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**RADIO ASTRONOMY WITH LOFAR-VLBI ON NEW GENERATION HPC
SYSTEMS: THE CASE OF ABELL 2255**

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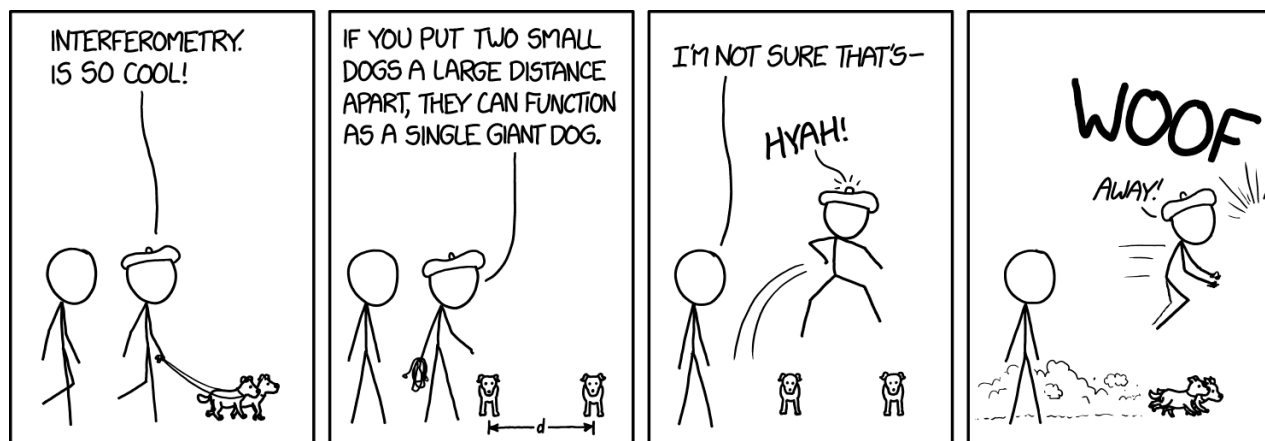
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Abstract

In the past decade, radio astronomy has undergone a major revolution. The advent of the Square Kilometre Array (SKA), together with its pathfinders and precursors, will provide a huge leap in scientific discoveries, pushing the boundaries of our knowledge to entirely new domains. Together with the scientific challenge, the community will have to deal with unprecedented technical and computational challenges. In fact, around 700 PB year^{-1} of data are expected to be produced, which must be collected, shared, and processed by the users. To face such data challenge, current software will have to be re-modeled, if not completely re-designed, exploiting modern high performance computing (HPC) architectures: new solutions, based on complex combinations of Central Processing Units (CPUs), Graphics Processing Units (GPUs), high-speed networks and composite storage devices need to be used in an efficient and effective way.

Although the SKA is not yet operational, pathfinders and precursors are already providing challenging data throughput. One of the best examples is the International LOw Frequency ARray (LOFAR) Telescope (ILT), a pan-European radio interferometer which operates between 10 and 240 MHz. It has 14 so-called *international stations* that provide sub-arcsecond resolution at 144 MHz. This unique capability at such low frequencies, that will remain unique even in the SKA era, comes with a large data challenge. With more than 3,000 antenna tiles, it produces around 4 TB of raw data (for a typical 8 hours observation), which then extend up to $\sim 20 \text{ TB}$ when calibrated. This represents, to date, one of the closest facilities to the SKA in terms of data volume, providing an ideal test bench for the development of HPC solutions for the new generation of interferometers.

Observationally, the combination of high-resolution and low-frequency provided by the ILT is beneficial for many scientific targets. One clear example is represented by a new intriguing phenomenon, the so-called *non-thermal filaments*. These structures have been increasingly observed within high-sensitive maps provided by modern interferometers. They are characterized by narrow (100s pc to few kpc), elongated shapes (10s–100s kpc), steep ($\alpha > 1.3$) radio spectra, and large fractional polarization (up to 40 – 50%), and are usually associated with radio galaxies in galaxy clusters and groups. They provide peculiar sites to study the physical properties of the intracluster medium, such as its magnetic processes and the origin of cosmic-ray electrons. However, their origin is still unclear. The steepness and thinness of the filaments make the ILT a unique tool to study their origin, being able to combine it with higher frequencies data for high-resolution spectral index study.

This Thesis work focuses on the exploitation of new HPC systems for ILT data, addressing both computational and scientific points of view. Computationally, we describe the development of *radio imaging code kernel* (RICK), a code which addresses part of the interferometric imaging steps exploiting advanced parallel and accelerated solutions. RICK uses a distributed approach to the problem, dividing the input dataset among multiple CPUs/GPUs in multiple nodes: this allows handling any problem size, providing the best solution to deal with SKA-size problems. The main feature of RICK is the possibility to run entirely on GPUs, starting from a calibrated dataset to produce a dirty image, copying the data between CPUs and GPUs only at the beginning and at the end of the code: this minimizes the data movement, and so the consequent communication overhead. It also deploys several optimized libraries, especially to distribute the communication and the Fourier transform problems among multiple GPUs, which are novel to radio astronomy. RICK was extensively tested on real ILT data with international stations, with huge improvements when executed fully on GPUs. While not yet ready for scientifically valid maps, we proved the large potential of this approach for interferometric imaging.

Scientifically, the main activity of this Thesis is the usage of ILT data to study the radio galaxies and the associated filamentary emission in the galaxy cluster Abell 2255. Combining multiple observations (7 observing nights of 8 hours each), we produced sub-arcsecond resolution images of the brightest cluster member radio galaxies, with particular focus on the tailed radio galaxies. For one target, namely the Original Tailed Radio Galaxy, we discovered the presence of several filamentary emission surrounding its tail, detectable only with such deep, low-frequency and high-resolution observations. To constrain their origin, we have imaged the whole cluster's field of view, calibrating the ILT data in the so-called *wide-field mode*. This was used for only three fields so far: this is the first time this technique was used specifically targeting a galaxy cluster. Still combining 56 hours of observations, the resulting map, with final resolution of $1.5''$, revealed the existence of additional filaments not directly related to any radio galaxy. By combining ILT with proprietary and archival higher frequency data, we determined the spectral properties of the filaments, and, consequently, an estimate on their radiative ages and equipartition magnetic fields. Polarization was also measured for parts of one filament. The spectral properties, together with the shape, suggest that these filaments could identify regions characterized by low-beta plasma, that is the presence of large magnetic fields, possibly enhanced by magnetic line stretching, or depletion of thermal plasma.

This Thesis is organized in the following structure.

- In Chapter 1, we provide a brief introduction on galaxy clusters, focusing on the main processes happening in the intracluster medium, as well as on its non-thermal properties. We also characterize the diffuse radio emission in clusters, which is instrumental for what is described later on the Thesis.
- In Chapter 2, we introduce the radio-loud active galactic nuclei and the radio galaxies, which are important object of our scientific analysis.
- In Chapter 3, the fundamental concepts of radio interferometry are described. We focus on the imaging algorithms, which have also been used in RICK later on. The main steps of the ILT data calibration and imaging are also enlisted, with particular attention on the international stations calibration, pivotal point of this Thesis.
- In Chapter 4, we present sub-arcsecond resolution maps of the brightest radio galaxies in the galaxy cluster Abell 2255. We highlight the discovery of radio filaments in one tailed radio galaxy, listing their morphological and emissivity properties.
- In Chapter 5, we extend the work of the previous Chapter, detailing the wide-field calibration and imaging of the cluster's field of view at $1.5''$ resolution. We highlight the detection and disentanglement of additional non-thermal filaments. Higher frequency data were combined for spectral index and polarization analysis. We conclude with possible scenarios to explain the formation of the filaments in Abell 2255.
- In Chapter 6, we introduce the main concepts of high performance computing, describing the shared and distributed memory parallelism as well as the GPUs programming paradigms. We present then RICK, enlisting all the developments which allowed the complete GPU offloading of the code. Benchmarks with real, ILT data are presented, showing the huge speed-up reached with such optimized approach.
- In Chapter 7, we outline the most relevant results presented in this Thesis.

Throughout this Thesis, we assume a flat Λ CDM cosmology, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. We also adopt the convention $S(\nu) \propto \nu^{-\alpha}$ for synchrotron spectrum.

