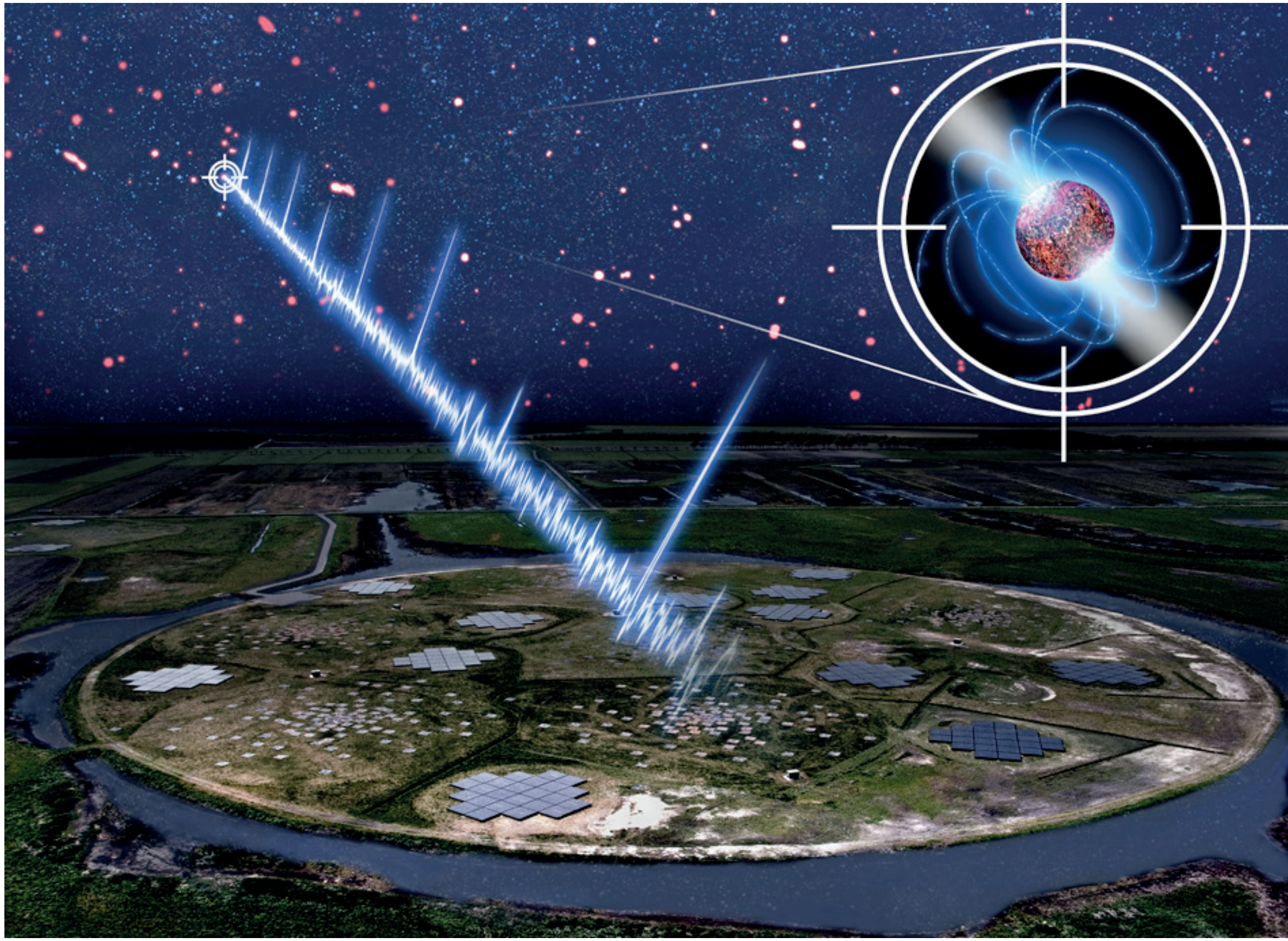
How LOFAR treats data collected by its stations.

Super-slow pulsar challenges theory

In 2017 LOFAR detects the slowest spinning radio pulsar to date. The neutron star spins around once only every 23.5 seconds almost three times more slowly than the slowest spinning radio pulsar detected up to that point (8.5 seconds).

The discovery is a joint effort of the University of Manchester, ASTRON and University of Amsterdam; University of Manchester PhD-student Chia Min Tan makes the discovery as part of the LOFAR Tied-Array All-Sky Survey, which searches for pulsars in the Northern sky. Each survey snapshot of the sky lasts for one hour, which is much longer compared to previous surveys. Solely due to this high sensitivity this slow rotating neutron star, which is approximately 14 million years old, can be detected.

The fact that such a slow spinning pulsar still emits radio waves strong enough to detect, challenges the current theories of how pulsars shine.



Artist’s conception of the 23.5-second pulsar. Radio pulses originating from a source in the constellation Cassiopeia travel towards the core of the LOFAR telescope array. (Credit: Danielle Futselaar/ASTRON)

Using the existing SurfNet infrastructure to connect international stations and its European counterparts

In addition to the 40 Dutch antenna stations, LOFAR has 14 antenna stations elsewhere in Europe. Just like the antenna stations in the Netherlands, the European stations also send their observation data via fiber optic connections to the central processor (CEP) of LOFAR at Groningen.

In the Netherlands, LOFAR uses its own, dedicated fiber optic network to send observation data from the stations to CEP. Although such an approach would be possible for the European part from a technical point of view, a European wide dedicated fiber optic LOFAR network can not be realised due to the extremely high construction and maintenance costs. For the European stations, a more cost-effective approach to data transport was chosen by using the facilities of the National Research and Education Networks (NRENs) in Europe.

At the time of the construction of LOFAR, so-called Lightpath technology became available at the European NRENs with which 10 Gb/s point-to-point connections can be realized. As one of the first users of Lightpath technology, all LOFAR stations in Europe are equipped with the required broadband, direct connections to Groningen. The construction of the lightpaths has been realized together with the Dutch NREN Surfnet, in collaboration with the other NRENs along the various connections. It was important to configure the interfaces of the NREN router systems in such a way that interconnections are possible.

Even 10 years after the opening of LOFAR, the LOFAR Lightpaths still provide the direct connections between the European LOFAR stations and Groningen that are required for the streaming data in the LOFAR telescope.

LOFAR station in Latvia. (Credit: ASTRON)

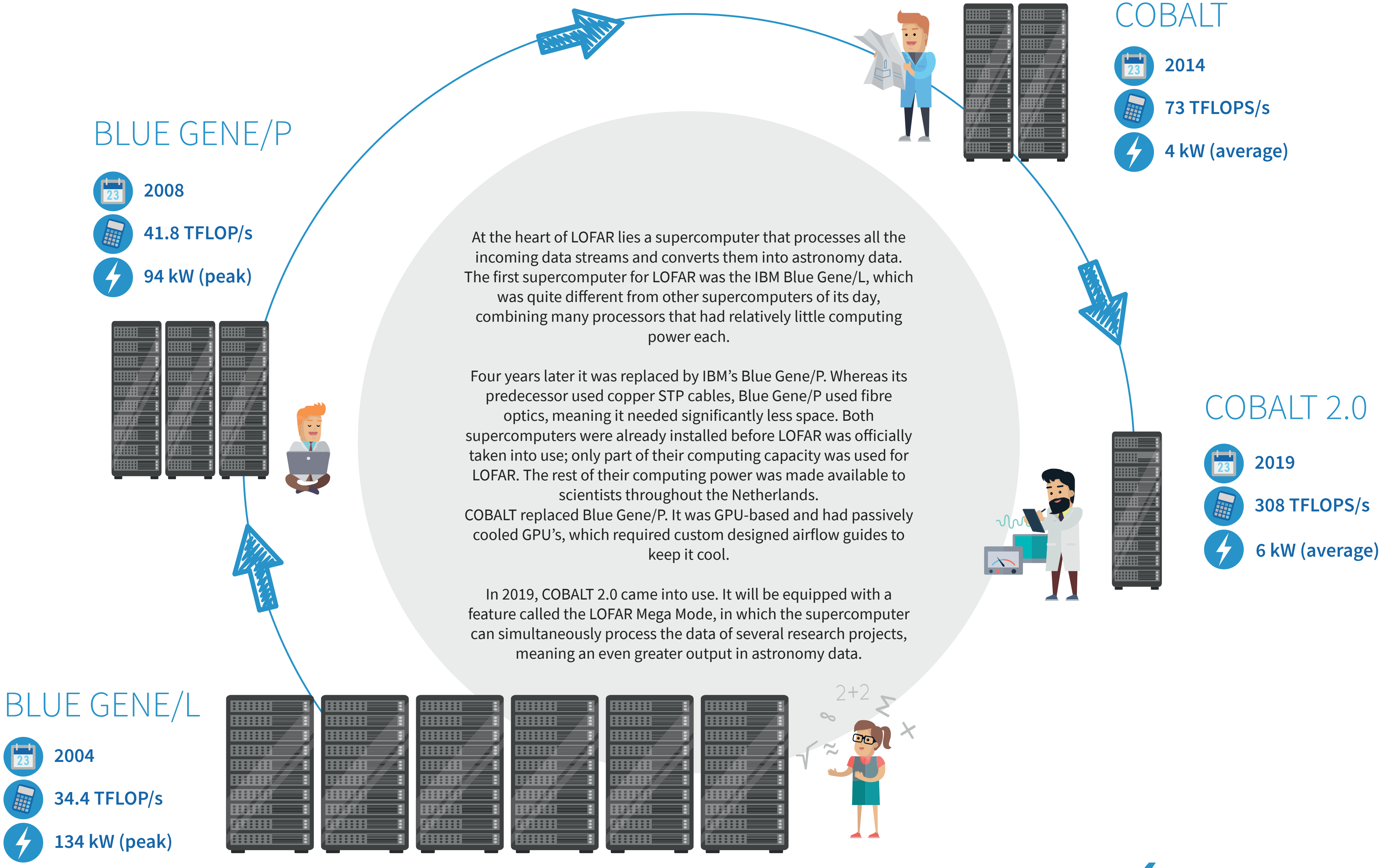
The construction and use of our own broadband optical data transport system

In the Netherlands, the LOFAR telescope consists of approximately 40 antenna stations that are spread over the entire North of the Netherlands. The amount of LOFAR data that needs to be transferred from these stations is so large that it cannot be sent via the regular Internet. Specially constructed fiber optic connections are required to transport a large amount of astronomy data from the stations to Groningen.

The antenna stations of LOFAR receive astronomical data which, after an initial processing step, are forwarded to a central computer system, which is placed at the Center for Information Technology (CIT) of the RU Groningen. During the construction of LOFAR, a new fiber optic cable was installed towards each station. Where possible, this cable is placed (blown) in an existing tube with other cables. But in many places, especially close to the antenna stations, digging also had to be done to get the fiber optic cables in the ground. Once all fiber optic cables were in place, special optical communication equipment was purchased via a tender. In this way, each LOFAR station was equipped with a 10 Gb/s optical connection to the CIT.

To date, this bandwidth has been sufficient to adequately provide data to all astronomers. Nowadays, consideration is being given to further increasing the bandwidth from each station. This possible upgrade can be realized by adjusting the communication equipment at the stations and at the CIT. The glass fibers do not need to be adjusted: thanks to their gigantic potential bandwidth, we can continue with them for years to come.

Infographic: The evolution of LOFAR supercomputers



At the heart of LOFAR lies a supercomputer that processes all the incoming data streams and converts them into astronomy data. The first supercomputer for LOFAR was the IBM Blue Gene/L, which was quite different from other supercomputers of its day, combining many processors that had relatively little computing power each.

Four years later it was replaced by IBM's Blue Gene/P. Whereas its predecessor used copper STP cables, Blue Gene/P used fibre optics, meaning it needed significantly less space. Both supercomputers were already installed before LOFAR was officially taken into use; only part of their computing capacity was used for LOFAR. The rest of their computing power was made available to scientists throughout the Netherlands.
COBALT replaced Blue Gene/P. It was GPU-based and had passively cooled GPU's, which required custom designed airflow guides to keep it cool.

In 2019, COBALT 2.0 came into use. It will be equipped with a feature called the LOFAR Mega Mode, in which the supercomputer can simultaneously process the data of several research projects, meaning an even greater output in astronomy data.

BLUE GENE/L

2004
34.4 TFLOP/s
134 kW (peak)

BLUE GENE/P

2008
41.8 TFLOP/s
94 kW (peak)

COBALT

2014
73 TFLOPS/s
4 kW (average)

COBALT 2.0

2019
308 TFLOPS/s
6 kW (average)

The 'evolution' of supercomputers used for LOFAR.

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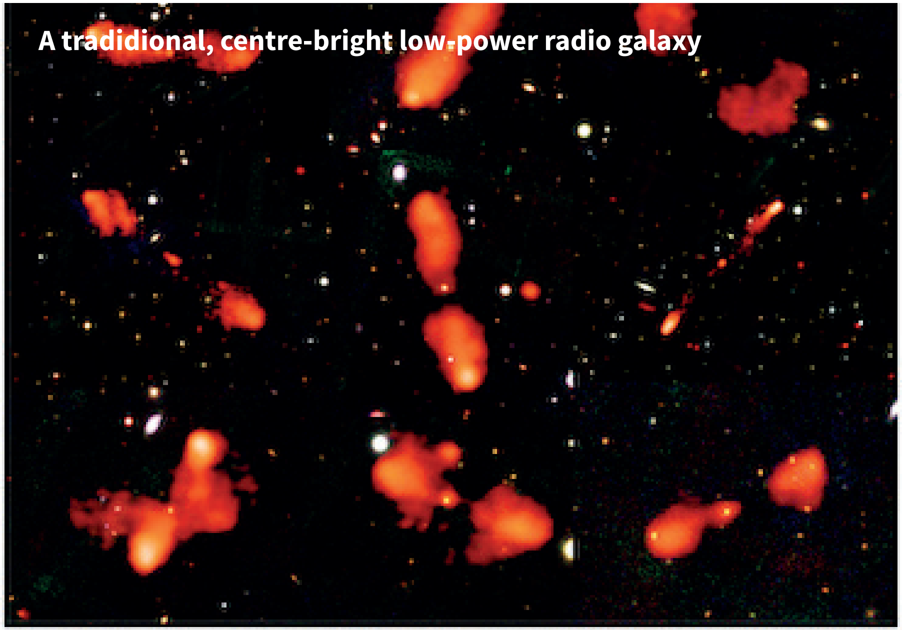
Revisiting the Fanaroff-Riley dichotomy and radio-galaxy morphology with the LOFAR Two-Metre Sky Survey

It has been known since the 1970s that the radio structures made by jets from black holes come in two types: very powerful jets are brightest at the edges and weaker jets are brightest in the middle and fade out at large distances.

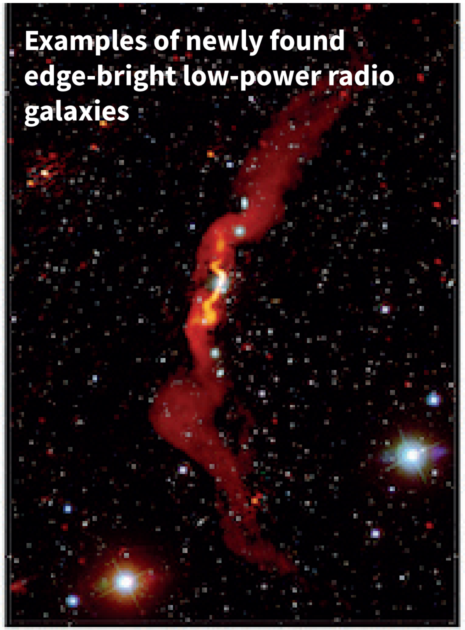
Our work with LOFAR has revealed a new population of low-power jets with an edge-bright appearance, which was mostly invisible to previous surveys, and which breaks this traditional view. These jets seem to live in smaller, less dense galaxies and so, although relatively weak, they do not get disrupted early on and can travel undisturbed for hundreds of thousands of light-years. Because the appearance of the jet is linked to its interaction with the environment it travels through, this population could shed new light on how black holes influence the galaxies and clusters they live in.