Part of the results carried out during the Ph.D. project, and presented in this Thesis, have been published in the following papers:

1. [Accelerating radio astronomy imaging with RICK](#)
De Rubeis E., Lacopo G., Gheller C., Tornatore L., Taffoni G. (2025), *Astronomy and Computing*, 50, 100895
2. [HPC and GPU solutions for radio interferometry using RICK](#)
De Rubeis E., Gheller C., Lacopo G., Tornatore L., Elahi P. J., Cytowski M., Taffoni G., Varetto U. (2025), *33rd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing (PDP)*, pp. 388 – 395
3. [Green computing toward SKA era with RICK](#)
Lacopo G., Gheller C., **De Rubeis E.**, Elahi P. J., Cytowski M., Tornatore L., Taffoni G., Varetto U. (2025), *Workshop Scientific HPC in the pre-Exascale era (part of ITADATA 2024)*
4. [Revealing the intricacies of radio galaxies and filaments in the merging galaxy cluster Abell 2255: I. Insights from deep LOFAR-VLBI sub-arcsecond resolution images](#)
De Rubeis E., Bondi M., Botteon A., van Weeren R. J., de Jong J. M. G. H. J., Rudnick L., Brunetti G., Rajpurohit K., Gheller C., Röttgering H. J. A. (2025), *Astronomy & Astrophysics*, 699, A229
5. [Revealing the intricacies of radio galaxies and filaments in the merging galaxy cluster Abell 2255: II. Properties of filaments using multi-frequency radio data](#)
De Rubeis E., Bondi M., Botteon A., van Weeren R. J., de Jong J. M. G. H. J., Brunetti G., Rudnick L., Brüggen M., Bruno L., Escott E. L., Gheller C., Morabito L. K., Rajpurohit K., Röttgering H. J. A. (2025), *in press*

The following publications are the result of work conducted in collaborative projects during the Ph.D., but not presented in this Thesis:

1. [HPC and GPU accelerated imaging toward the SKA era](#)
Gheller C., Lacopo G., **De Rubeis E.**, Taffoni G., Tornatore L. (2024), *Software and Cyberinfrastructure for Astronomy VIII*. ed. by J. Ibsen and G. Chiozzi. Vol. 13101. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 131011H
2. [A JVLA, LOFAR, e-Merlin, VLBA, and EVN study of RBS 797: can binary supermassive black holes explain the outburst history of the central radio galaxy?](#)
Ubertosi F., Giroletti M., Gitti M., Biava N., **De Rubeis E.**, Bonafede A., Feretti L., Bondi M., Bruno L., Liuzzo E., Ignesti A., Brunetti G. (2024), *Astronomy & Astrophysics*, 688, A86
3. [Magnetic fields in the outskirts of PSZ2 G096.88+24.18 from a depolarization analysis of radio relics](#)
De Rubeis E., Stuardi C., Bonafede A., Vazza F., van Weeren R. J., de Gasperin F., Brüggen M. (2024), *Astronomy & Astrophysics*, 691, A23
4. [Mapping diffuse radio sources using TUNA: a transformer-based deep learning approach](#)
Sanvitale N., Gheller C., Vazza F., Bonafede A., Cuciti V., **De Rubeis E.**, Govoni F., Murgia M., Vacca V. (2025), *Monthly Notices of the Royal Astronomical Society*, 541, 4, 3479
5. [Resurging from the ashes: A spectral study of seven candidate revived radio fossils in nearby low-mass galaxy clusters](#)
Bruno L., Botteon A., Dallacasa D., Venturi T., Balboni M., Biava N., Brienza M., Brüggen M., Brunetti G., de Gasperin F., **De Rubeis E.**, Di Gennaro G., Gastaldello F., Ignesti A.,

Pasini T., Rajpurohit K., Shulevski A., Srikanth K. S. L., van Weeren R. J., Zhang X. (2025),
Astronomy & Astrophysics, 704, A245

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List of Abbreviations

ADAF	A dvection D ominated A ccretion F low
AGN	A ctive G alactic N uclei
API	A pplication P rogram I nterface
BCG	B rightest C luster G alaxy
BIPP	B luebird I maging P lus P lus
BRATS	B roadband R adio A stronomy T ools S uite
CASA	C ommon A stronomy S oftware A pplications
CC	C ool C ore
CI	C ontinuous I njection
CR	C osmic R ay
CRe	C osmic R ay electrons
CRp	C osmic R ay protons
CS	C ore S tations
CST	C ollimated S ynchrotron T hread
CPU	C entral P rocessing U nit
CUDA	C ompute U nified D evice A rchitecture
cuFFT	C UDA F ast F ourier T ransform
cuFFTMp	C UDA F ast F ourier T ransform M ulti- p rocess
CWL	C ommon W orkflow L anguage
DDE	D irection- D ependent E ffect
DIE	D irection- I ndependent E ffect
DP3	D efault P re P rocessing P ipeline
DSA	D iffusive S hock A cceleration
EDFN	E uclid D eep F ield N orth
FFT	F ast F ourier T ransform
FFTW	F astest F ourier T ransform in the W est
FoV	F ield of V iew
FR0	F anaroff- R iley 0
FRI	F anaroff- R iley I
FRII	F anaroff- R iley II
FT	F ourier T ransform
FWHM	F ull- W idth H alf- M aximum
GC	G alaxy C luster
GPS	G lobal P ositioning S ystem
GPU	G raphics P rocessing U nit
GSB	G MRT S oftware B ackend
GSM	G lobal S ky M odel
GWB	u G MRT W ideband B ackend
HBA	H igh- B and A ntenna
HeFFTe	H ighly E fficient F ast F ourier T ransform for E xascale
HERG	H igh E xcitation R adio G alaxy

HIP	H eterogeneous-computing I nterface for P ortability
HPC	H igh P erformance C omputing
HPBW	H alf- P ower B eam W idth
HT	H ead- T ail
IC	I nverse C ompton
ICM	I ntracluster M edium
IDG	I mage D omain G ridder
ILT	I nternational L OFAR T elescope
ILoTSS	I nternational L oFAR T wo-Metre S ky S urvey
ISM	I nterstellar M edium
IS	I nternational S tations
JP	J affe- P erola
KP	K ardashev- P acholczyk
LAS	L argest A ngular S cale
LBA	L ow- B and A ntenna
LBCS	L ong B aseline C alibrator S urvey
LERG	L ow E xcitation R adio G alaxy
LINC	L OFAR I nitial C alibration
LoTSS	L oFAR T wo-Metre S ky S urvey
LoTSS-HR	L oFAR T wo-Metre S ky S urvey H igh- R esolution
LTA	L ong T erm A rchive
MHD	M agnetohydrodynamics
MIMD	M ultiple I nstructions M ultiple D ata
MORESANE	M ODEL R Econstruction by S ynthesis A Nalysis E stimators
MPI	M essage P assing I nterface
MS	M easurement S et
NAT	N arrow A ngle T ail
NCC	N on C ool C ore
NCCL	N VIDIA C ollective C ommunication L ibrary
NRAO	N ational R adio A stronomy O bservatory
NUMA	N on-Uniform M emory A ccess
NVSS	N RAO V LA S ky S urvey
PanSTARRS	P anoramic S urvey T elescope & R apid R esponse S ystem
PCI	P eripheral C omponent I nterconnect
RAM	R andom A ccess M emory
RCCL	R OCm C ollective C ommunication L ibrary
RDMA	R emote D irect M emory A ccess
RFI	R adio F requency I nterference
RICK	R adio I maging C ode K ernel
RM	R otation M easure
rocFFT	roc F ast F ourier T ransform
RS	R emote S tations
SARA	S parsity A veraging R eweighted A nalysis
SIMD	S ingle I nstructions M ultiple D ata
SKA	S quare K ilometre A rray
SPAM	S ource P eeling and A tmospheric M odeling
TGSS ADR	T IFR G iant M etrewave R adio T elescope S ky S urvey A lternative D ata R elease
TJP	T ribble- J affe- P erola
uGMRT	u pgraded G iant M etrewave R adio T elescope

USSRH	U ltra S teep S pectrum R adio H alo
VLA	K. Jansky V ery L arge A rray
VLBI	V ery L ong B aseline I nterferometry
VLSS	V LA L ow-frequency S ky S urvey
WAT	W ide A ngle T ail
WENSS	W esterbork N orthern S ky S urvey
WSClean	W -Stacking C LEAN
WSRT	W esterbork S ynthesis R adio T elescope
XRISM	X -Ray I maging and S pectroscopy M ission

Physical Constants

Speed of Light	$c = 2.998 \times 10^{10} \text{ cm s}^{-1}$
Boltzmann's constant	$k = 1.381 \times 10^{-16} \text{ cm}^2 \text{ g s}^{-1} \text{ K}^{-1}$
Planck's constant	$h = 6.626 \text{ cm}^2 \text{ g s}^{-1}$
Proton mass	$m_p = 1.673 \text{ g}$
Electron charge	$e = 4.803 \times 10^{-10} \text{ g}^{1/2} \text{ cm}^{3/2} \text{ s}^{-1}$
Electron mass	$m_e = 9.109 \times 10^{-28} \text{ g}$

Chapter 1

Galaxy clusters

Galaxy clusters (GCs) are the largest gravitationally bound systems in the Universe, with masses reaching $10^{15} M_{\odot}$ and radii between $1 - 5$ Mpc. The dominant mass component (around 80%) is in dark matter, while $\sim 15\%$ of the total mass (Vikhlinin et al., 2006) is represented by a hot ($10^7 - 10^8$ K) and rarefied ($\sim 10^{-4} - 10^{-2} \text{ cm}^{-3}$) thermal plasma that permeates the cluster volume known as intracluster medium (ICM). Clusters typically contain 100-1000s galaxies, which constitute only up to $\sim 5\%$ of the total mass of a cluster. According to the currently standard hierarchical structure formation scenario, objects are thought to form via gravitational collapse of peaks in the initial primordial density field characterized by the density contrast (or overdensity) field (Kravtsov & Borgani, 2012). Once the collapse started, matter is accumulated and grows via accretion of smaller systems, which grow over cosmic time, ending up in what we observe today as massive GCs (Press & Schechter, 1974; Voit, 2005). In this Chapter, we describe the main thermal and non-thermal components of galaxy clusters, providing a brief description of the turbulent phenomena of the ICM, useful for the following Chapters of this Thesis, as well as of the different species of diffuse radio sources.

1.1 The intracluster medium

1.1.1 Thermal emission

Most of the barionic matter in galaxy clusters (GCs) is in the form of a hot and rarefied plasma called intracluster medium (ICM). At temperatures above 2×10^7 K, thermal bremsstrahlung in the X-rays is the dominant cooling process for the ICM (Sarazin, 1986; Böhringer & Werner, 2010, for reviews). For a plasma with temperature T and an ion number density n_i , the bremsstrahlung specific emissivity at frequency ν is

$$\epsilon_{\nu} \propto Z^2 n_e n_i g_{ff}(Z, T, \nu) T^{-1/2} e^{-\frac{h\nu}{kT}}, \quad (1.1)$$

where Z is the atomic number, n_e the electron number density, k is the Boltzmann constant and g_{ff} is the Gaunt factor which accounts for quantum mechanics effects. ICM temperature and density can be derived from the X-ray spectrum. X-ray thermal diffuse emission of the ICM (Figure 1.1) represents also a powerful tool to select GCs, covering a wide range of masses and redshifts, using imaging X-ray all-sky surveys: they exhibit, in fact, luminosities of $L_X \sim 10^{41} - 10^{45} \text{ erg s}^{-1}$ in the soft energy band $0.2 - 2.3 \text{ keV}$ (Bulbul et al., 2024). At lower temperatures, line emission becomes a more important (if not even dominant) cooling process and it can be used to measure the abundance of heavy elements, the cluster redshift, and also the temperature. On average, a typical abundance value for the ICM is $Z \sim 0.2 - 0.3 Z_{\odot}$ (Arnaud et al., 1992, where $Z_{\odot}$ is the solar metallicity): such high metallicity indicates that the composition of the ICM was enriched by the galactic activity rather than having primordial origin (Böhringer & Werner, 2010; Mernier et al., 2018).

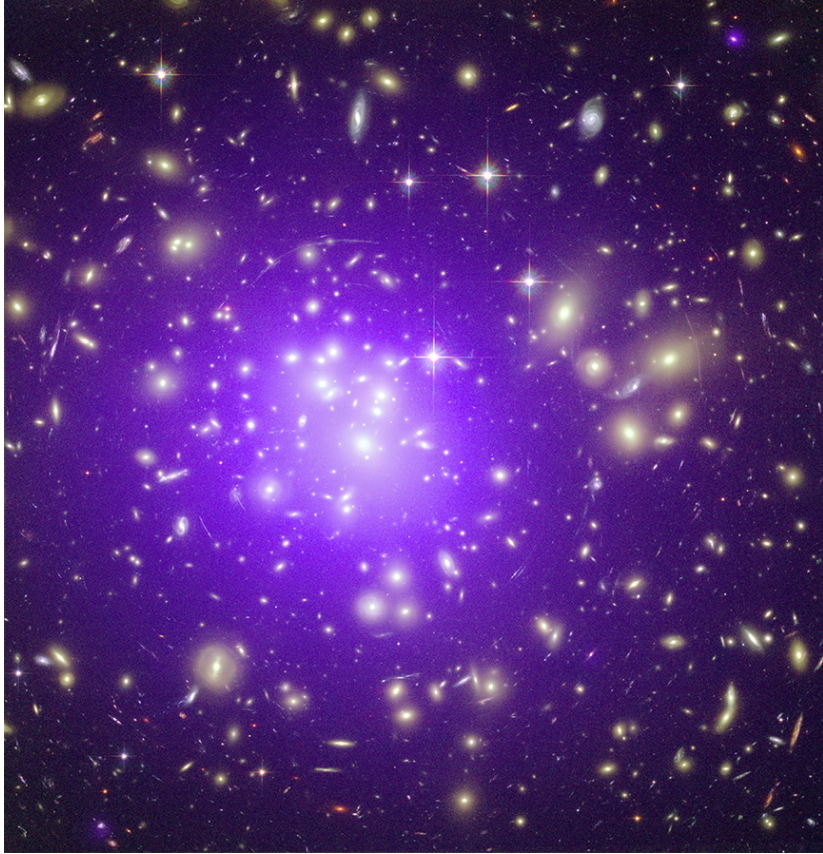


FIGURE 1.1: Composite X-ray (Chandra, in purple) and optical (Hubble Space Telescope, in yellow) image of the galaxy cluster Abell 1689 (Peng et al., 2009).

Measurements of the ICM properties, such as density ρ and temperature T profiles (which can be inferred from X-ray observations, e.g., Ettori et al., 2013), allow also the estimation of the mass of a galaxy cluster. Under the hypothesis of a gas distribution in hydrostatic equilibrium in the cluster's gravitational potential and spherically symmetric, it is possible to derive the total mass inside a given radius r as

$$M(\leq r) = -\frac{kTr}{G\mu m_p} \left[\frac{d \ln \rho}{dr} + \frac{d \ln T}{dr} \right], \quad (1.2)$$

where m_p is the proton mass, while μ represents the mean atomic weight and depends on the mass abundances of the gas. The radial distribution of density and temperature can be found fitting analytical models to reproduce the observed X-ray surface brightness profile and spectrum, respectively. The general morphology of the ICM can be approximated by the hydrostatic isothermal model, also known as β -model (Cavaliere & Fusco-Femiano, 1976; Cavaliere & Fusco-Femiano, 1978), which leads to a density profile described by

$$n(r) = n(0) \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2}\beta}, \quad (1.3)$$

where $n(0)$ is the central density, r_c is the core radius, and $\beta = \frac{\mu m_p \sigma_r^2}{kT}$ represents the ratio between the kinetic energy of the galaxies (with σ_r being the radial velocity dispersion) and the thermal energy of the gas. This is commonly used to fit the ICM emission (Jones & Forman, 1984; Vikhlinin et al., 1999), providing a good description of the data.

1.1.2 Cluster mergers and injected turbulence

Following their formation, galaxy cluster mergers and the accretion of matter at the virial radius can induce large-scale motions within massive clusters. In the context of this Thesis, it is worth briefly discussing cluster mergers and the resulting turbulence they create in the ICM. Mergers between galaxy clusters are the most energetic phenomena in the Universe after the Big Bang, able to dissipate kinetic energies of $10^{63} - 10^{64} \text{ erg s}^{-1}$ in $\sim \text{Gyr}$ time-scales. During this stage, shocks and turbulence driven in the ICM affect the acceleration and propagation of CRs (Section 1.1.3), having a crucial role for the formation of diffuse radio emission in galaxy clusters (Section 1.2). Cassano and Brunetti (2005) suggest that turbulence in the ICM is transient being mostly injected during the most massive mergers. However, since more frequent minor mergers may also contribute to the injection of such turbulence, some minimum level of turbulence should be rather ubiquitous in the ICM. Turbulence is an important ingredient in the physics of the ICM as it is necessary to understand the amplification of magnetic fields in clusters (Section 1.1.3).

A fluid becomes turbulent when the rate of viscous dissipation at the injection scale, L_0 , is much smaller than the energy transfer rate, that is, when the Reynolds number Re is

$$Re = \frac{v_0 L_0}{\nu_K} \gg 1, \quad (1.4)$$

where v_0 is the injection velocity and ν_K is the kinetic fluid viscosity. If the ICM is not magnetized, $\nu_K \sim l_{\text{mfp}} v_i / 3$, where v_i is the velocity of thermal ions and l_{mfp} is the ion-ion mean free path length. This, in absence of magnetic field, is determined by pure Coulomb collisions (Spitzer, 1956)

$$l_{\text{mfp}} \approx 15 \left(\frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left(\frac{kT}{8 \text{ keV}} \right)^2 \left(\frac{40}{\ln \Lambda} \right) \text{ kpc}, \quad (1.5)$$

where $\ln \Lambda$ is the Coulomb logarithm (Longair, 2011). Thus, the corresponding Reynolds number, for example during a major merger, would be (Brunetti et al., 2007)

$$Re \sim 52 \left(\frac{v_L}{10^3 \text{ km s}^{-1}} \right) \left(\frac{L}{300 \text{ kpc}} \right) \left(\frac{n_e}{10^{-3} \text{ cm}^{-3}} \right) \left(\frac{kT}{8 \text{ keV}} \right)^{-5/2} \left(\frac{\ln \Lambda}{40} \right), \quad (1.6)$$

where L is a typical eddy size (ideally the injection scale of the turbulence) and v_L is the root-mean-square velocity within this scale. Thus, based on typical values of the ICM, the Reynolds number would hardly reach $Re \sim 10^2$ in most conditions (Donnert et al., 2018). However, the ICM is magnetized ($B \sim \mu\text{G}$, e.g., Clarke et al., 2001; Carilli & Taylor, 2002; Govoni & Feretti, 2004; Brüggen et al., 2012), hence the particles are scattered by the magnetic field fluctuations starting on the Larmor gyroradius-scale (Braginskii, 1965)

$$r_L \approx 3 \times 10^{-12} \left(\frac{kT}{10 \text{ keV}} \right) \left(\frac{B}{\mu\text{G}} \right)^{-1} \text{ kpc}. \quad (1.7)$$