This highlight is based on the article *Revisiting the Fanaroff-Riley dichotomy and radio-galaxy morphology with the LOFAR Two-Metre Sky Survey (LoTSS)* Mingo, B.;Croston, J. H.;Hardcastle, M. J.;Best, P. N.;Duncan, K. J.;Morganti, R.; Rottgering, H. J. A.; Sabater, J.; Shimwell, T. W.;Williams, W. L.;Brienza, M.;Gurkan, G.;Mahatma, V. H.;Morabito, L. K.; Prandoni, I.;Bondi, M.;Ineson, J.;Mooney, S.

doi: 10.1093/mnras/stz1901



A tradidional, centre-bright low-power radio galaxy



Examples of newly found edge-bright low-power radio galaxies

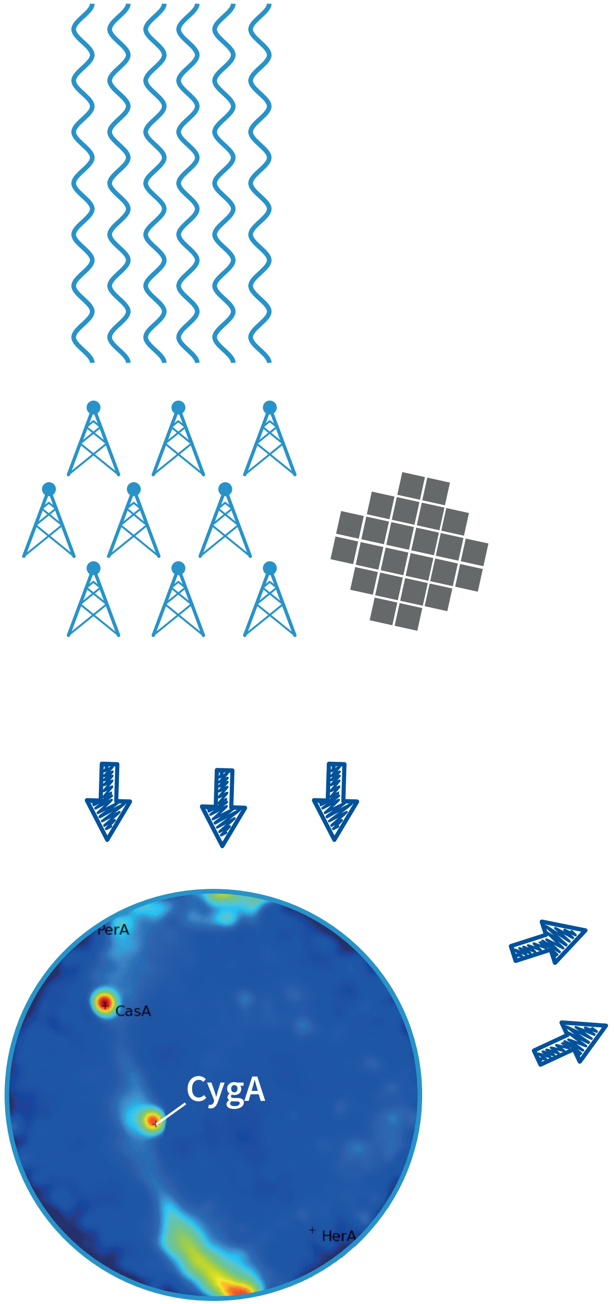
Credit image on the left: Mingo, Croston & LOFAR surveys team, credit image on the right: Heesen & LOFAR surveys team

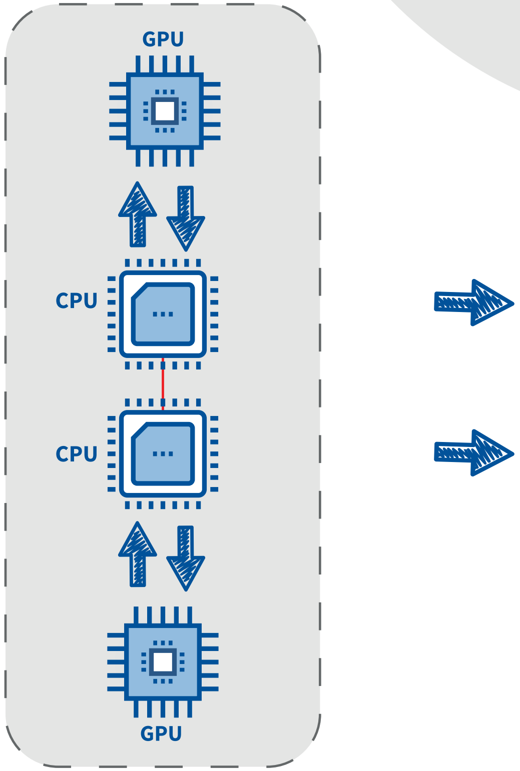
Infographic: Off the shelf GPU's

INFOGRAPHIC

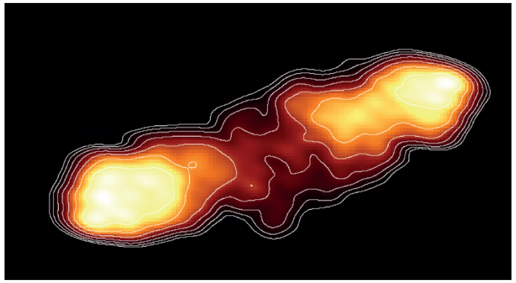
Off the shelf GPU's for LOFAR

An antenna field receives radio waves from the sky and forms an image of Cygnus A (CygA), the constellation Swan. These data are processed by a combination of hardware and software.
CPU's in the hardware receive the data and transfer them to high-end GPU's, which are extremely suited to perform parallel calculations. The correlator holds 44 GPU's (and 44 CPU's) in total, which can process terabits of data per second. The GPU's process the data, using complicated algorithms and delete all non-essential data. Then they send the processed data back to the CPU's, which forward it to store it onto hard disks.
From the processed data a far more detailed image of Cygnus A is now produced.





CygA



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A complete image of the visible sky every second

The behaviour of black holes and neutron stars can expose some of the most extreme tests of physical law. Therefore, this behaviour can be used to find answers to questions as to how black holes are born and to the origin of magnetic fields and cosmic rays. To be able to observe these extreme and transient objects, one must not only survey large areas of sky, but also do this quickly and often. But how do you do this?

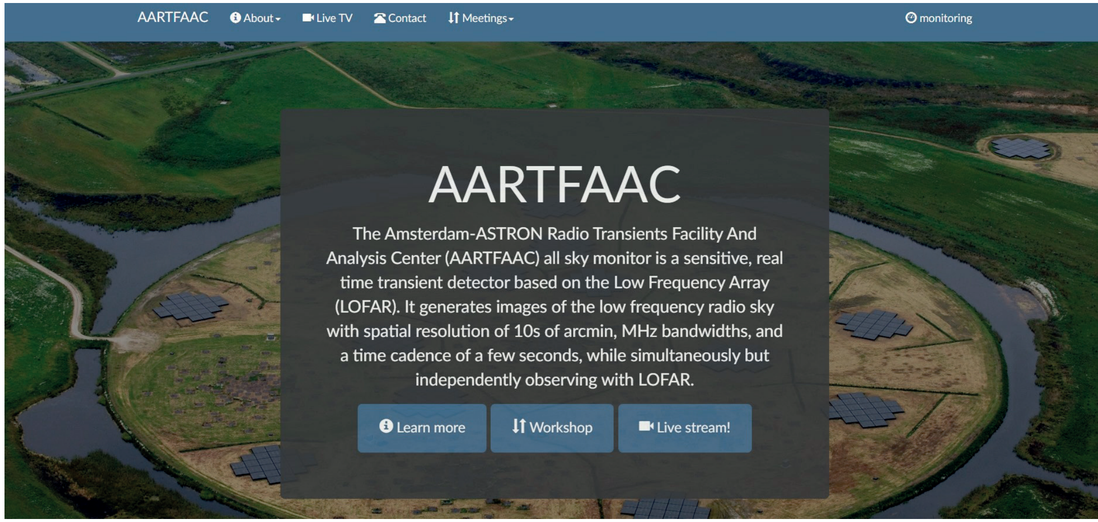
Project AARTFAAC (Amsterdam-ASTRON Radio Transients Facility And Analysis Center) is a real-time transient detector. It utilizes 576 LOFAR antennae to create an image of the visible sky every second.

AARTFAAC creates images of the low frequency radio sky with a spatial resolution of 10 arcseconds. AARTFAAC is able to quickly create sky images. The clever thing is that AARTFAAC does this simultaneously with, but independently from observations with LOFAR.

Each second the data of 576 LOFAR antennae are collected at a GPU correlator, consisting of 20 GPUs (graphic processor units). There, the data are combined (correlated) with each other. Next. the correlated data are calibrated, and transformed into sky images. Then, specially developed software analyses these images to determine whether there are so called transients – sudden changes – present between them. These transients could point to the aforementioned transient objects.

Principal investigator and spiritual father of AARTFAAC is prof. Ralph A.M.J. Wijers from the University of Amsterdam. AARTFAAC is a collaboration of ASTRON (development of Uniboard correlators, co-development of software and science exploitation) and Oxford Astrophysics/e-Research Centre (station hardware development, co-operation on streaming data pipeline) and primarily an experimental system, which has taught astronomers how to build such an all-sky instrument.

LOFAR can create far more detailed images than AARTFAAC can. It uses far more antennae and observes through a far larger bandwidth than AARTFAAC does. But where LOFAR only can capture a small piece of the visible sky simultaneously, AARTFAAC captures the entire visible sky in a single second.



AARTFAAC

The Amsterdam-ASTRON Radio Transients Facility And Analysis Center (AARTFAAC) all sky monitor is a sensitive, real time transient detector based on the Low Frequency Array (LOFAR). It generates images of the low frequency radio sky with spatial resolution of 10s of arcmin, MHz bandwidths, and a time cadence of a few seconds, while simultaneously but independently observing with LOFAR.

The LOFAR Two-metre Sky Survey

A detailed radio image of the entire northern sky in the frequency range of 120-168 MHz. That is what the LOFAR Two-metre Sky Survey (LoTTS) aims to achieve.

To do that, scientists must observe no less than 3170 pointings for 8 hours each. When they achieve this impressive feat, the scientists will be able to achieve 5” resolution images with a sensitivity of 100 µJy/beam and accomplish the main scientific aims of the survey: to explore the formation and evolution of massive black holes, galaxies, clusters of galaxies and large-scale structures.

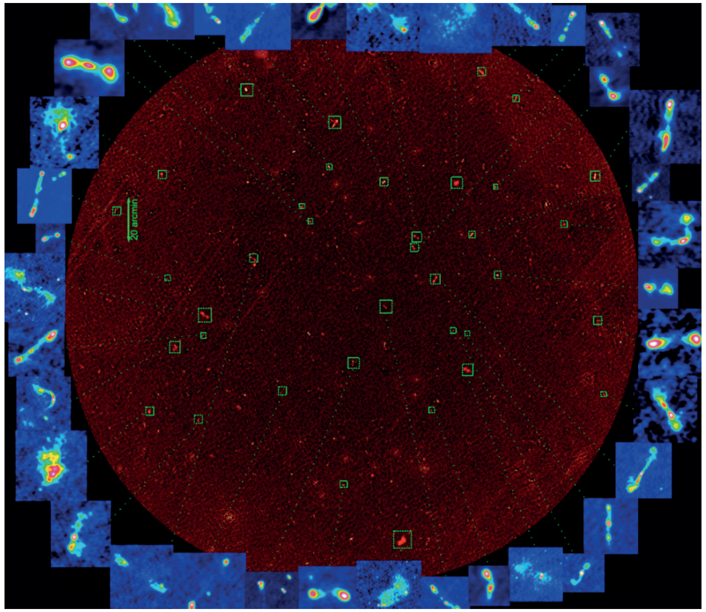
An impossible task? ‘We are now a bit over 50 percent of the observations,’ says ASTRON astronomer dr. Timothy Shimwell. Quite an achievement already and one that has been made with a team of about 250 scientists. Shimwell: ‘We’re spread over 20 countries and about 60 institutes.’

Why so many scientists? Because there were quite a few challenges to overcome with different expertises. For example: LOFAR uses supercomputers that handle large data rates, and a large number of specially written algorithms and software.

To what does the ‘Two-metre’ refer? ‘To the 150 MHz-band’, Shimwell explains. So basically, to the bandwidth that LOFAR is surveying. And quite effectively, Shimwell adds. ‘One of LOFAR’s strengths is to map the sky at very low frequencies with very high resolution and sensitivity, within a reasonable amount of time.’

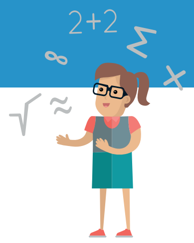
The project started in 2014 and has thus far produced over a hundred scientific papers. And even though the LOFAR Two-metre Sky Survey had passed the halfway mark, it is unknown when it will be finished. Shimwell: ‘Just like everyone else we have to send in proposals to get some time allocated to do our surveys. We generally put in a big proposal and on average get allocated around a thousand hours per six months.’ To put things into perspective: the whole survey will take about 14,000 hours of observations.

Particularly important about the survey is the openness, explains Shimwell: ‘We are trying to ensure that the data we collect become public in the best possible quality. That way, the whole international scientific community can benefit from it.’



High-resolution LOFAR High Band Antenna image of the Boötes field, made at 130-169 MHz. The image is a result of the LOFAR Two Metre Sky Survey. (credit: Wendy Williams)

Improved upper limits on the 21 cm signal power spectrum of neutral hydrogen at z ≈ 9.1 from LOFAR

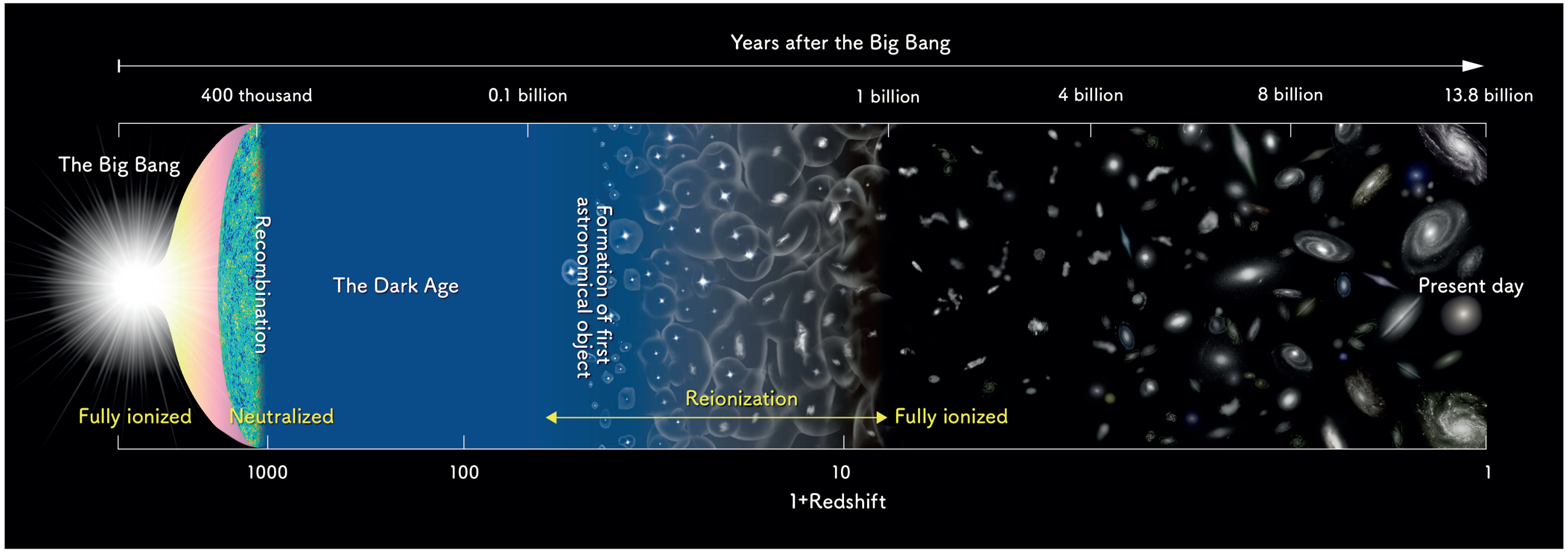


13.8 billion years ago, our Universe was created in an event called the Big Bang. “Only” 0.5 billion years later, the Universe entered a pivotal stage. At that time, the Universe was filled with cold hydrogen, and the first objects, such as early stars and galaxies, had just formed. These objects started to heat the hydrogen, causing “bubbles” of heated hydrogen to form around the radiating sources. This process is called the Epoch of Reionization.

A group of researchers is using LOFAR to improve our understanding of this early phase of our Universe. The bubbles of heated hydrogen leave a particular inprint behind in the signals that LOFAR receives, and can therefore be detected by LOFAR. However, this requires advanced modelling techniques and combining many observations to detect the weak inprint behind all the nearby bright objects.

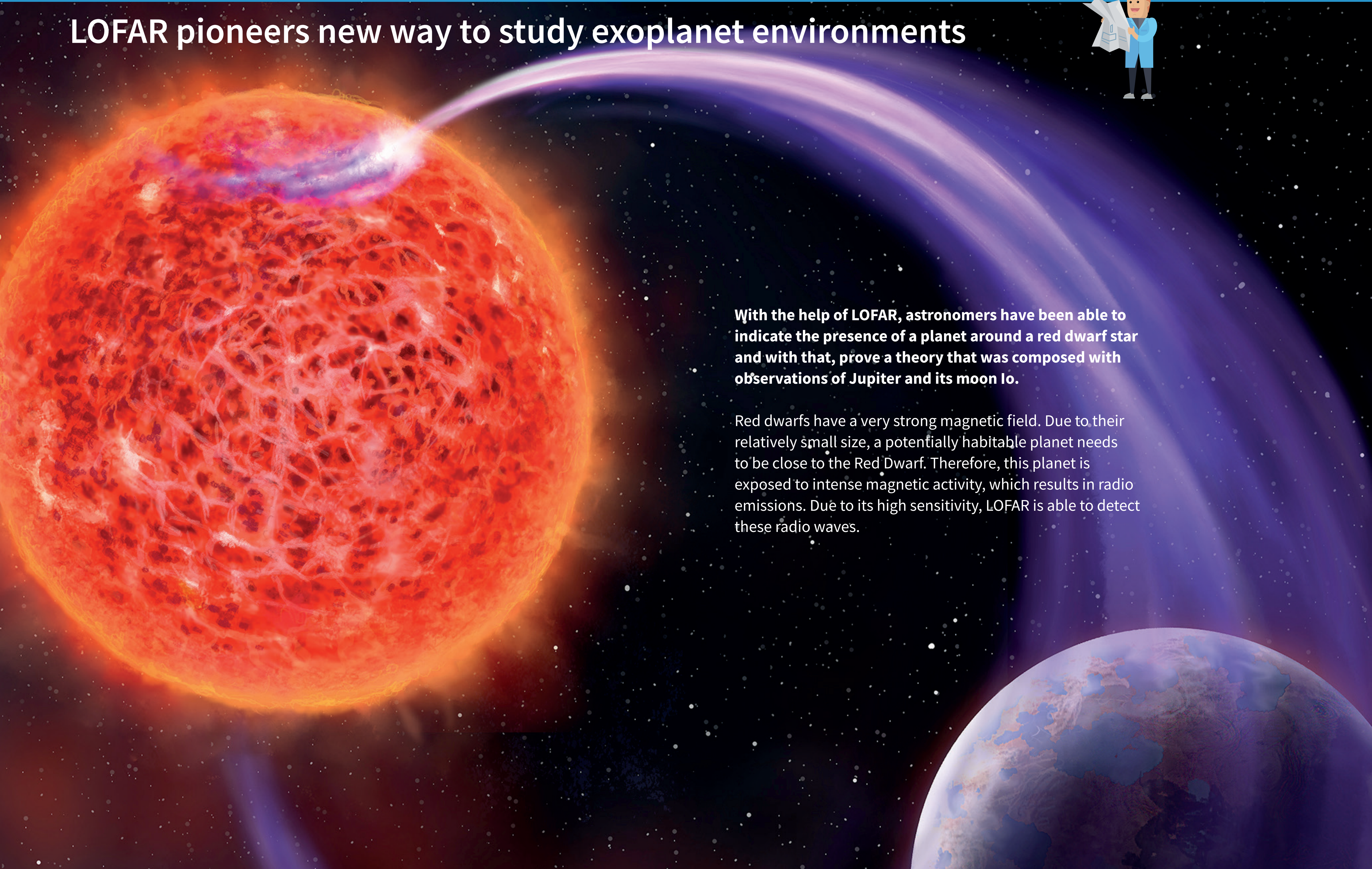
In this highlight, researchers have shown that they have made a significant step forward. By analyzing 141 hours of observing, they have have been able to rule out, for the first time, that the inprint exceeds a certain brightness. They will continue using LOFAR to try and find direct proof of this mysterious era in the evolution of our Universe.

The article this highlight is based on *Improved upper limits on the 21-cm signal power spectrum of neutral hydrogen at z≈9.1 from LOFAR* F. G. Mertens, M. Mevius, L.V.E Koopmans, A. R. Offringa and others.
doi: 10.1093/mnras/staa327



Schematic representation of the evolution of our universe. (credit: NAOJ)

LOFAR pioneers new way to study exoplanet environments



With the help of LOFAR, astronomers have been able to indicate the presence of a planet around a red dwarf star and with that, prove a theory that was composed with observations of Jupiter and its moon Io.

Red dwarfs have a very strong magnetic field. Due to their relatively small size, a potentially habitable planet needs to be close to the Red Dwarf. Therefore, this planet is exposed to intense magnetic activity, which results in radio emissions. Due to its high sensitivity, LOFAR is able to detect these radio waves.

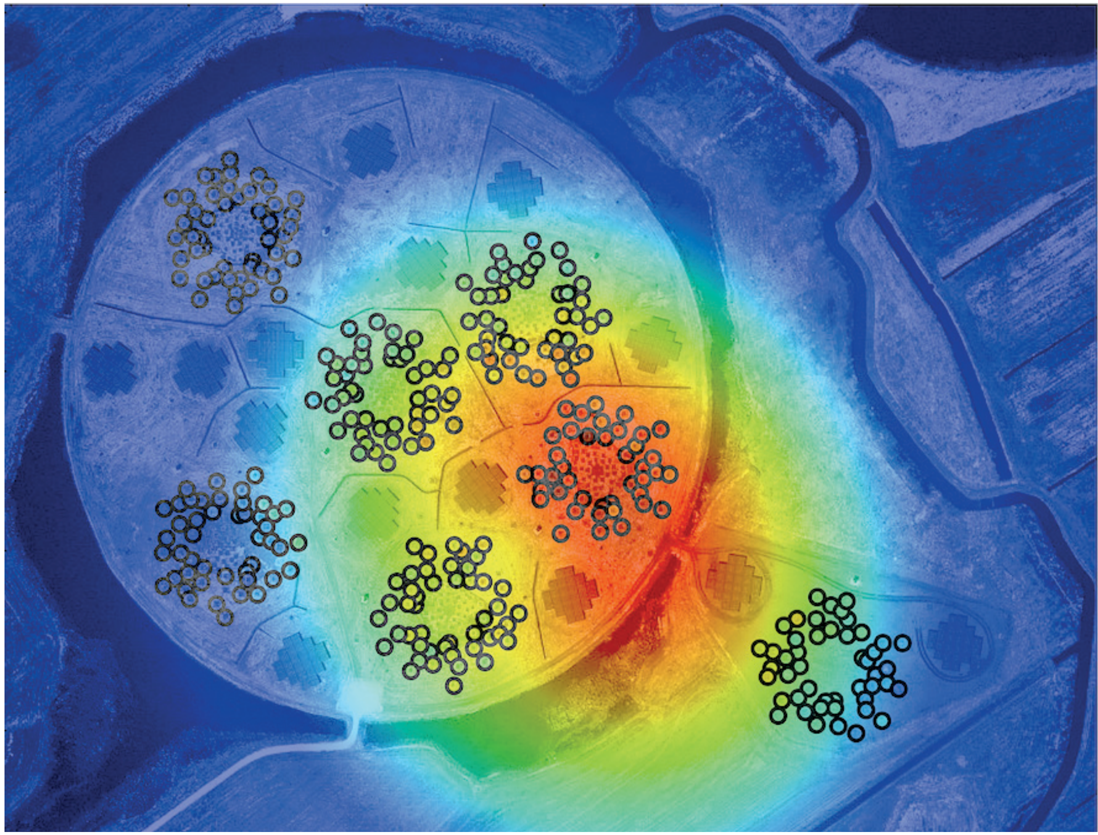
A large light-mass component of cosmic rays at 10^{17}-$10^{17.5}$ eV from radio observations

LOFAR is a highly flexible instrument, which can be utilized for many things. Each antenna, for example, has a 5-second buffer, which can be used to measure very short, strong signals. With this attribute from LOFAR, scientists study cosmic radiation, elementary parts, such as protons and iron cores with high amounts of energy, which are approaching earth.

One such particle has so much energy that with $E = mc^2$ many other particles are formed. This is what we call a particle shower. In the earth's magnetic field these particles produce radio waves that can be detected with LOFAR over a surface with a radius of several hundred metres.

The LOFAR Radboud air shower array measures these particles and sends a signal to LOFAR to read out the radio data. Therefore, LOFAR measures these radio waves at different locations. By comparing simulations of the particle shower with the actual measurements the energy and type of particle can be determined. This article describes which parts, containing which amounts of energy are reaching earth and measures that 80% of the particles at 0.3 EeV are a mixture of light parts, such as hydrogen, helium and carbon. The explanation for this, given here is that such a thing as galactic super accelerators exist, for example Wolf-Rayet stars, 500,000 times stronger than the Large Hadron Collider at CERN.

Article referenced: A large light-mass component of cosmic rays at 10^{17}-$10^{17.5}$ electronvolts from radio observations
doi: 10.1038/nature16976



The figure above shows a simulation using LOFAR data. The colour represents the clarity of the radio signal. In the circles the colour indicates the antenna signal, which matches the simulation nicely.

The use of a monitor & control system that monitors a physically widely distributed instrument

The day-to-day LOFAR operations require highly specialized monitoring and control systems. We use a system that easily enables us to visualize any values we put in our database in a graphic interface or time-sequenced graphs. ASTRON uses a Supervisory Control and Data Acquisition (SCADA) system called Simatic WinCC Open Architecture (WinCC OA). We can fill the database of this system in many ways: from custom-built interfaces to SNMP (Simple Network Management Protocol) input channels.

Organisations in many countries use WinCC OA for large scale projects like the monitoring and controlling of gas/energy distribution or waterways. Even the Large Hadron Collider in CERN is controlled in this way. Because it is specialised in handling millions of data points on many distributed systems, WinCC OA is a perfect fit for us.

In the LOFAR control-room, you will always see the main panel opened. The operator can easily see all the stations in the LOFAR network with a birds-eye view, see how they are performing, and get alerts if action needs to be taken. We can set these alert thresholds (low / suspicious / high) when the need arises, to make sure elements that start having problems can be discovered even before they fail completely.

All kinds of events can be displayed like when a fan stops working, a power supply drops out, cabinet/board temperatures rise too high, or when there is a network hick-up or power cut. It also gives us the ability to turn off antennas remotely and put a note in the system when and why it was turned off, so we can send an engineer to the station to do a repair. This way we are always sure that the observation that is running only includes stations that are working perfectly and the faulty elements are not included in the data.

And when there is a large scale problem, we can stop the observation from the user interface. We do this to make sure no time is lost and we can restart observing later when the system is back in optimum condition.

Because all the elements can be viewed and the reason why they failed is in the database, it also gives us the option to make reports and set priorities for the maintenance cycle. The number of failed elements in HBA/LBA can be viewed and from there we can start making a priority list for the field engineers. We do this roughly four times per year. All the stations in the Dutch network get a maintenance visit every round, making sure we get the most out of LOFAR.

Control-room video wall in Dwingeloo showing “the Navigator”, our Monitoring & Control system

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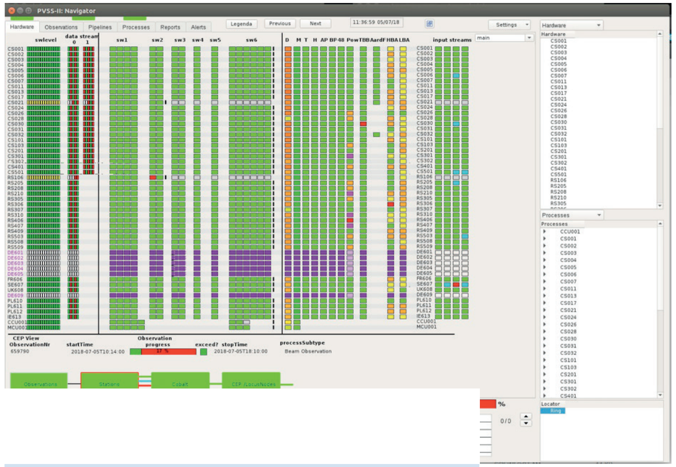
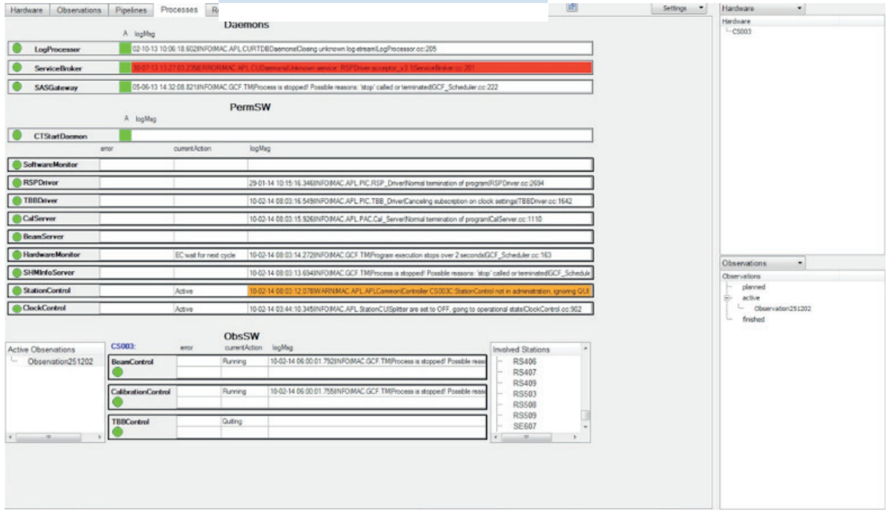
The use of a monitor & control system that monitors a physically widely distributed instrument

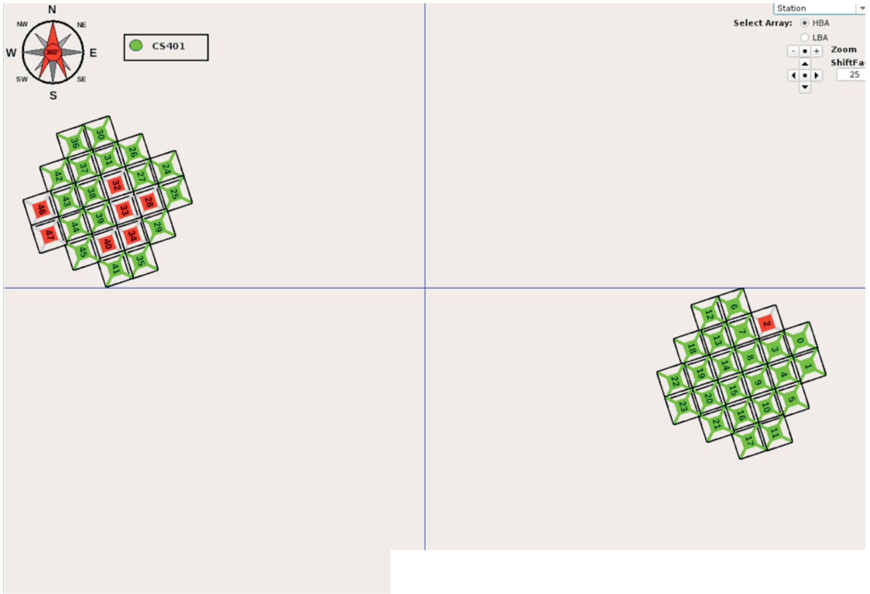


The main panel shows the whole system in color-coded boxes. Hovering over them gives us more information when we need it, clicking on them takes us deeper into the system. As alarms cascade through the system, even the smallest event deep in the system will be viewable on the top level. Here you see two stations in software level 2 for maintenance. And the German stations do not have a network connection right now as they have been switched to local mode.