For the ICM, $l_{\text{mfp}} \gg r_L$: this means that the charged particles, before colliding with single other particles, interact with the rest of particles through the mediation of the magnetic field. In this regime, the plasma is called *weakly collisional*, and instabilities and kinetic effects play important roles in regulating its micro-physical properties (e.g., Schekochihin et al., 2005; Schekochihin et al., 2010; Brunetti & Lazarian, 2011; Yan & Lazarian, 2011). Wave particle interactions become more important than Coulomb collisions. This has two main effects. On one hand, the possibility that

wave-particles interactions can mediate momentum exchange at a rate faster than Coulomb particle-particle interactions provides a motivation for a fluid treatment of the ICM (e.g., Santos-Lima et al., 2017, and references therein). On the other hand, the importance of micro-instabilities and collisionless kinetic processes in the ICM opens up the possibility to a fraction of the energy of the large-scale motions that are generated by the process of cluster formation into electromagnetic fluctuations and collisionless particle acceleration mechanisms on much smaller scales (Brunetti & Jones, 2014, for a review). This is fundamental to understand the processes leading to the formation of diffuse radio sources in merging galaxy clusters (Section 1.2). In presence of magnetic fields, the Reynolds number for motions in the direction perpendicular to the magnetic field gets extremely high, essentially because the perpendicular mean free path of particles is limited to the Larmor gyroradius-scale (Equation 1.7). Furthermore, in the weakly collisional regime, plasma instabilities in the ICM imply that collisionless effects govern microphysics, reducing the effective mean free path. This increases the effective Reynolds number of the ICM to $Re \gg 10^3$, suggesting a highly turbulent medium (Schekochihin & Cowley, 2006; Lazarian & Beresnyak, 2006).

In the MHD limit, turbulence can excite three MHD waves, of which two have compressive nature (fast and slow modes, similar to sound waves) and one is solenoidal (Alfvén mode). The *Alfvén speed* is (Alfvén, 1942)

$$v_A = \frac{B}{\sqrt{4\pi\rho}} = 69 \frac{B}{1 \mu\text{G}} \left(\frac{n_i}{10^{-3} \text{ cm}^{-3}} \right)^{-1/2} \text{ km s}^{-1}. \quad (1.8)$$

Numerical simulations of cluster formation found turbulent velocities at the outer scale of several hundred of km s^{-1} (Miniati, 2014). Turbulence in the ICM is then super-Alfvénic, meaning an injection velocity larger than the Alfvén one. In this case, the turbulent hydrodynamic motions can easily bend the magnetic field lines (Brunetti et al., 2007). The effective mean free path of a particle is determined by the scale at which the magnetic tension can withstand the hydrodynamic forces, that is, the scale at which the turbulent velocity, v_{l_A} , gets equal to the Alfvén one. This scale, at which turbulence becomes MHD, is

$$l_A \sim L_0 \left(\frac{v_A}{V_L} \right)^3 \quad (1.9)$$

and assuming typical conditions in Mpc regions at the center of massive clusters it is

$$l_A \sim 100 \left(\frac{B}{\mu\text{G}} \right)^3 \left(\frac{L_0}{300 \text{ kpc}} \right) \left(\frac{v_L}{10^3 \text{ km s}^{-1}} \right)^{-3} \left(\frac{n_i}{10^{-3} \text{ cm}^{-3}} \text{ pc} \right)^{-3/2} \text{ pc}. \quad (1.10)$$

This scale, known as *Alfvén scale*, is smaller than l_{mfp} , leading to $Re > 10^3$ which ensures that the ICM gets turbulent (Brunetti et al., 2007).

Observationally, hints of turbulent motions in the ICM have been firstly reported by Schuecker et al. (2004) from XMM-Newton maps of the Coma cluster; recent theory progress has shown that the analysis of X-ray surface brightness fluctuations in the ICM can be connected to the velocity ones, so to constrain the turbulent Mach number of the medium (e.g., Churazov et al., 2012; Gaspari & Churazov, 2013; Gaspari et al., 2014; Zhuravleva et al., 2014). The first measurement of turbulence in a galaxy cluster was done by the Hitomi observatory through the broadening of the emission lines due to gas motions, which constrained the line of sight velocity dispersion in the Perseus core to be $164 \pm 10 \text{ km s}^{-1}$ (Hitomi Collaboration et al., 2016). More recently, the X-Ray Imaging and Spectroscopy Mission (XRISM) satellite (Tashiro et al., 2025) performed spectral line measurements for several galaxy clusters, reporting velocity dispersions of $\sim 120 - 190 \text{ km s}^{-1}$ for cool-core clusters (Xrism Collaboration et al., 2025a; XRISM Collaboration et al., 2025; Fujita et al., 2025; Rose et al.,

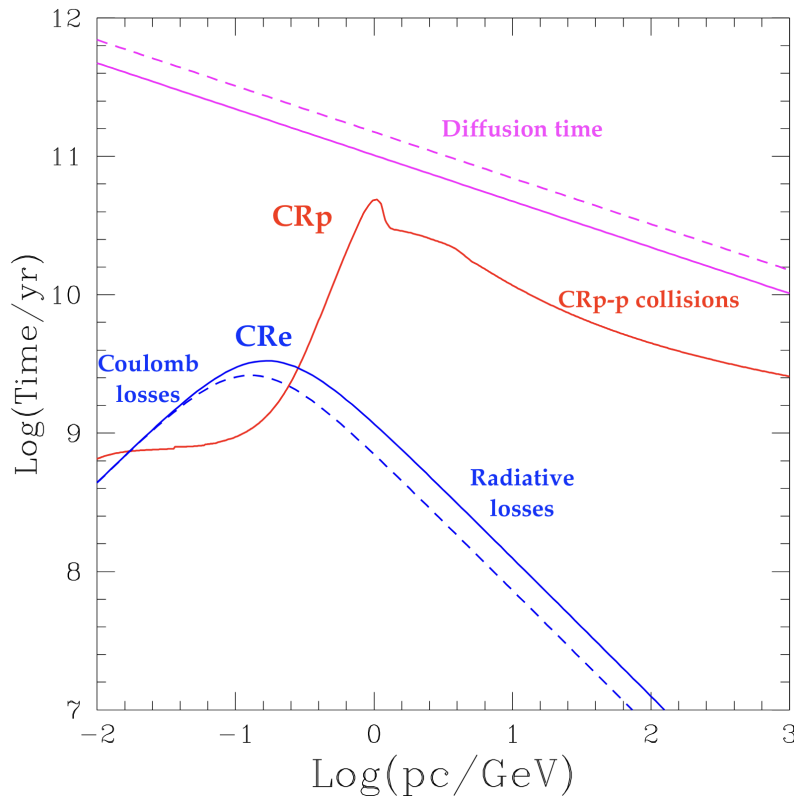


FIGURE 1.2: Time scale for energy losses of protons (red) and electrons (blue) in the ICM at redshift $z = 0$. The magenta lines in the top part are the diffusion time on Mpc scales for protons for a Kolmogorov spectrum of magnetic fluctuations (adapted from Blasi et al., 2007).

2025), and $\sim 200 \text{ km s}^{-1}$ for the merging Coma cluster (Xrism Collaboration et al., 2025b), which appear to be lower than the simulation predictions. This apparent inconsistency is currently being studied (e.g., Vazza & Brunetti, 2026).

1.1.3 Non-thermal emission

In the past decades, radio observations of diffuse synchrotron emission in some galaxy clusters (Section 1.2, Feretti et al., 2012; van Weeren et al., 2019, for reviews) probed the presence of non-thermal components spread on Mpc-scales in the ICM. This extended emission is the signature of the presence of relativistic particles (or cosmic rays, CR) at $\sim \text{GeV}$ energies. Today, there is broad consensus that the hierarchical process of structure formation in the Universe plays a significant role in generating non-thermal components within the ICM (Dolag et al., 2008; Brunetti & Jones, 2014). Shocks that occur during the cluster assembly are believed to be the main injectors of cosmic ray electrons (CRe) and protons (CRp) in the ICM (Miniati et al., 2001; Ryu et al., 2003). Other possible generators of CRs in clusters are individual galaxies, both through relativistic *active galactic nuclei* (AGN) outflows (Section 2.1, Miley, 1980; Hardcastle & Croston, 2020, for reviews) and star formation activity (Völk et al., 1996; Bykov, 2001), and magnetic reconnection regions (Lazarian & Brunetti, 2011; Brunetti & Lazarian, 2016).