There are all kinds of different processes / software / firmware and daemons that we monitor during running observations in the monitoring system



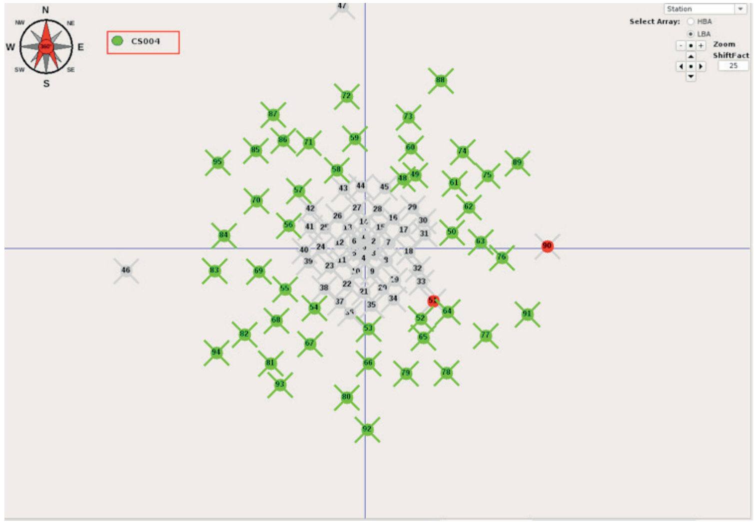
```
Daemons
                  A  logMsg
LogProcessor         02-10-13 10:06:18.602|INFO|MAC.APL.CURTDBDaemons|Closing unknown log-stream|LogProcessor.cc:205
ServiceBroker        30-07-13 13:27:03.235|ERROR|MAC.APL.CUDaemons|Unknown service: RSPDriver:acceptor_v3.1|ServiceBroker.cc:201
SASGateway           05-06-13 14:32:08.821|INFO|MAC.GCF.TM|Process is stopped! Possible reasons: 'stop' called or terminated|GCF_Scheduler.cc:222

PermSW
                  A  logMsg
CTStartDaemon
                 error   currentAction          logMsg
SoftwareMonitor
RSPDriver                                       29-01-14 10:15:16.346|INFO|MAC.APL.PIC.RSP_Driver|Normal termination of program|RSPDriver.cc:2694
TBBDriver                                       10-02-14 08:03:16.549|INFO|MAC.APL.PIC.TBB_Driver|Canceling subscription on clock settings|TBBDriver.cc:1642
CalServer                                       10-02-14 08:03:15.926|INFO|MAC.APL.PAC.Cal_Server|Normal termination of program|CalServer.cc:1110
BeamServer
HardwareMonitor          EC:wait for next cycle 10-02-14 08:03:14.272|INFO|MAC.GCF.TM|Program execution stops over 2 seconds|GCF_Scheduler.cc:163
SHMInfoServer                                   10-02-14 08:03:13.694|INFO|MAC.GCF.TM|Process is stopped! Possible reasons: 'stop' called or terminated|GCF_Schedule
StationControl           Active                 10-02-14 08:03:12.078|WARN|MAC.APL.APLCommon|Controller CS003C:StationControl not in administration, ignoring QUI
ClockControl             Active                 10-02-14 03:44:10.345|INFO|MAC.APL.StationCU|Splitter are set to OFF, going to operational state|ClockControl.cc:902

ObsSW
CS003:           error   currentAction  logMsg
BeamControl              Running        10-02-14 06:00:01.792|INFO|MAC.GCF.TM|Process is stopped! Possible reas
CalibrationControl       Running        10-02-14 06:00:01.755|INFO|MAC.GCF.TM|Process is stopped! Possible reas
TBBControl               Quiting
```

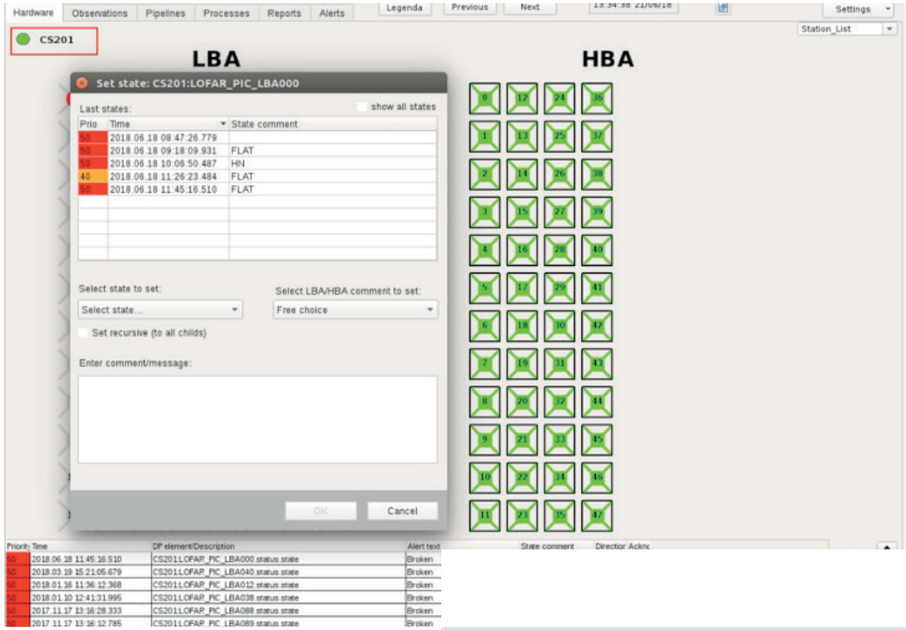


HBA faulty elements above / LBA elements below (green = on in this specific observation, gray = off, red = faulty). This view also shows us the lay-out and position of the station elements so we can guide the people in the field.

ASTRON
Netherlands Institute for Radio Astronomy

The use of a monitor & control system that monitors a physically widely distributed instrument





Set state: CS201:LOFAR_PIC_LBA000

Last states: ☐ show all states

Prio	Time	State comment
50	2018.06.18 08:47:26.779	
50	2018.06.18 09:18:09.931	FLAT
50	2018.06.18 10:06:50.487	HN
40	2018.06.18 11:26:23.484	FLAT
50	2018.06.18 11:45:16.510	FLAT

Select state to set: Select state...

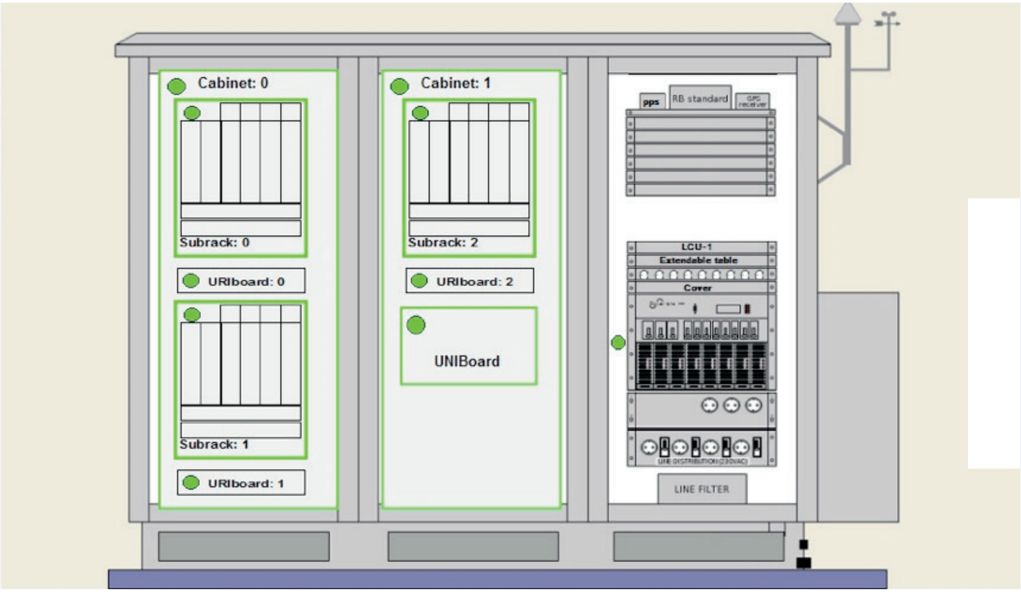
Select LBA/HBA comment to set: Free choice

☐ Set recursive (to all childs)

Enter comment/message:

OK Cancel

Priority	Time	DP element/Description	Alert text	State comment	Direction	Ackn
50	2018.06.18 11:45:16.510	CS201:LOFAR_PIC_LBA000.status.state	Broken			
50	2018.03.19 15:21:05.679	CS201:LOFAR_PIC_LBA040.status.state	Broken			
50	2018.01.16 11:36:12.368	CS201:LOFAR_PIC_LBA012.status.state	Broken			
50	2018.01.10 12:41:31.995	CS201:LOFAR_PIC_LBA038.status.state	Broken			
50	2017.11.17 13:16:28.333	CS201:LOFAR_PIC_LBA088.status.state	Broken			
50	2017.11.17 13:16:12.785	CS201:LOFAR_PIC_LBA089.status.state	Broken			



Cabinet view: you can go as deep as you want into it. From LOFAR -> Station -> Cabinet -> Rack -> Subrack -> Board -> Element -> Software / Firmware / etc

Turning off elements and leaving a note for the field engineers we usually go with short codes like: OSCILLATION (OSC) / FLAT (FLAT) / HIGH NOISE (HN) / SHORT (SHORT) / DOWN (DOWN) / SUMMATOR NOISE (SN) / LOW NOISE (LN). And afterwards we leave a note when and what was done to repair it. So if it happens again we know what repair was already done.

A LOFAR View of the Turbulent Ionosphere

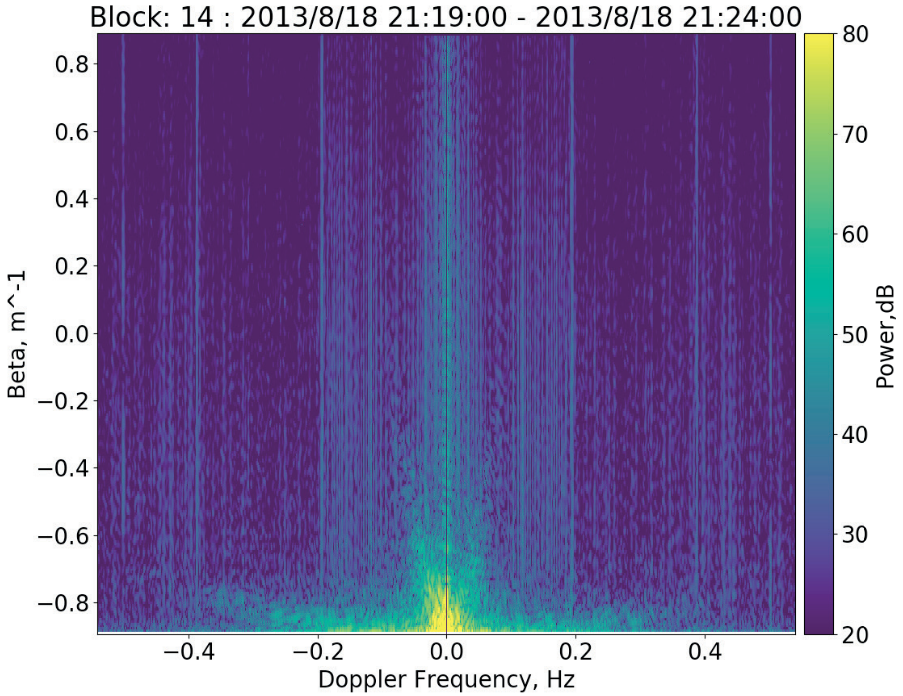
The view of the radio universe at the VHF frequencies of LOFAR is strongly affected by the Earth's ionosphere. This dynamic region, which exists from about 60km altitude upwards, is where the neutral particles making up the lower atmosphere become ionised leading to radio waves from the rest of the cosmos being refracted and scattered as they pass through it.

The effect for astronomers is that the images they are trying to take of distant radio sources can be heavily distorted, appearing to shift and shimmer and vary in their strength. It is exactly the same effect as us looking up at the stars in the night sky and seeing them twinkle in visible light due to the effects of the lower atmosphere, or trying to view a pebble at the bottom of a pool of disturbed water. However, in science, one person's noise is another's data: The ionospheric effects that most astronomers are trying to remove can also be used to gain information on the structure and dynamics of the ionosphere itself, and one team of researchers is doing exactly that.

The ionosphere is known to be highly active at polar latitudes, where spectacular displays of aurora can be seen, and at equatorial latitudes, but is much quieter at the mid-latitudes, which is one of the main reasons that LOFAR was built where it is. The effect of the ionosphere can be seen clearly in a movie showing how the intensity of a strong radio source, received by all LOFAR stations simultaneously, changes over the dense core of stations at LOFAR's centre. Peaks and dips in the received intensity are shown in red and blue respectively, with the locations of the stations themselves marked as solid circles. The intensity pattern varies significantly with bands of intensity moving generally north-west to south-east over the core stations, but some patterns appearing to move in a different direction.

One of the main advantages of using LOFAR for studies such as these is its wide bandwidth. How much a radio wave is scattered depends, amongst other things, on its wavelength, with longer wavelengths (and so lower frequencies) generally scattered more than shorter wavelengths. This means that the intensity received at one wavelength will appear shifted in both time and frequency compared to another.

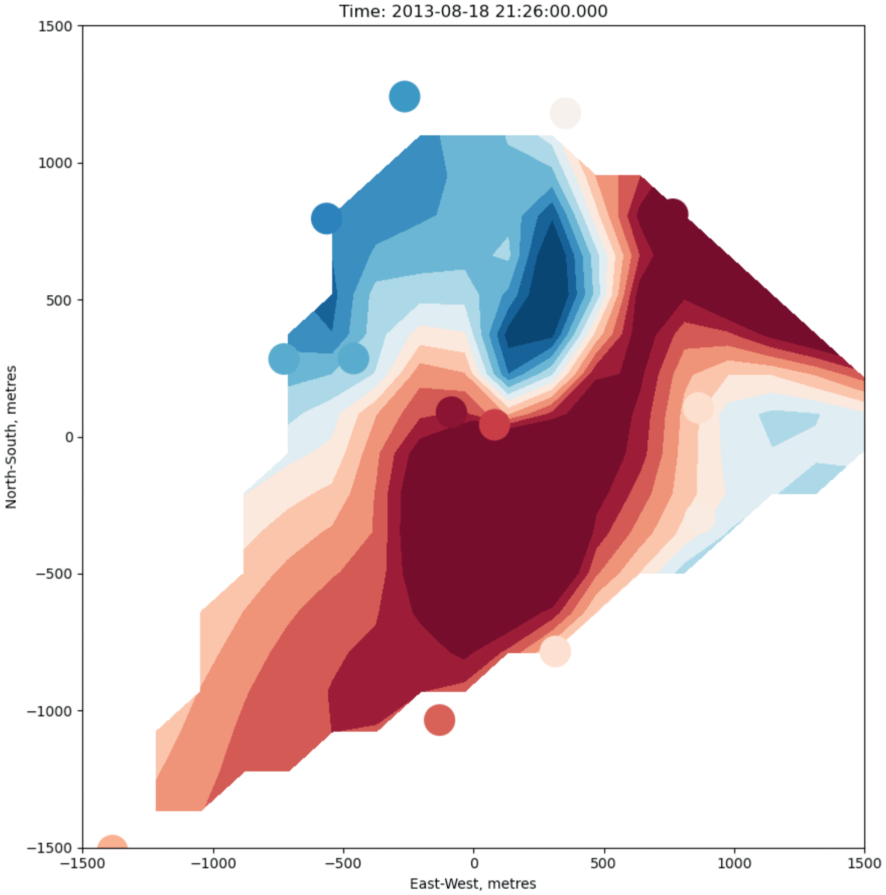
When analysed over a wide band, these shifts can form an arc structure which gives information on the altitude of the scattering region and how fast it's moving.

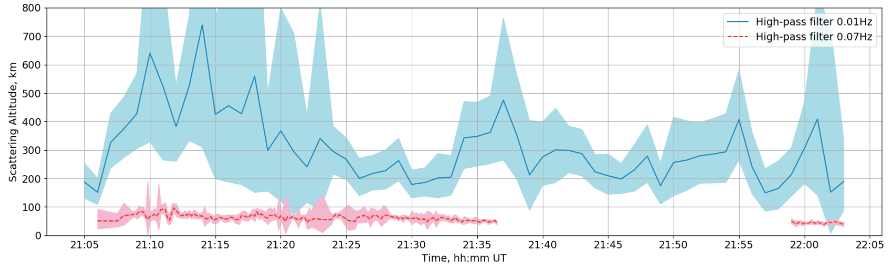


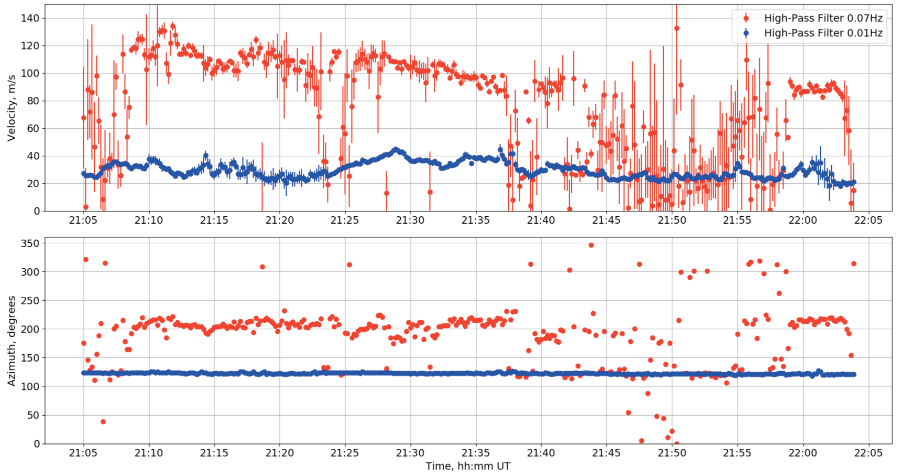
This observation showed two arc structures, indicating that the scattering causing such variations in the received intensity was caused by two different layers in the ionosphere, one with material at an altitude of several hundred kilometres, flowing north-west to south-east at a relatively slow speed, and the other with material very low down in the ionosphere, moving north-east to south-west at a much higher speed.

A LOFAR View of the Turbulent Ionosphere

We think that this is the result of two, simultaneous disturbances in the ionosphere: One most likely comes from activity at high latitudes propagating southwards to affect the ionosphere above LOFAR, and the other is likely to be the result of activity lower down in the atmosphere bubbling up. It is, we think, the first time that these two effects have been directly observed simultaneously.







ASTRON
Netherlands Institute for Radio Astronomy

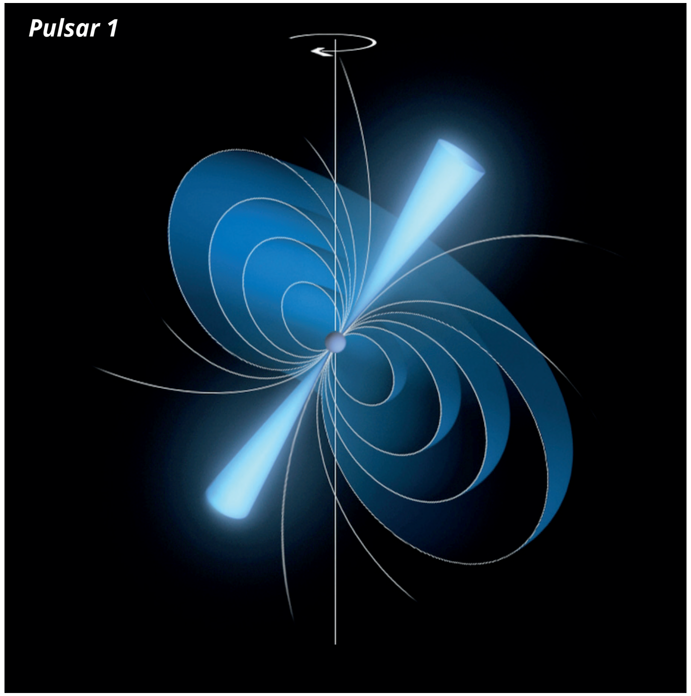
Pulsar shows sudden mood swings

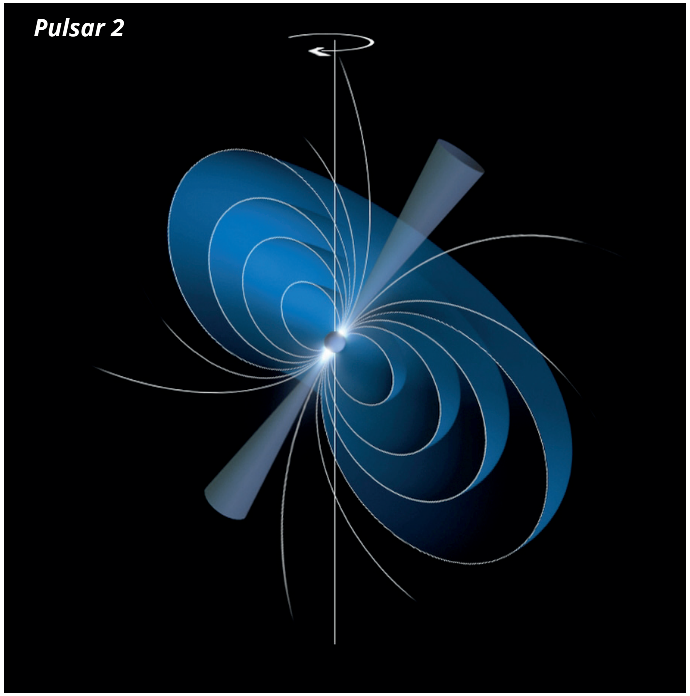
In 2013 an international research team – led by Dutch astronomers (SRON, NOVA and ASTRON) – discovers that pulsar PSR B0943+10 can both radically change the amounts of radio waves and X-ray waves it emits within seconds. Never before have scientists been able to determine whether a change in the amounts of emitted radio waves, a common phenomenon with pulsars, also influences the amount of X-ray waves that some pulsars emit.

Thanks to LOFAR's sensitivity, a team of scientists is able to closely monitor the amount of radio waves PSR B0943+10 emits. At the same time X-ray space telescope XMM-Newton measures the amount of X-rays the pulsar emits.

The scientists find that when PSR B0943+10 emits strong radio signals and clear pulses, the X-rays are weak. But when the radio emission switches to weak, the X-rays synchronously intensify. 'To our surprise we found that when the brightness of the radio emission decreased to half the original brightness, the X-ray emission brightened by a factor of two!' says project leader Wim Hermsen (SRON Netherlands Institute for Space Research/UvA). And only then the X-ray emission is pulsed. Lucien Kuiper (SRON), who scrutinised the data from XMM-Newton, concluded that this strongly suggests that a temporary 'hotspot' close to the pulsar's magnetic pole switches on and off with the change of state.

Most striking is that this 'mood swing' takes place within seconds, after which the pulsar remains stable in its new state for a few hours. The researchers publish their results in the scientific journal Science.





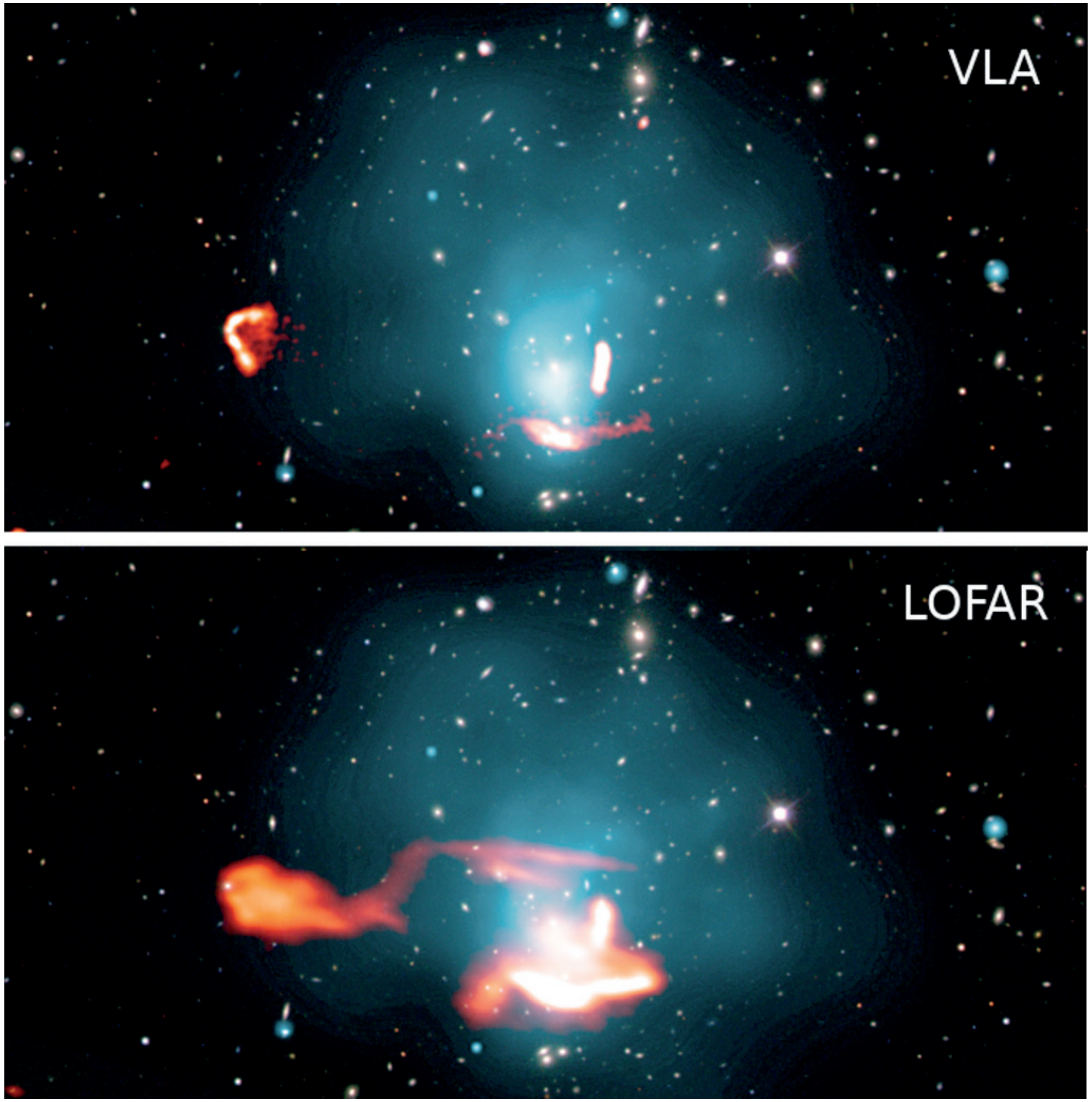
Pulsar 1
A pulsar with glowing cones of radiation stemming from its magnetic poles – a state referred to as 'radio-bright' mode. (credit: ESA/ATG medialab)

Pulsar 2
A pulsar with glowing 'hot-spots' that are located at its magnetic poles, the likely sites of X-ray emission from old pulsars. In particular, the illustration shows the pulsar in a state characterised by bright X-ray emission, arising from the polar caps, and relatively low radio emission from the cones that stem from the pulsar's magnetic poles ('X-ray-bright/radio-quiet' mode). (credit: ESA/ATG medialab)

Gentle reenergization of electrons in merging galaxy clusters

Supermassive black holes can leave a trail of energetic particles that astronomers are able to detect using radio telescopes. Usually the radio emissions from these particles fade away and become invisible. However, in the merging galaxy cluster Abell 1033, the Low Frequency Array discovered that some of these particles can be rejuvenated and start shining again when observed at very low radio frequencies.

A composite (false-colour) image of the galaxy cluster Abell 1033. Optical light from individual galaxies, visible as coloured spots across the image, is obtained by the Sloan Digital Sky Survey, while in blue the X-ray emission observed with the Chandra satellite traces the hot gas. Radio emission from LOFAR and the VLA is shown in orange and traces a complex of radio sources including a tail of particles left behind by the galaxy moving towards the left of the image.

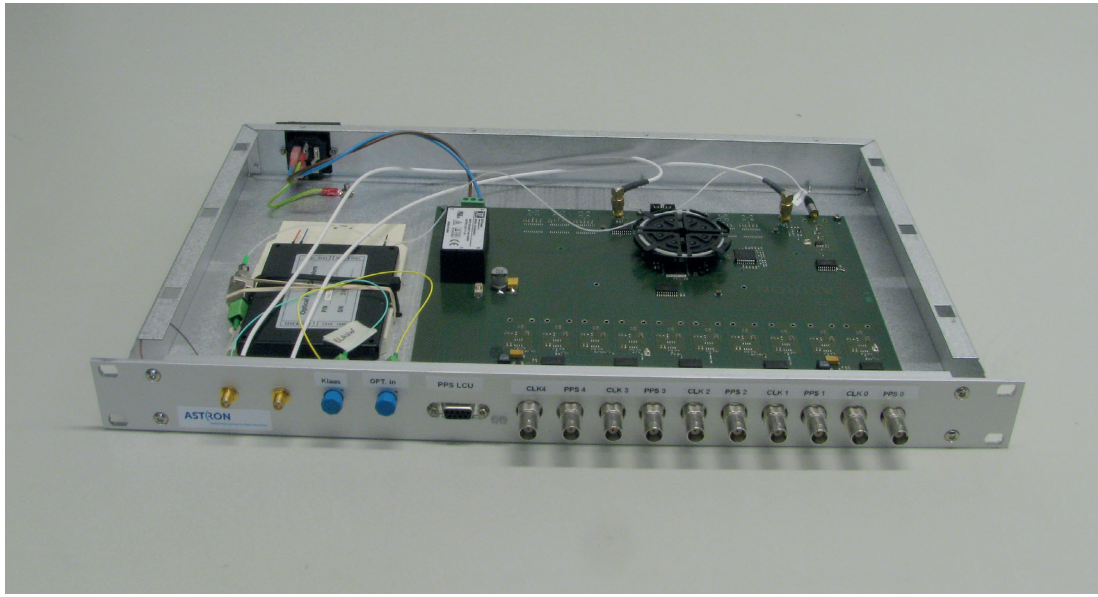


The use of GPS receivers and rubidium modules to sync the stations

One of the important aspects of radio telescopes, in general, is the synchronisation in between antennas and for LOFAR in particular the synchronization between stations. Normally a clock is distributed from a central location to antennas. However, the stations are far apart and the distribution of a clock signal over distances of 100's and even 1000's of kilometers is not trivial. Therefore, it was decided not to distribute the clock but generate the clock locally near each station.

For this a three-staged approach was taken to ensure stability on:
1. the long-term by the usage of GPS signals,
2. the mid-term by a Rubidium module and
3. the short-term by applying a crystal.

Soon, it turned out that the differential clock drifts between stations required an additional real-time calibration for the Tied-Array mode, which could be prevented by a central clock distribution. Since in the early days the Tied-Array mode used primarily the superterp stations, a central clock distribution was implemented for the superterp stations. The clock source was installed in the concentrator node and from there on the clock signals were distributed via a fiber link to the six superterp stations in the year 2010. Due to the great success of this, the central clock solution was extended to all 24 core stations in 2012. Currently, the optical clock distribution system results in a timing accuracy between the core stations within one nanosecond, which equals 0.000000001 seconds. In LOFAR2.0 also the remote stations will be synchronized via the same central clock source in the concentrator node which is located in the heart of LOFAR. In the future the ambition is, to include also the international stations in the central clock distribution such that at the end all stations are synchronized via the same central clock source.