Relativistic particles undergo energy losses that limit their lifetime in the ICM and also the maximum energy at which they can be accelerated (Sarazin, 1999; Brunetti & Jones, 2014), as shown in Fig 1.2. For CRe, Coulomb losses are the dominant cooling process at low energies, while radiative losses are

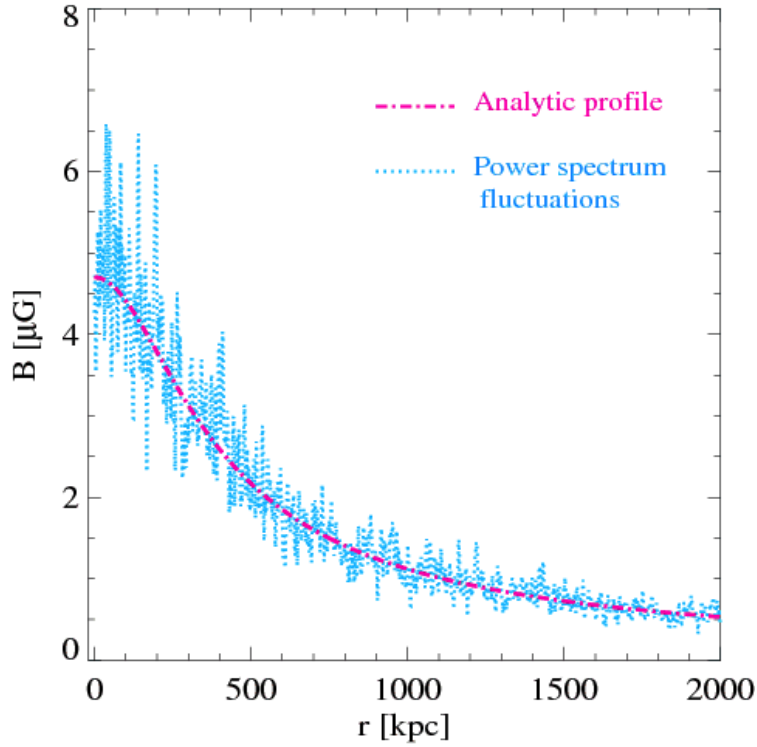


FIGURE 1.3: Magnetic field radial profile for the Coma cluster, from rotation measure study of radio galaxies (Bonafede et al., 2010).

dominant at high energies. Considering a particle with Lorentz factor γ (usually $\gamma \sim 10^4$ for CRe), its time evolution due to synchrotron and inverse Compton (IC) radiation is

$$\frac{d\gamma}{dt} \propto -(B^2 + B_{\text{CMB}}^2)\gamma^2, \quad (1.11)$$

where B is the magnetic field intensity of the relativistic plasma and

$$B_{\text{CMB}} = 3.25(1+z)^2 \mu\text{G} \quad (1.12)$$

is the equivalent magnetic field due to IC with the CMB photons at redshift z . When $B > B_{\text{CMB}}$, synchrotron becomes the dominant radiative process, otherwise IC prevails. The maximum lifetime of CRe (~ 1 Gyr) occurs at energies ~ 100 MeV, where radiative losses are roughly equivalent to Coulomb losses. The CRe that emit synchrotron radiation in the radio band have usually higher energies (several GeV), so their lifetime is shorter (10 – 100 Myr). For CRp, energy losses are dominated by ionization and Coulomb scattering at low energies, and by inelastic proton-proton collisions at higher energies. CRp are long-living particles in the ICM (Völk et al., 1996; Berezhinsky et al., 1997), and are confined for several Gyr within the cluster volume.

Cluster magnetic fields play a fundamental role for the non-thermal component of the ICM. However, knowledge of the origin and evolution of magnetic fields in clusters is still very limited (Carilli & Taylor, 2002; Govoni & Feretti, 2004; Ryu et al., 2012, for reviews). The information on magnetic fields is directly provided from radio observations of diffuse radio sources (e.g., van Weeren et al., 2010; Bonafede et al., 2013; Rajpurohit et al., 2018; Stuardi et al., 2021; Rajpurohit et al., 2022a; De Rubeis et al., 2024; Hu et al., 2024) and from Faraday rotation of polarized radio sources embedded in the cluster or behind them (Section 2.2.2 and references therein). Measurements of

IC X-ray emission can also be used to determine the magnetic field strength (Rephaeli et al., 2008, for a review). These methods established the presence of magnetic fields with strengths of a few μG in the centers of non-cool core (NCC) clusters. In contrast, cool core (CC) systems typically exhibit stronger magnetic fields, possibly due to the dynamic processes occurring in their central regions (Perley & Taylor, 1991; Taylor & Perley, 1993; Allen et al., 2001). Observations suggest that the magnetic field declines with cluster radius, with a profile similar to that of the thermal gas (Dolag et al., 2001; Govoni et al., 2001; Murgia et al., 2004; Bonafede et al., 2010, Figure 1.3). μG magnetic fields can exist even at large distances ($\gtrsim \text{Mpc}$) from the cluster center, as proved by the presence of diffuse radio emission in some cluster outskirts. To explain the field strength measured in clusters, amplification processes are required (e.g., Dolag et al., 2008; Donnert et al., 2018). From early magnetohydrodynamical simulations of merging galaxy clusters (Roettiger et al., 1996; Roettiger et al., 1999), it became clear that shocks, bulk flows, and turbulence play an important role in the amplification of the magnetic fields. The turbulent dynamo is expected to be the main process for the amplification of magnetic field seeds (e.g., Brandenburg & Subramanian, 2005; Subramanian et al., 2006; Ryu et al., 2008; Iapichino & Brüggen, 2012; Federrath, 2016; Iapichino et al., 2017; Miniati & Beresnyak, 2015; Vazza et al., 2018), while turbulent diffusion is expected to spread magnetic fields out to cluster outskirts (Xu et al., 2009). There is still a debate about the origin of the initial magnetic field seeds. One theory suggests they are *primordial*, generated in the early Universe before recombination (Widrow et al., 2012; Subramanian, 2016, for reviews). Another proposes they are *galactic*, originating from AGN ejecta (Enßlin et al., 1999; Furlanetto & Loeb, 2001), galactic winds (Völk & Atoyan, 2000), or star formation activity (Kronberg et al., 1999).

1.2 Diffuse radio emission

Steep spectrum ($\alpha \geq 1$), diffuse radio emission extended on cluster scales is observed in a number of galaxy clusters. The emission is clearly associated with the ICM and not individual sources, implying the existence, as stated in the previous Section, of relativistic electrons and magnetic fields mixed with the ICM. The evidence of diffuse synchrotron radio emission over Mpc-scales opens fundamental questions on their origin as well as their impact on both the physics of the ICM and the cluster evolution (Brunetti & Jones, 2014, for a review). The connection between diffuse radio emission in the ICM and dynamically disturbed systems (Cassano et al., 2010b; Cassano et al., 2013; Cuciti et al., 2015) suggests that cluster mergers play a crucial role in the formation of non-thermal components in galaxy clusters (Section 1.1.2). This section provides a brief overview of the main classes of diffuse radio sources and their key properties, as some of these will be referenced later in this Thesis: refer to van Weeren et al. (2019) for a comprehensive review.

1.2.1 Radio halos

Radio halos are extended sources at the center of galaxy clusters. Their emission is fairly regular in morphology, and permeates the volume of the ICM, typically correlating with the thermal X-ray emission (Govoni et al., 2001; Cassano et al., 2006; Rajpurohit et al., 2018; Botteon et al., 2020b; Bonafede et al., 2022). Depending on their size and origin, radio halos are classified in *giant* and *mini*. Giant radio halos are mostly found in massive, dynamically-disturbed clusters (Giovannini et al., 1999; Cassano et al., 2010a). They have typical sizes of about 1 – 2 Mpc, and 1.4 GHz radio powers between $10^{23} - 10^{26} \text{ W Hz}^{-1}$ (van Weeren et al., 2019, and references therein). Most radio halos have integrated spectral indices in the range $1.1 < \alpha < 1.4$ (Giovannini et al., 2009). An extreme class of radio halos with $\alpha > 1.5$, the so-called *ultra-steep spectrum radio halos* (USSRH, Brunetti et al., 2008; Dallacasa et al., 2009; Macario et al., 2010; Macario et al., 2013; Wilber et al., 2018), is also observed, best at low frequencies (Cassano et al., 2010a; Cassano et al., 2012). Radio halos are found to be generally unpolarized, mainly due to the limited angular resolution (resulting in