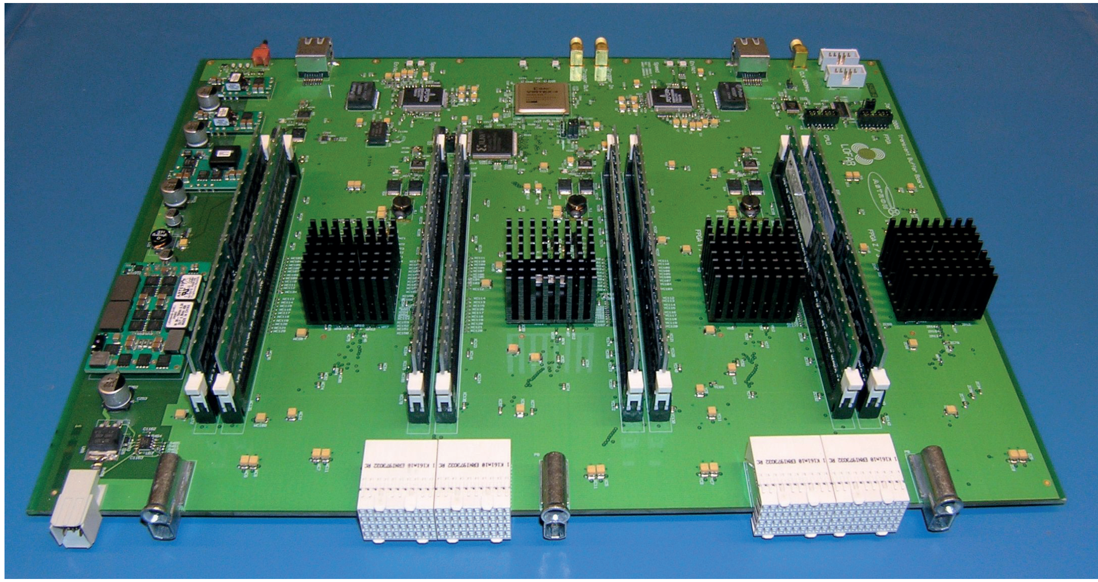


Synchoptics board. (Credit: ASTRON)

The TBB boards that act as a time machine

The LOFAR Transient Buffer Board (TBB) gave the LOFAR radio telescope a unique extra capability: looking back in time.

For this the TBB had the latest DDR2 (Double Data Rate) memory technology onboard, at the time of installation. This was in particular required for cosmic ray and lightning studies. After a cosmic ray event trigger the data in the memory was stopped and consequently downloaded for further study of the raw antenna data. The system was able to look 5 seconds back in time for the full bandwidth. The time to look back could be increased by sacrificing bandwidth for that. A unique capability at that time!



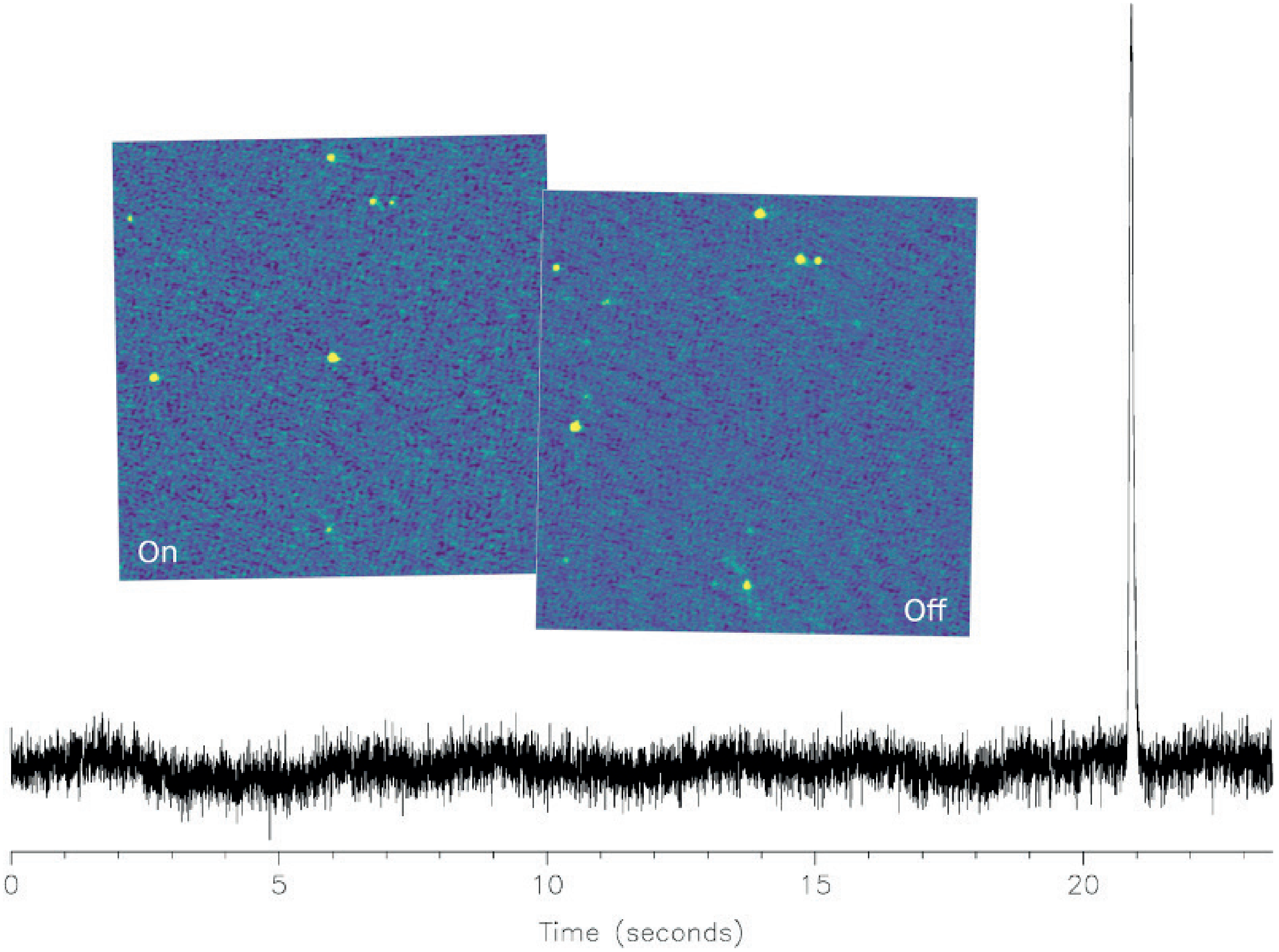
TBB board. (Credit: ASTRON)

WHAT WE LOOK FORWARD TO IN LOFAR 2.0

Searching for extreme pulsars

During the 10 years since the LOFAR opening, the telescope has proven itself as an excellent instrument for the study of radio pulsars, rotating neutron stars whose radio beams act as lighthouses. LOFAR has discovered over 80 new pulsars, from the slowest spinning pulsar, rotating once every 23.5 seconds, to one of the fastest, rotating 707 times each second.

Thanks to the exquicite depth of the LOFAR imaging survey, searching for new and more extreme pulsars will enter a new era, where instead of blindly searching for periodic signals, pulsar candidates can be identified from point sources with (ultra-) steep radio spectra and/or high degrees of linear or circular polarization. These new pulsars, as well as previously known pulsars will allow radio astronomers to map the electron density and the topology of the Galactic magnetic field, use the Solar wind for space weather forecasts, study the emission properties of pulsars and probe the physics of ultra-dense matter.



LOFAR discovered the slowest spinning pulsar, rotating once every 23.5 seconds. The black line shows the average radio pulse, where the pulsar is only visible for a fraction of each rotation. The rotation is slow enough that the pulsed emission can be seen in LOFAR images. (Credit: ASTRON)

Simultaneous LBA and HBA observing

LOFAR uses two types of antennas. Each type listens to different wavelengths of the radio spectrum. Different wavelengths provide complementary information about the Universe and its constituents.

Currently, LOFAR can use only one type of antenna at the same time. In 2022 the digital brains of LOFAR are upgraded to simultaneously observe with both types of antennas. New pioneering astrophysical research will be possible using the absolute lowest radio frequencies visible from Earth. With this new system, the northern sky can be surveyed > 100x more sensitive and at > 5x higher-resolution compared to any previous or planned survey at these exceptionally long wavelengths.

Low Band Antenna

WHAT WE LOOK FORWARD TO IN LOFAR 2.0:

Simultaneous LBA and HBA observing

High Band Antenna

A brain transplant for LOFAR

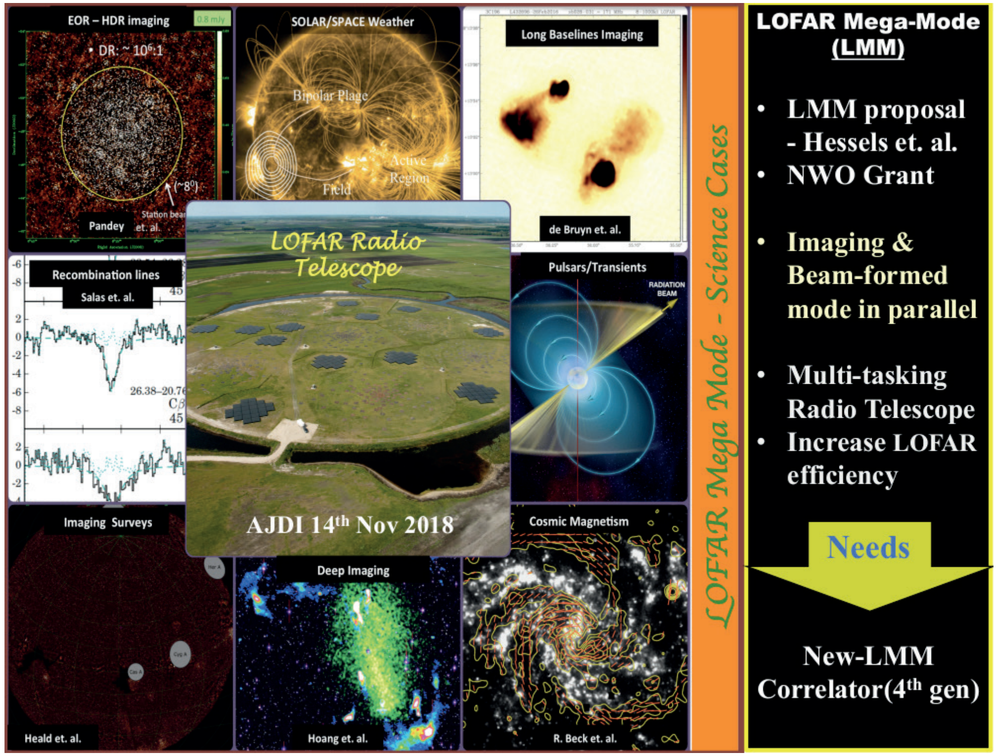
If the antennae of LOFAR are the senses of the radio telescope, then the central correlator is its brain. It is the place where all the data streams come together and are converted into astronomy data. LOFAR's current brain is called COBALT 2.0 (Correlator and Beamforming Application platform for the LOFAR Telescope).

The correlator team at ASTRON has delivered a remarkable piece of technology with COBALT 2.0. It is the successor to the previous COBALT correlator, which reached its end of life early 2019 as the warranty was going to expire. 'The replacement was planned well in advance in the form of a LOFAR Mega Mode (LMM) proposal, led by Jason Hessels at ASTRON and University of Amsterdam,' says Vishambhar Nath Pandey, system researcher at ASTRON. The main idea of the LMM proposal was to turn LOFAR into a truly multitasking radio telescope thus significantly boosting the science returns per observing hour, without changing the hardware on the ground. It received an NWO-M grant in 2017 where NWO (Nederlandse Organisatie voor Wetenschappelijk Onderzoek) and ASTRON funded the project together.

The works on this new brain commenced in 2018, starting with the detailed design and procurement phase through an open EU wide tender. Pandey: 'COBALT 2.0 is state of the art and future proof in terms of its design and flexibility. It is also amongst the most energy efficient High Performance and High Throughput Computing (HPC/HTC) correlators possible with the current technology.' The hardware for COBALT 2.0 arrived early 2019. Pandey: 'After successful validation tests for hardware compliance in February 2019, the existing COBALT software was installed, and optimized where necessary, which was made easier due to hardware software codesign of the correlator.' In the summer of 2019, after it had passed all tests successfully, COBALT 2.0 was officially put into regular use. 'Thus far it has been a great success.'

MEGA MODE

'LOFAR's antennae fields, spread across Europe, each generate about 3.1 Gb/s in data streams. Those arrive at the central correlator, which appropriately processes and combines all the data streams into a readily usable data form for astronomers', says Pandey. These are the data that researchers use in their studies. The central correlator COBALT2.0 is capable to simultaneously receive and process the data streams from both 48 high-band antennae fields and 96 low-band antennae fields. Those combined data streams are 148 Gb/s and 296 Gb/s respectively, which roughly translates to equivalent data rate of a million single sided single layer Digital Video Discs (DVD-5) per day.



The idea for LOFAR Mega Mode. (Credit: V.N. Pandey/ASTRON)

A brain transplant for LOFAR

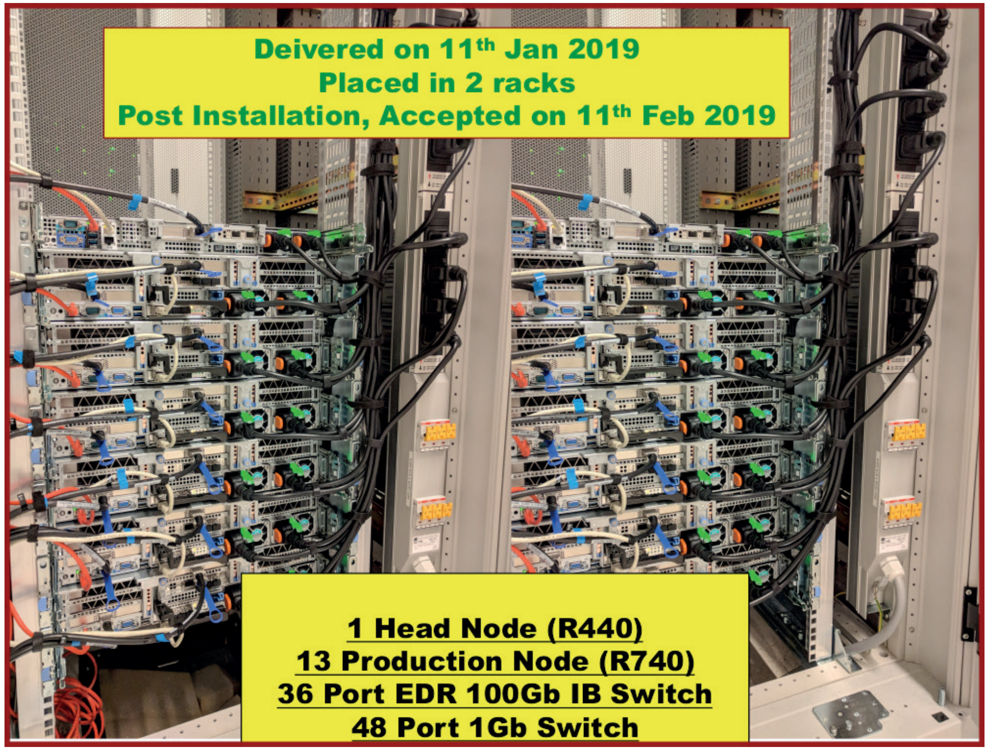
Usually a correlator can only process the data of a single project at a time. COBALT 2.0 however, can simultaneously process the data of several projects simultaneously. Pandey: ‘We call that the LOFAR Mega Mode.’ The concept is as follows: for a certain research project LOFAR looks at a specific part of the sky, from which data streams are collected. ‘It may well be possible that this part of the sky encompasses the area which is subject of the project of another researcher,’ Pandey says. ‘That means that the data streams can be used for that second research project as well. You have to appropriately combine the data streams for that second research project, but that is something COBALT 2.0 is capable of due to its immense computing and throughput power.’