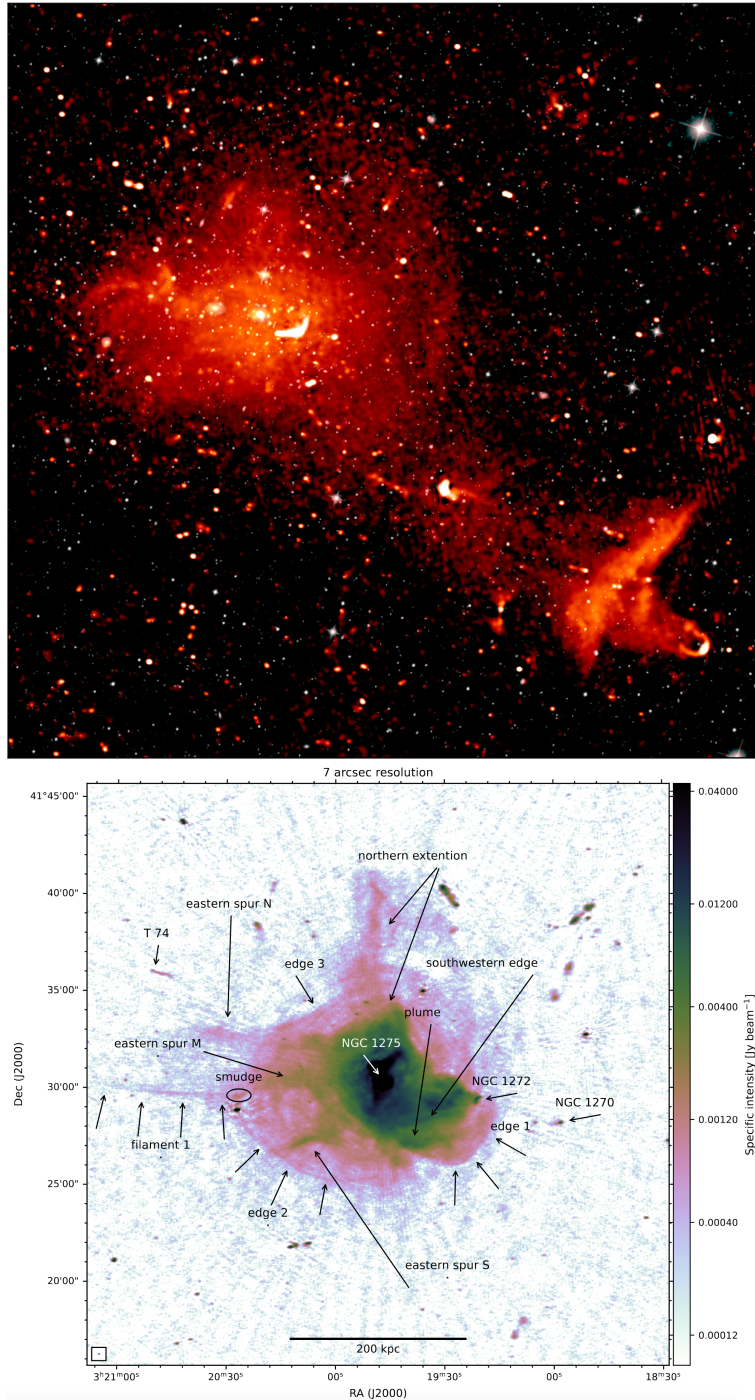


FIGURE 1.4: Examples of radio halos as seen at 144 MHz. *Top*: radio halo in the Coma cluster at 1' resolution (Bonafede et al., 2022). *Bottom*: Radio halo in the Perseus cluster at 7'' resolution, showing the multiple filamentary extensions recently discovered by van Weeren et al. (2024).

beam depolarization) and sensitivity of current radio interferometers. Govoni et al. (2013) modeled the radio halo polarization signal at 1.4 GHz, inferring that these objects should be intrinsically polarized at about 15 – 35% at the cluster centers.

Giant halos are believed to be formed by turbulent re-acceleration of CRe, which become radio-emitting by turbulence injected into the ICM by cluster mergers (Brunetti et al., 2001; Petrosian, 2001; Brunetti et al., 2007; Miniati & Beresnyak, 2015). Further support for the relation between cluster mergers and the presence of radio halos is the radio bi-modality found between merging and relaxed clusters (Brunetti et al., 2007; Brunetti et al., 2009; Kale et al., 2015). Secondary particles, produced via hadronic collisions in the ICM, may provide an additional mechanism to generate CRe in clusters (e.g., Blasi & Colafrancesco, 1999; Dolag & Enßlin, 2000; Pfrommer et al., 2008); however, the current gamma-ray limits disfavor this scenario (Pinzke et al., 2017; Brunetti et al., 2017).

The increasing sensitivity and resolution of modern interferometers are uncovering larger extents of giant radio halos exceeding 2 Mpc in a growing number of systems (Sikhosana et al., 2023; Bruno et al., 2023; Rajpurohit et al., 2021; Bonafede et al., 2022). Deepest low-frequency observations ever made for a galaxy cluster, namely Abell 2255, revealed diffuse emission having total extent of ~ 5 Mpc (Botteon et al., 2022). Moreover, recent low-frequency observations suggested the existence of a new class of radio halos, called *mega-halos*, characterized by a two-component radial radio surface brightness profile, with the outer component exhibiting an ultra-steep spectrum ($\alpha \geq 1.5$). However, also some classical giant radio halos exhibit multiple components within the halo (Rajpurohit et al., 2021; Bruno et al., 2023; Rajpurohit et al., 2023), so whether the mega-halos constitute a new class of sources remains an open question.

Mini-halos have sizes of $\sim 100 - 500$ kpc and are found in relaxed cool core clusters, with the radio emission surrounding the central radio loud BCG (Gitti et al., 2015, for a review). Mini-halos have 1.4 GHz radio powers in the range of $10^{23} - 10^{25}$ W Hz $^{-1}$; compared to giant radio halos, the synchrotron volume emissivities of mini-halos are generally higher (Cassano et al., 2008; Murgia et al., 2009). Spectral index values are similar to those found in giant radio halo, although few detailed studies exist (Sijbring, 1993; Mazzotta & Giacintucci, 2008; Govoni et al., 2009; Hlavacek-Larrondo et al., 2013; Giacintucci et al., 2014). Hadronic (e.g., Pfrommer & Enßlin, 2004) or turbulent re-acceleration models (Gitti et al., 2002) have been invoked to explain the presence of synchrotron emitting electrons. Unlike giant radio halos, mini-halo would trace the turbulence in the cluster cores generated by gas sloshing (ZuHone et al., 2013; ZuHone et al., 2015). The central AGN is a likely candidate for the source of fossil electrons that are re-accelerated (Fujita et al., 2007), while the confinement of mini-halos by cold fronts (Mazzotta & Giacintucci, 2008) supports a scenario where turbulence induced by gas sloshing motions re-accelerates particles.

Detailed high-quality resolved images of mini-halos revealed filamentary structures in Perseus cluster (Gendron-Marsolais et al., 2017; van Weeren et al., 2024), possibly associated to local variations of the magnetic field strength, localized sites of particle re-acceleration, or a non-uniform distribution of fossil electrons (see Section 2.3).

1.2.2 Radio relics

Radio relics are mostly found in the outskirts of galaxy clusters and are characterized by elongated shapes (0.5–2 Mpc) and strong polarization at GHz frequencies ($\gtrsim 20\%$, Enßlin et al., 1998; Stuardi et al., 2022). They are believed to originate from shock fronts generated in the ICM when galaxy clusters merge (Enßlin et al., 1998; Roettiger et al., 1999). In an idealized binary merger, after the dark matter core passage, two shocks are launched in opposite directions along the merger axis, which can explain the formation of cluster double radio shocks in observed merging clusters (van Weeren et al., 2011b; van Weeren et al., 2011c; Molnar & Broadhurst, 2017). The strength of the shocks can be quantified by the *Mach number*

$$\mathcal{M} = \frac{v}{c_s}, \quad (1.13)$$

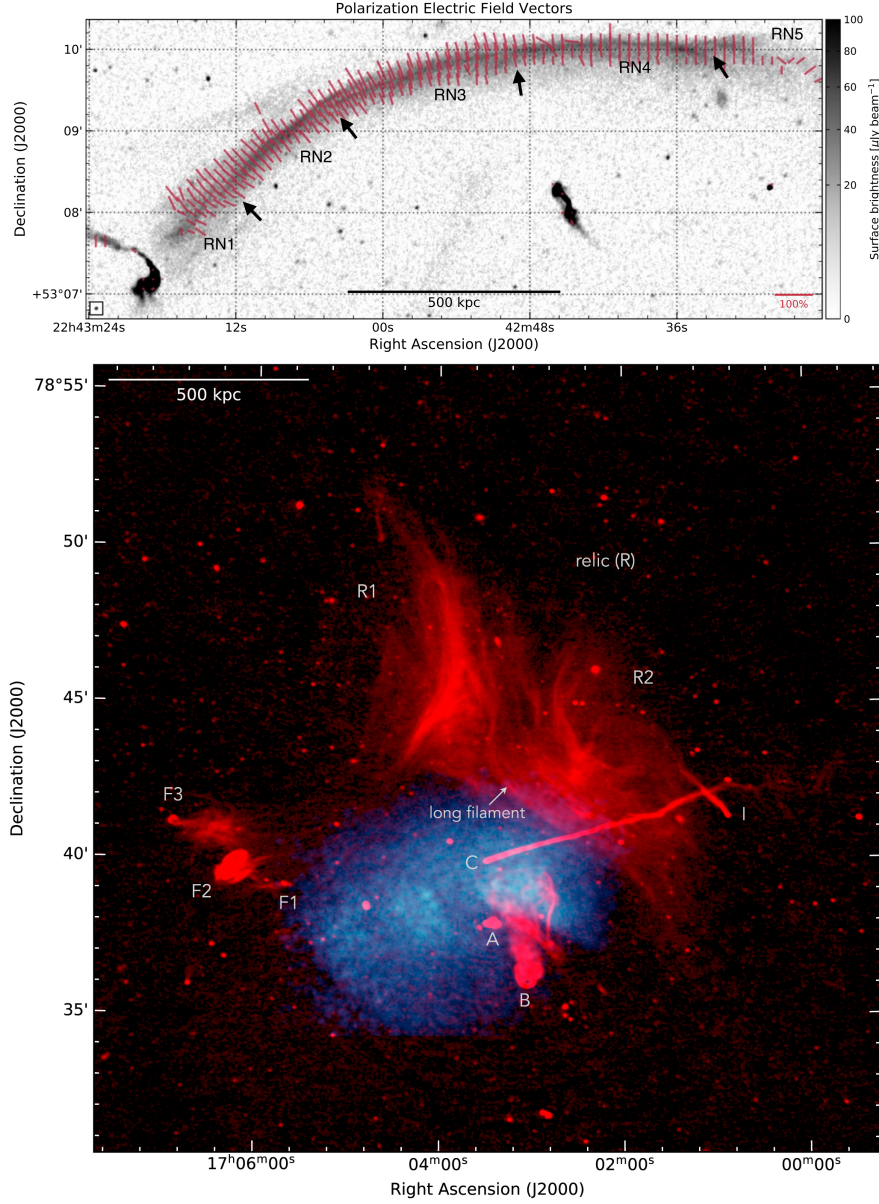


FIGURE 1.5: Radio relics. *Top*: electric field vectors (in red) superimposed on the total intensity map of the Sausage relic in the galaxy cluster CIZA J2242.8 + 5301 (Di Gennaro et al., 2021). *Bottom*: filamentary composition of the relic in Abell 2256 observed in L and S band. Radio emission is shown in red, while X-ray emission from the thermal ICM in blue (Rajpurohit et al., 2022b).

with v being the velocity of the shock and

$$c_s = \sqrt{\frac{\gamma_a kT}{\mu m_p}} \quad (1.14)$$

the sound speed in the pre-shock medium, with γ_a being the adiabatic index. Typical Mach numbers range between $\mathcal{M} \sim 2 - 5$ (van Weeren et al., 2010; Akamatsu & Kawahara, 2013; Wittor et al., 2017; Botteon et al., 2020a), inferred both from radio spectral index (Blandford & Eichler, 1987) or from the Rankine-Hugoniot jump conditions (Landau & Lifshitz's, 1959) in temperature or density.

Relic show quite steep integrated spectra ($1.0 < \alpha < 1.5$, Bonafede et al., 2012; Feretti et al., 2012; de Gasperin et al., 2014), with spectral index steepening moving from the edge of the relic towards the cluster center (e.g., Bonafede et al., 2009; Bonafede et al., 2011; van Weeren et al., 2010; de Gasperin et al., 2015b; Hoang et al., 2018; Di Gennaro et al., 2018; Rajpurohit et al., 2018; Rajpurohit et al., 2020) thought to be caused by synchrotron and IC losses in the shock downstream region. Radio relics are also among the most polarized sources in the extragalactic sky: polarization fractions can reach, in some cases, up to 60% (e.g., Harris et al., 1993), with magnetic field vectors found to be well aligned oriented parallel to the shock front (e.g., van Weeren et al., 2010; Di Gennaro et al., 2021). These evidences further support the connection between radio relics and shocks.

The current understanding of radio relic formation is still a topic of debate. Formation scenarios involve, namely, shock acceleration, shock re-acceleration, and adiabatic compression, and differ in the predictions of the morphological and spectral characteristics of the relics. In the shock acceleration scenario, it is believed that the kinetic energy dissipated by shocks powers the radio emission via diffusive shock acceleration (DSA) of thermal electrons in the ICM (e.g., Enßlin et al., 1998; Blasi & Colafrancesco, 1999; Dolag & Enßlin, 2000; Hoeft & Brüggen, 2007). To be accelerated, particles cross back and forth across the shock front as they scatter from magnetic field inhomogeneities in the shock down and upstream region. At each crossing, particles gain additional energy, forming a power-law energy distribution of CR; the synchrotron radio power related to the DSA model is $P \propto \eta_e(\mathcal{M}) \times \mathcal{M}^3$, where η_e is the shock acceleration efficiency. In the re-acceleration scenario, the shock front re-accelerates electrons via DSA from an existing population of mildly relativistic electrons (Markevitch et al., 2005; Kang & Ryu, 2016); there are indeed many examples showing a connection between relics and lobes of AGN, which provide electron seeds (see the examples in Section 2.2.2). Lastly, relics can be produced by adiabatic compression of fossil radio plasma by the passage of a shock front in the ICM (Enßlin & Gopal-Krishna, 2001).

Recent sensitive, high-resolution observations provided evidence of filaments on various scales, e.g., in Abell 2256 (Owen et al., 2014; Rajpurohit et al., 2022c, Figure 1.5), 1RXS J0603.3+4214 (Rajpurohit et al., 2018), CIZA J2242.8 + 5301 (Di Gennaro et al., 2018), Abell 2255 (Botteon et al., 2020b; Botteon et al., 2022), Abell 3667 (de Gasperin et al., 2022), and MACS J01017.5+3745 (van Weeren et al., 2017). These filaments, whose origin is still unknown, are largely discussed in Section 2.3.

1.2.3 Revived fossil plasma and radio phoenixes

This class of objects traces AGN radio plasma that has somehow been re-energized through processes in the ICM, unrelated to the radio galaxy itself. These sources have been named *phoenixes* (Kempner & David, 2004). Phoenixes have linear extents of hundreds of kiloparsecs (de Gasperin et al., 2015a), and come in a variety of shapes, from roundish (e.g., Abell 1664, Giovannini et al., 1999; Kale & Dwarakanath, 2012) to elongated and filamentary (e.g., Abell 13, Abell 85, Abell 2048, Abell 2593, Abell 4038, Abell 2443, Abell 1033, Abell 1914, Abell 1931, and the Ophiucus cluster, Slee et al., 2001; van Weeren et al., 2011a; Raja et al., 2024; de Gasperin et al., 2015a; van Weeren et al., 2009; Mandal et al., 2020; Murgia et al., 2010; Brüggen et al., 2018; Mandal et al., 2019). Recent observations also helped in clarifying the nature of some of these objects, like the phoenix in the Ophiucus cluster that has been recently re-interpreted in the context of a radio galaxy whose jet is undergoing kink instability (Botteon et al., 2025). Phoenixes are found both in merging (e.g., Abell 2256, van Weeren et al., 2009) and relaxed (e.g., Abell 4038, Kale et al., 2018) clusters, indicating that major mergers event are not required for their formation. Radio phoenixes have typically steep ($\alpha > 1.5$) integrated spectra, with some cases showing high-frequency spectral steepening (e.g., Slee et al., 2001; Cohen & Clarke, 2011; van Weeren et al., 2009; Raja et al., 2024). The spectral index distribution across these sources is irregular, without clear common trends (van Weeren et al., 2011a; Kale & Dwarakanath, 2012; Mandal et al., 2020; Raja et al., 2024). Due to their steep spectrum,

low-frequency radio surveys are expected to detect an increasing number of these sources, but the low spatial resolution makes it difficult to distinguish between diffuse radio emission and emission from individual radio galaxies.

The current favored scenario is that phoenixes trace old radio plasma from past episodes of AGN activity. When a shock compresses this old plasma, the resulting increase in the momentum of the relativistic electrons and the magnetic field strength can produce a source characterized by a steep and curved radio spectrum (Enßlin & Gopal-Krishna, 2001). Simulations also predict that these sources should often have complex morphologies (Enßlin & Brüggen, 2002). However, so far direct observational evidence for a connection between shocks waves and phoenixes is still missing: therefore, the formation scenario for these revived fossil plasma sources remains somewhat uncertain.

Chapter 2

Tailed radio galaxies and non-thermal filaments

This chapter lays the essential groundwork for understanding the extended radio sources that are central to this Thesis. We begin with a concise overview of radio-loud AGN, focusing specifically on the diverse morphologies of extended radio galaxies that populate galaxy clusters. Our primary focus is on the unique class of tailed radio galaxies, namely the narrow-angle tail (NAT) and wide-angle tail (WAT), which are instrumental to the scientific investigations detailed in Chapters 4 and 5. We characterize the fundamental distinctions between these two classes, focusing on their key observational differences in spectral and polarization properties. This analysis provides the necessary context for interpreting their physical state, which is closely connected with understanding the evolution of the non-thermal electron populations ejected from these sources. To this end, we review the principal radiative aging models used to predict the energetic lifetimes of these populations, as well as the Faraday rotation effect and the definition of rotation measure. Finally, we introduce a relatively new and intriguing phenomenon often observed in high-sensitivity cluster surveys: non-thermal filaments. These structures present a compelling opportunity to study the complex interplay of magnetic fields and relativistic particles, offering a unique window into the physics of the ICM.

2.1 Active galactic nuclei and radio galaxies

AGN are associated with the accretion of material on to supermassive black holes ($\gtrsim 10^6 - 10^{10} M_\odot$, Blandford et al., 2019) located at the centers of their host galaxies. These black holes are found in essentially all massive galaxies (Magorrian et al., 1998; Kormendy & Ho, 2013), but only a small fraction of them ($\sim 10\%$) have an active one (e.g., Padovani et al., 2011). Mass accretion on to the supermassive black hole is usually quantified through the mass accretion rate

$$\dot{M} = \frac{L_{\text{bol}}}{\eta c^2}, \quad (2.1)$$

where η is the mass-energy conversion factor (typically assumed to be 0.1, e.g., Davis & Laor, 2011; Heckman & Best, 2014), c is the speed of light, and L_{bol} is the bolometric luminosity. Since this process produces a huge amount of energy ($10^{40} \lesssim L_{\text{bol}} \lesssim 10^{48} \text{ erg s}^{-1}$), there is growing evidence that AGN activity may play an important role in shaping the evolution of the host galaxy. The feedback exerted by such a powerful energy release on the surrounding gas and stars is imprinted into the observed correlations between black hole mass and galaxy properties (e.g., stellar mass or velocity dispersion, Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Tremaine et al., 2002; Marconi

& Hunt, 2003), and is also responsible for controlling or terminating star formation (Cattaneo et al., 2009).