Another thing that COBALT 2.0 can do, is to produce both imaging data and beam formed data from the same data streams. Imaging data are used to produce high angular resolution images of a certain part of the sky; beam formed data can be used for high time and frequency resolution applications, like discovery and high cadence monitoring of exotic pulsars, solar and planetary studies, for example. In a very simplified way to produce imaging data, the data streams are appropriately multiplied; by appropriately adding the data streams the correlator can produce beam formed data. And COBALT 2.0 can produce both simultaneously.

Presently the team is busy implementing the new features in LOFAR Mega Mode to the existing COBALT software in order to realize the full potential of COBALT 2.0. Once completed, the resulting increased efficiency and capabilities of LOFAR will lead to new discoveries to help understand and unravel more scientific mysteries of the universe in the years to come.

EXTREMELY ENERGY EFFICIENT

The COBALT 2.0 system has an optimal combination of the most appropriate set of components, CPUs, GPUs, network topologies and most energy efficient power supplies. A CPU, a central processing unit, is skilled in performing lots of different calculations simultaneously; a GPU, a graphic processing unit – the name stems from the fact that these processors were originally developed for graphic cards – is extremely skilled in performing one specific type of programmable calculation. COBALT 2.0 optimally utilizes the CPUs and GPUs for tasks where they are most efficient at.



Deivered on 11th Jan 2019
Placed in 2 racks
Post Installation, Accepted on 11th Feb 2019

1 Head Node (R440)
13 Production Node (R740)
36 Port EDR 100Gb IB Switch
48 Port 1Gb Switch

COBALT 2.0. (Credit: ASTRON)

ASTRON
Netherlands Institute for Radio Astronomy

A brain transplant for LOFAR

The new correlator is amongst the most energy efficient ones. Given the fact that the apparatus will be running 24/7, 365 days a year, that is an important feat. Pandey: ‘Despite COBALT 2.0 being several times faster than its predecessors and its LOFAR Mega Mode capability to process several projects simultaneously, its energy budget even at peak load is well within around € 1.000 a month.’

ALREADY A BIG SUCCESS

COBALT 2.0 isn’t only a future highlight for LOFAR, but it can already be called a success: Scientists and Engineers of the French NenuFAR telescope chose the COBALT 2.0 design after comparisons with other possible designs for their own correlator named NICKEL (NenuFAR Imager Correlation Kluster Elaborated from LOFAR’s). Pandey: ‘Our shared work and knowledge saves them years of work, also because they are reusing the correlator software suite developed by ASTRON for LOFAR. They are actually a few years ahead due to this. So, this is an example implementation of ASTRON’s philosophy of open source technical collaboration.’

In addition, the availability of Tensor Cores in Volta V100 GPUs in COBALT 2.0, which can further speed up performance for half precision (than presently used full precision) computations by about a factor of 5, opens up the exciting future possibility of exploring future new astronomical observing modes which can be carried out with lower precision.

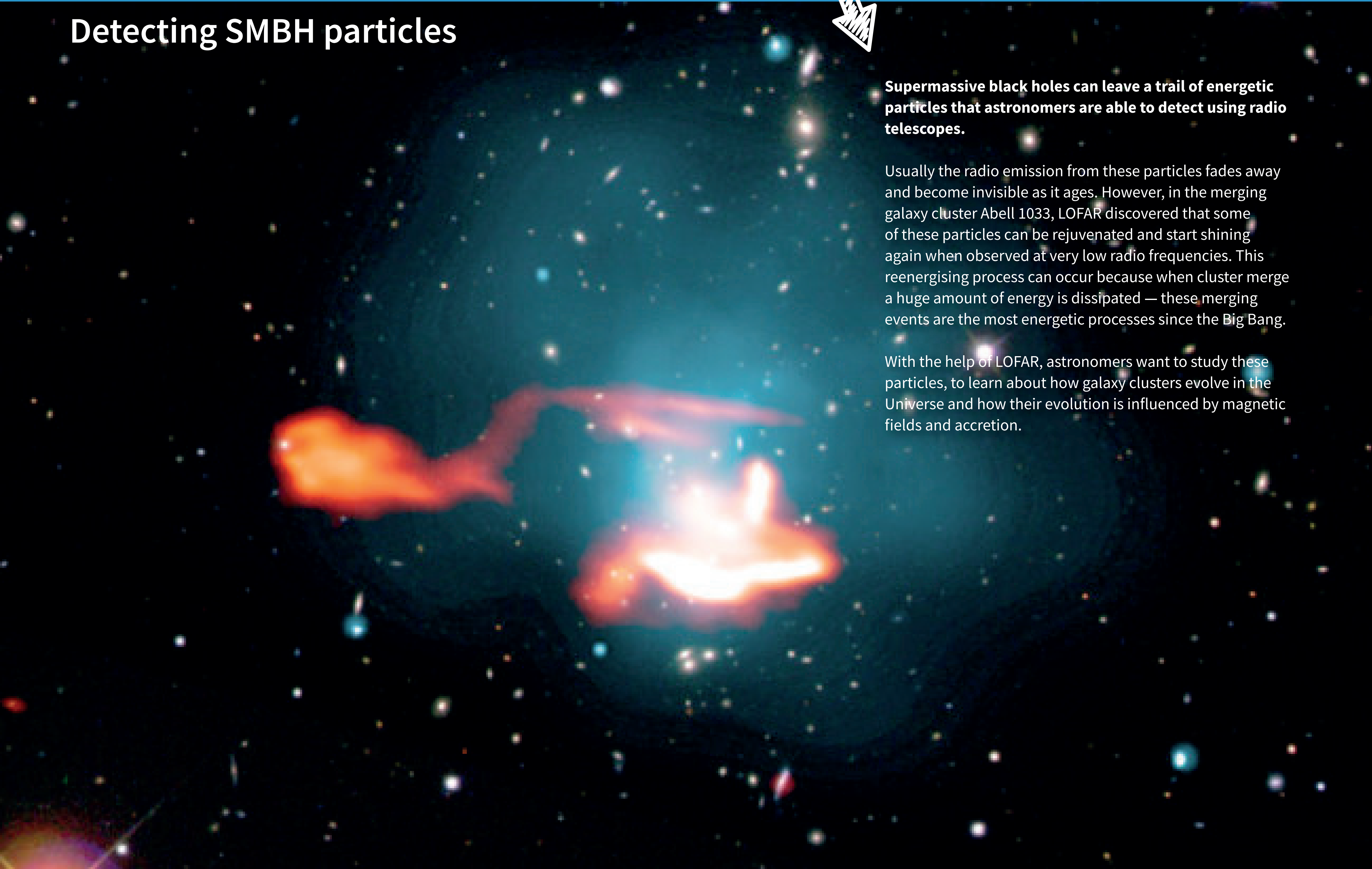
COBALT 2.0 will play a pivotal role in defining the future scientific capabilities of LOFAR. The success of this project is possible due to the pioneering modern digital design of the LOFAR telescope, and learnings from involvement in adapting state of the art new technologies during the GPU based COBALT (2013) and the earlier CPU based IBM Blue Gene -L/P (2004/2008) correlators.

SPECIFICATIONS OF COBALT AND COBALT 2.0

	COBALT	COBALT 2.0
Size	9 nodes	13 nodes
CPU’s	18x Intel Xeon E52660 2.20GHz	26x Intel Xeon Gold SP6140 2.30GHz
GPU’s	18x Tesla K10	26x Tesla V100
InfiniBand	18x FDR - 54 Gb/s	26x EDR - 100 Gb/s
Data Input	36x 10GbE	104x 10GbE
CPU compute capacity	6 TFLOP/s	63 TFLOP/s
GPU compute capacity	82 TFLOP/s	364 TFLOP/s
Power consumption (peak)	6 kWh	10 kWh

This was a coordinated effort of the correlator team, comprising of: V.N. Pandey, J. J. D. Mol, P. C. Broekema, J. Romein, C. Bassa, J. Hessels, R. Kaptijn, J. Klipic, R. Bokhorst, J. Schaap, K. Stuurwold, P. Boven, B. Veenboer, Y. Grange, A. Coolen along with the collaboration with the Center for Information Technology (CIT) at the University of Groningen.

Detecting SMBH particles



Supermassive black holes can leave a trail of energetic particles that astronomers are able to detect using radio telescopes.

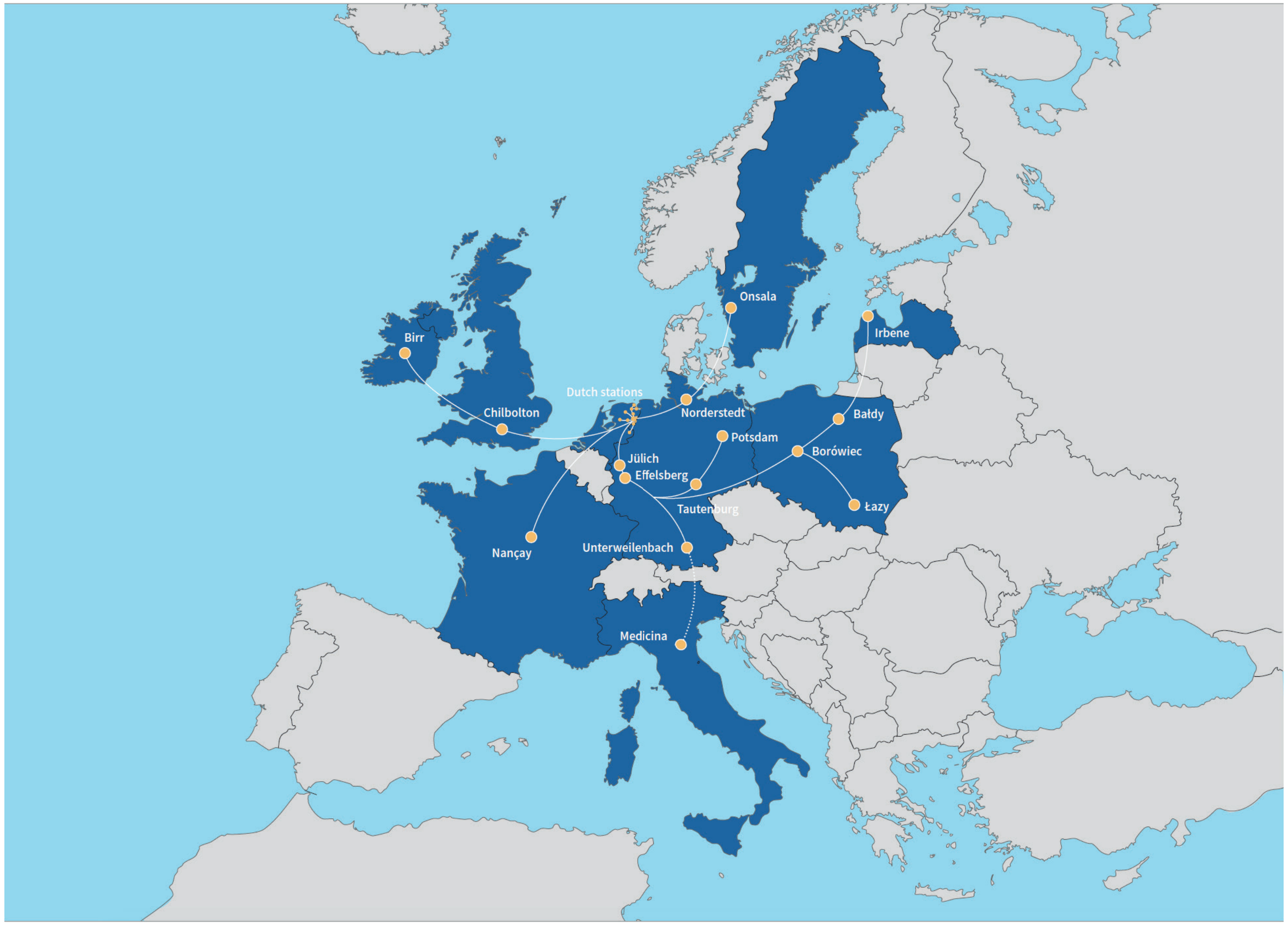
Usually the radio emission from these particles fades away and become invisible as it ages. However, in the merging galaxy cluster Abell 1033, LOFAR discovered that some of these particles can be rejuvenated and start shining again when observed at very low radio frequencies. This reenergising process can occur because when cluster merge a huge amount of energy is dissipated — these merging events are the most energetic processes since the Big Bang.

With the help of LOFAR, astronomers want to study these particles, to learn about how galaxy clusters evolve in the Universe and how their evolution is influenced by magnetic fields and accretion.

High-precision clock to all Dutch stations

In the LOFAR radio telescope, the observation data is synchronized over time for accurate processing of the received signals. Until now, the telescope uses GPS techniques to synchronize the observation data, achieving an accuracy between 1 ns and 10 ns.

To further expand the scientific possibilities of LOFAR, the accuracy of its time synchronization system will be improved in the coming time. Instead of using GPS, the Dutch part of LOFAR will be equipped with a new timing system that uses synchronous optical clock distribution via LOFAR’s fiber-optic network. This clock system upgrade will be accomplished using state-of-the-art clock distribution technology capable of achieving timing accuracies of better than 100 ps.

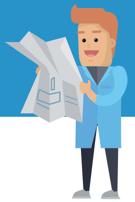


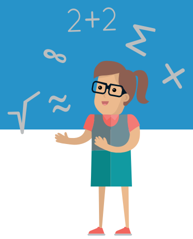
A new specification and scheduling system

In 2021, ASTRON will deliver TMSS (Telescope Manager Specification System), which is a brand-new platform for the specification, administration, and scheduling of LOFAR observations.

TMSS is revolutionary in many aspects. It delivers a dynamic scheduling system and other specification and data flow improvements which enhance the efficiency and automation of LOFAR operations. By also improving the adaptability and maintainability of the software for future extensions, it prepares LOFAR in the best possible way for its next challenges. These involve evolving towards LOFAR 2.0 and performing the next low frequency surveys, which will open up an important discovery space for the user community.

TMSS has seen its first light in April 2020, when it successfully performed a survey observation. This was an important milestone for the project and a first of several more expected in the next months.





LOFAR expands to Italy

In 2018, Italy officially joined the International LOFAR Telescope (ILT) and in the near future the LOFAR station in Italy will become operational. The station in Italy will be equipped with newly developed hardware of the 2.0 generation. The station is to be installed at the Medicina Radio Observatory site near Bologna. This Italian LOFAR station will be operated under supervisory of the Italian National Institute for Astrophysics (INAF).

Italy is an important partner for the ILT, but also for the Netherlands. Both countries have a distinguished track record in radio astronomy and this partnership reinforces the long-standing bonds of exchange and collaboration on radio astronomy in Europe, which already dates from the earliest times of the Westerbork telescope. With a LOFAR station in Italy there will be a significant wider distributed antenna network across Europe, this will benefit the image quality for all astronomers and other scientific users.

Besides LOFAR operations in the future, INAF participates in the ASTRON-led drive to develop next generation state-of-the-art LOFAR electronics. INAF also is involved in software development and algorithms for data processing.

PATHFINDER FOR SKA

LOFAR is a pathfinder for the next-generation Square Kilometre Array (SKA) telescope. The Netherlands and Italy will also partner up for the SKA telescope in which both countries are deeply involved. LOFAR won't stop operating once the SKA is built, it will continue to do top-level scientific observations. LOFAR gives us the opportunity to train new generations of scientists in the use of SKA.

Cranking up LOFAR’s robustness

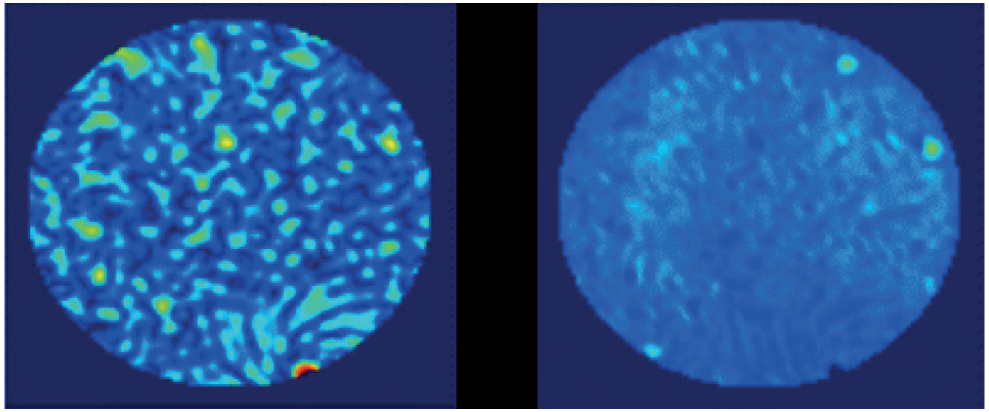
In order to receive radio signals from across the Universe, LOFAR needs to be very sensitive. The downside of that sensitivity is susceptibility to radio interference: other sources that produce radio signals that LOFAR detects, but does not want to measure. ASTRON staff members are working out technologies to make LOFAR more robust against interference.

A big source of interference are wind turbines. Wind farms around LOFAR produce radio waves that are detected by LOFAR. By knowing the source and frequency of this interference, they can be filtered out of the data, but that creates a blind spot.

“In 2016, we, together with the Ministry of Economic Affairs and the wind farm builders, drew up a covenant,’ says ASTRON’s senior researcher Stefan Wijnholds. ‘Part of that covenant is that we will be allowed to ask the wind farm owners to turn off their turbines at the moment that we want to make our most sensitive observations. As compensation we will make our telescope more robust against the radio interference of wind turbines. For this, we have received government funding.”

Wijnholds: “We have selected the most promising techniques, which are now being worked out further. The most promising method is a technique called ‘spatial filtering.’” LOFAR looks into the sky in a single direction. All radio signals that LOFAR receives from that particular direction are added together, so that these signals strengthen each other. “You can do the exact opposite for signals that you do not want to observe,” Wijnholds says. “You can make these signals counteract one another, nulling them out completely. In 2004 we successfully demonstrated this technique with a LOFAR prototype station.”

Another measure that could be taken is expanding the wire meshes under the Low Band Antennas (LBA). Wijnholds: “Each LBA is built on a grid of 3-by-3 metres of wire mesh. Without that, the antennas would be sensitive for radio signals from the horizon, which are signals you do not want to measure.” The wind turbines are positioned at such a distance that from the antenna stations of LOFAR, they appear to be close to the horizon, Wijnholds explains. “The wire meshes that are currently placed under the antennas, already filter out much of this ‘horizon interference’, but due to cost reductions, the wire mesh does not cover the entire area covered by the station. If we cover the ground below the antenna field entirely with wire mesh, horizon interference will be even further suppressed. We are already implementing this with SKA, the Square Kilometre Array.”



An example of nulling. Radio interference (left) can be removed by nulling (right). (Credit: Albert-Jan Boonstra, from Radio Frequency Interference Mitigation in Radio Astronomy, 2005)

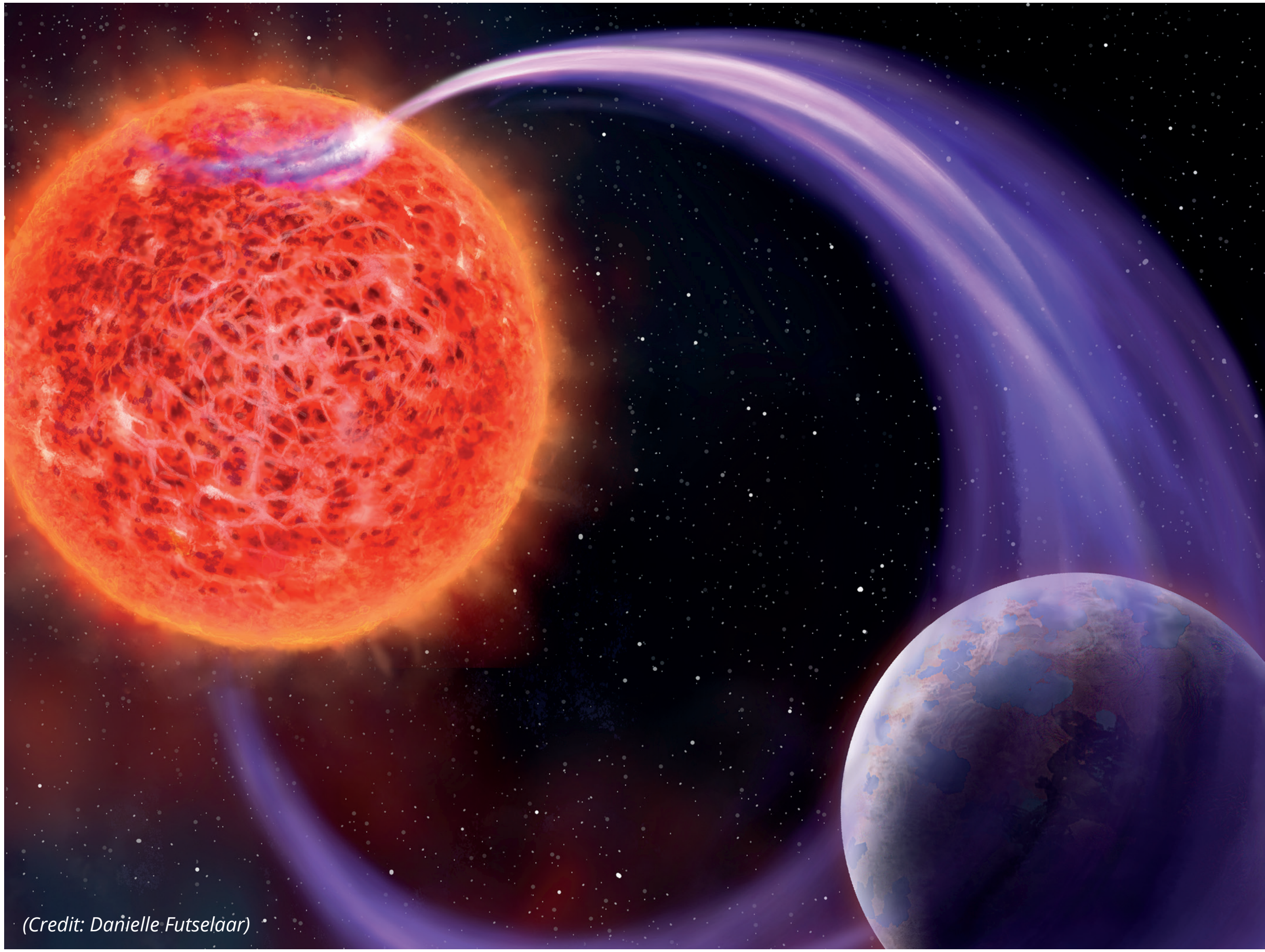
Habitability of alien worlds

The Earth receives its life-sustaining energy from Sunlight, but "explosions" on the Sun can also be life-threatening. Explosions on the Sun's surface, called flares, can spew out large masses of plasma and harmful radiation towards the planets. Radio telescopes have been instrumental in detecting and studying the physics of solar flares. With an exquisitely sensitive telescope like LOFAR, we can now look for similar radio signatures on other stars to decipher how conducive to life their exoplanets are.

This quest reached its first milestone recently with the detection of radio-waves from the star GJ1151 pictured below. The waves carry the predicted signature of a plasma bridge (bluish ribbon in picture) between the star and its planet.

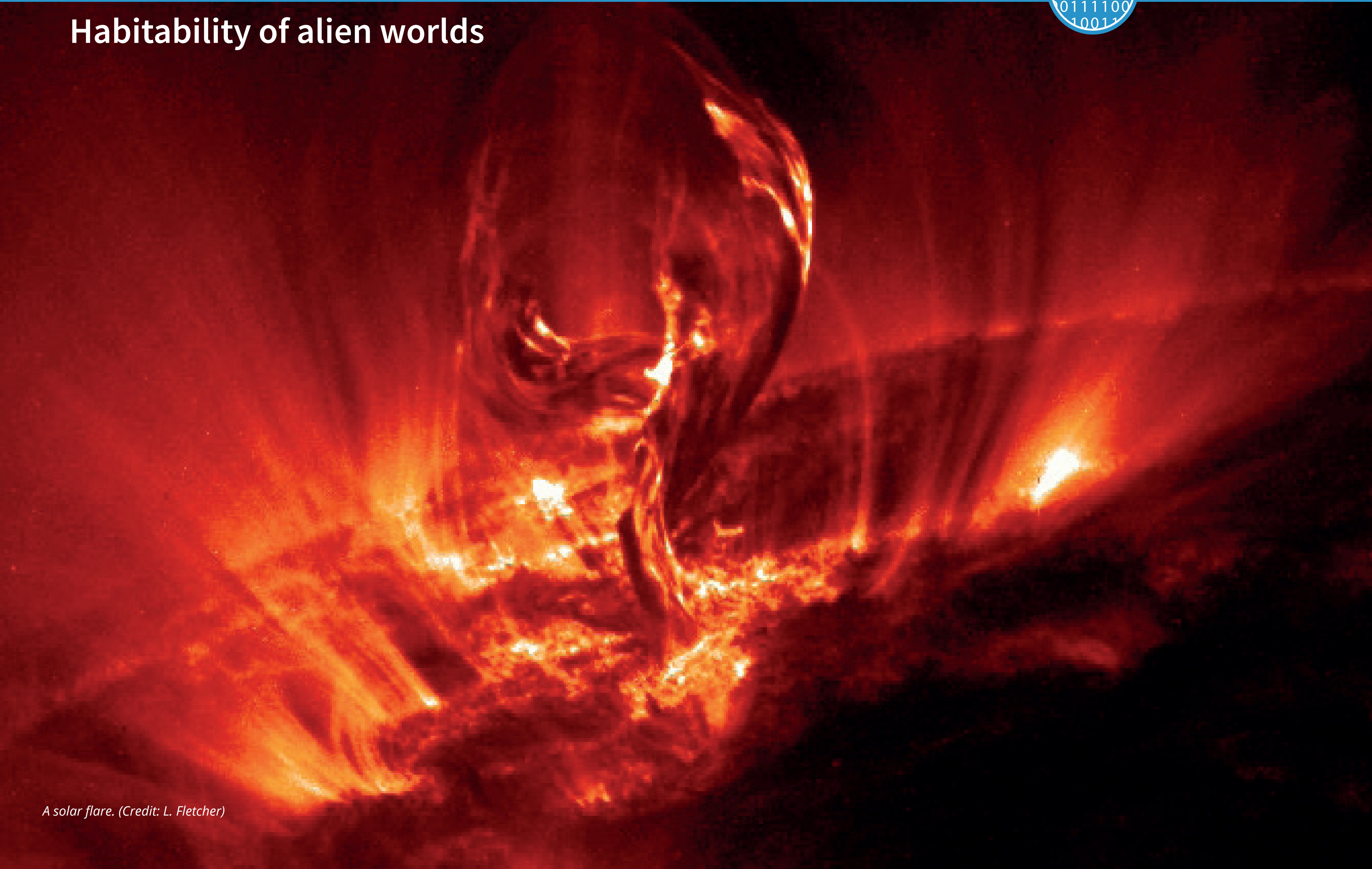
This is the beginning of an exciting path for LOFAR 2.0. The search for exoplanets is one of the specific science cases that LOFAR 2.0 will be engaged in.

The plasma bridge is just one way stars influence exoplanets. We expect to detect emission from several phenomena affecting the "space-weather" around exoplanets. With upcoming observations, we also aim to detect the magnetic fields of exoplanets which are their defence mechanism against stellar flares.



(Credit: Danielle Futselaar)

Habitability of alien worlds



A solar flare. (Credit: L. Fletcher)

Live warning system to study solar eruptions

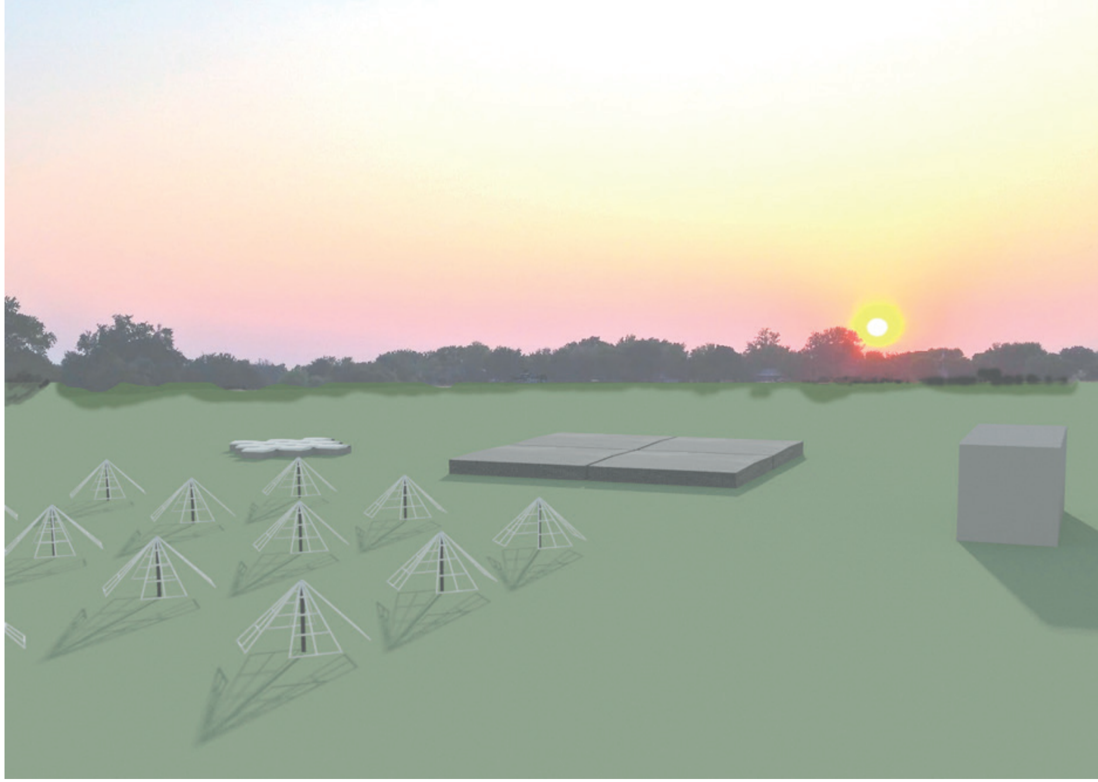
The Sun's activity appears not only in the well-known 11-year Sunspot cycle, but also in short duration eruptions as flares and coronal mass ejections (CMEs). Such eruptive events, also known as space weather, can harmfully influence our Earth's environment and technologies, such as GPS navigation, satellite communications and electric power grids. These events are accompanied with an enhanced radio emission of the Sun, especially in the frequency range (30-240 MHz) covered by LOFAR.

Hence, LOFAR is of great interest for solar physicists, since LOFAR with its spectroscopic and imaging capabilities is well suited for studying active processes in the Sun's corona. This is the reason why the Key Science Project "Solar Physics and Space Weather with LOFAR" was founded. During LOFAR's commissioning phase and the first cycles of regular observations, the solar KSP performed observations of the Sun, together with ASTRON.

DISTURB

On 30 January 2019, ASTRON, together with S[&]T started the design of a solar radio telescope to directly detect eruptions on the sun, at the request of the Ministry of Defence; the Royal Netherland Meteorological Institute (KNMI) is also involved. The project is called DISTURB (Disturbance detection by Intelligent Solar Radio Telescope or (Un)perturbed Radiofrequency Bands). "We finished the initial development phase on June 15th,' says ASTRON senior scientist Michiel Brentjens. "Currently we are looking for funding, so that in the next three to five year we can build a fully functional prototype." That prototype will then be able to directly detect eruptions on the Sun. Eventually the solar telescope might be scaled up to seven to twelve stations worldwide, providing global coverage.

Brentjens points out that DISTURB is not so much an expansion of LOFAR as it is reusage of its technology. However, the development of this solar radio telescope will enable LOFAR 2.0 to study space weather more quickly and more accurately. DISTURB warns LOFAR that a solar eruption is taking place, so that LOFAR immediately can start measuring solar radio waves. Brentjens: "We no longer will have to stare at the Sun for weeks up to months without something happening; now we can immediately respond to a live warning from DISTURB; much more efficient!"



An impression of what the solar radio telescope will look like. (Credit: ASTRON)

ASTRON
Netherlands Institute for Radio Astronomy