Although the AGN population presents a large variety of observational properties (e.g., Padovani et al., 2017, for a complete review), different AGN classes have historically been brought into a single framework by the standard *unified model* (e.g., Antonucci, 1993; Urry & Padovani, 1995), for which all AGN belong to a small number of physical classes, with many of the observed differences between them resulting from different viewing angles with respect to the observer's line of sight. This model seems to explain well the differences observed between many of the AGN classes, and has been tested and refined over the years (e.g., Bianchi et al., 2012; Mateos et al., 2016; Ramos Almeida & Ricci, 2017; Padovani et al., 2017, and references within). These studies have emphasized that, in addition to the inclination, other physical parameters affect the observed differences between the various AGN classes. Such parameters include: the morphological type of the host galaxy, the accretion rate, the presence (or absence) of strong radio-emitting outflows of relativistic particles (i.e. the *radio jets*), and possibly the host galaxy environment. In particular, there is strong empirical evidence that the low-redshift ($z < 0.1$) population of AGN can be divided into two main categories, mainly determined by the nature of their dominant (but not exclusive) energetic output (Antonucci, 2012; Heckman & Best, 2014). One is the *standard* accretion mode, also referred to as *quasar-mode* or *radiative-mode*, usually associated with quasars or Seyfert galaxies. In this category, the dominant energetic output is in the form of electromagnetic radiation produced by the material accreted on to the black hole through a radiatively efficient, optically thick, geometrically thin accretion disk (e.g., Shakura & Sunyaev, 1973). These AGN are known to radiate across a broad range of the electromagnetic spectrum (e.g., Elvis et al., 1994), and a small fraction of these objects are *radio-loud* (RL-AGN), possessing powerful radio jets that can extend for tens or hundreds of kpc. The second accretion mode consists of objects in which the accretion of material on to the black hole leads to little radiated energy. It was shown that these sources exhibit no accretion-related X-ray or infrared emission (e.g., Hardcastle et al., 2007b), and are also hosted by different host galaxies from the quasar-like AGN (Best et al., 2005). These AGN, also referred to as *radiatively inefficient* or *radio-mode*, are believed to be fueled through advection-dominated accretion flows (ADAF), which are optically-thin, geometrically thick, accretion flows (e.g., Narayan & Yi, 1995). The primary energetic output takes then the form of the bulk kinetic energy transported in two-sided collimated jets (e.g., Merloni & Heinz, 2007), which may be ultimately powered by the accretion of gas or by tapping the spin energy of the supermassive black hole. The jets are most easily detected via radio wavelength synchrotron emission, indicating the presence of magnetic fields and ultra-relativistic electrons/protons, which extend from pc to Mpc scales (e.g., Blandford et al., 2019, for a complete review). Although the total cosmic contribution of the energetic output of jets is nearly two orders of magnitudes lower than that of radiation from the quasar mode AGN (e.g., Cattaneo & Best, 2009), the jet energy is all deposited locally to the system, potentially producing a very efficient feedback mechanism. This is most directly observed in the bubbles and cavities that radio-AGN evacuate in the hot hydrostatic gas halos of their host galaxies or in the surrounding groups and clusters (e.g., Boehringer et al., 1993; Carilli et al., 1994; McNamara et al., 2000; McNamara et al., 2005; McNamara et al., 2009; McNamara & Nulsen, 2012; Fabian et al., 2006; Fabian, 2012; Gitti et al., 2012; Eckert et al., 2021; Ubertosi et al., 2021).

According to the unified model, galaxies hosting a jetted AGN whose jets point at large angles with respect to the observer line of sight are called *radio galaxies*. In this Section, we briefly discuss the main properties of extended ($\gtrsim 10$ s kpc) radio galaxies, categorized from radio observations. An overview diagram, with the size and radio luminosity range spanned by different classes of RL-AGN, is shown in Figure 2.1. We highlight that jet-driven AGN cover a large range in both linear size (six orders of magnitude) and radio luminosity (nearly 10 orders of magnitude). Since their

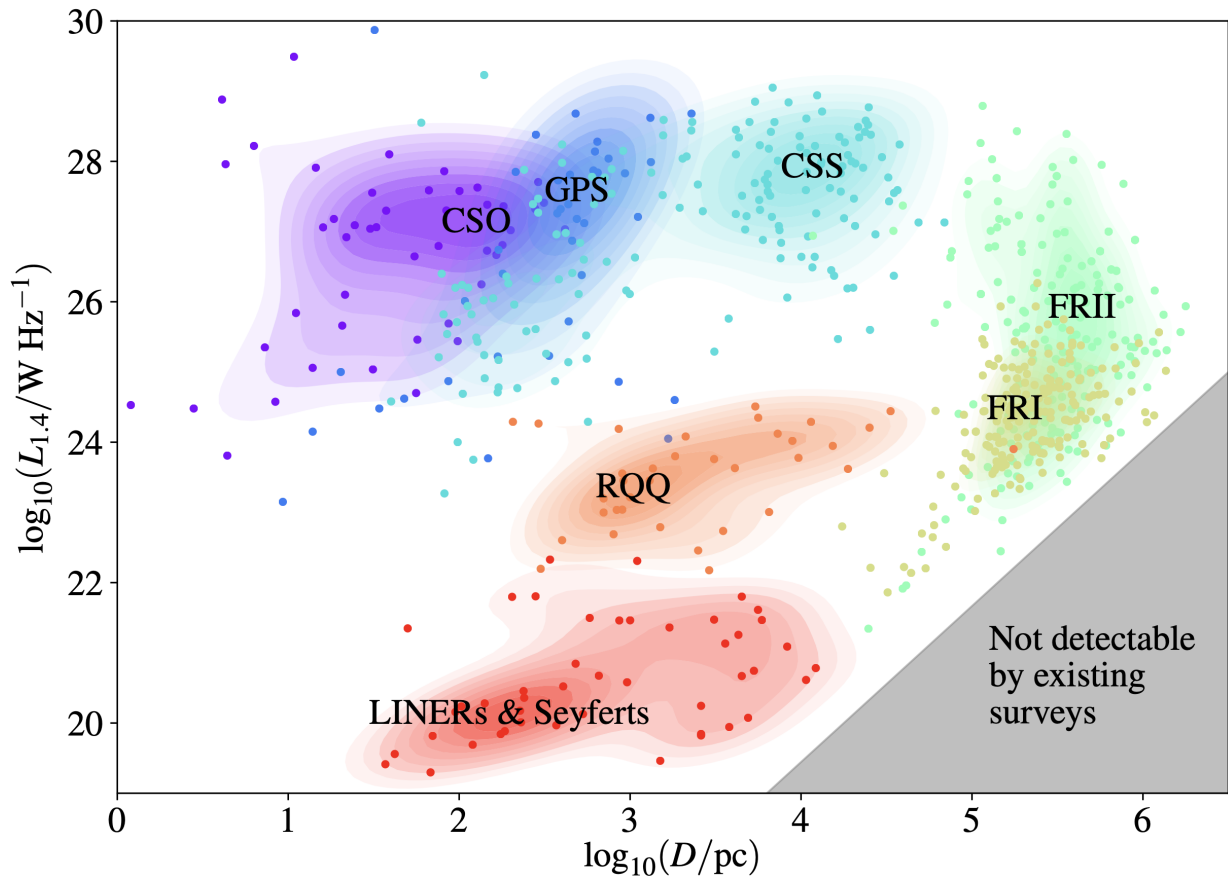


FIGURE 2.1: Power versus linear size plot for different types of radio-loud and radio-quiet AGN (Hardcastle & Croston, 2020, and references therein).

discovery, our understanding of the diversity of radio galaxy populations has evolved dramatically. Still, despite their well-known multi-wavelength manifestation (e.g., Hardcastle & Croston, 2020, for an overview), radio observations remain key to an understanding of their origin, dynamics, and energetics. Although radio emission from jets is the cleanest method for selecting samples of RL-AGN, other methods also exist (for a complete description, see Padovani et al., 2017). These include the radio-to-optical flux ratio (defined as $R = S_{5\text{GHz}}/S_{4400\text{\AA}} \gtrsim 10$, e.g., Schmidt, 1970; Kellermann et al., 1989), radio-to-X-ray luminosity ratio ($\log R = \nu L_\nu(5\text{ GHz})/L_{2-10\text{ keV}} > -4.5$, Terashima & Wilson, 2003), X-ray power ($L_{2-10\text{ keV}} \gtrsim 10^{42}\text{ erg s}^{-1}$, Szokoly et al., 2004) and spectrum (Vattakunnel et al., 2012, and references within), infrared color-color diagram (e.g., Donley et al., 2012), *radio excess* (with respect to the infrared emission, e.g., at 20 or 70 μm , Bonzini et al., 2013, and references within), and optical indicators (e.g., the presence of broad or high-excitation emission lines, or specific emission lines ration, Baldwin et al., 1981; Kauffmann et al., 2003; Buttiglione et al., 2010; Best & Heckman, 2012).

2.1.1 The Fanaroff-Riley morphological dichotomy

The Fanaroff-Riley (Fanaroff & Riley, 1974) classification is a morphological distinction between core- and edge-brightened extended radio galaxy (Figure 2.2), widely adopted in the literature. Despite the observational nature of this classification, the FR divide is thought to be fundamentally linked to the jet dynamics: the edge-brightened FRII radio galaxies are thought to have jets that remain relativistic and well collimated for 10s-100s kpc, before terminating into a *hotspot*, while the core-brightened FRI are known to have initially relativistic jets that decelerate on kpc scale (Laing

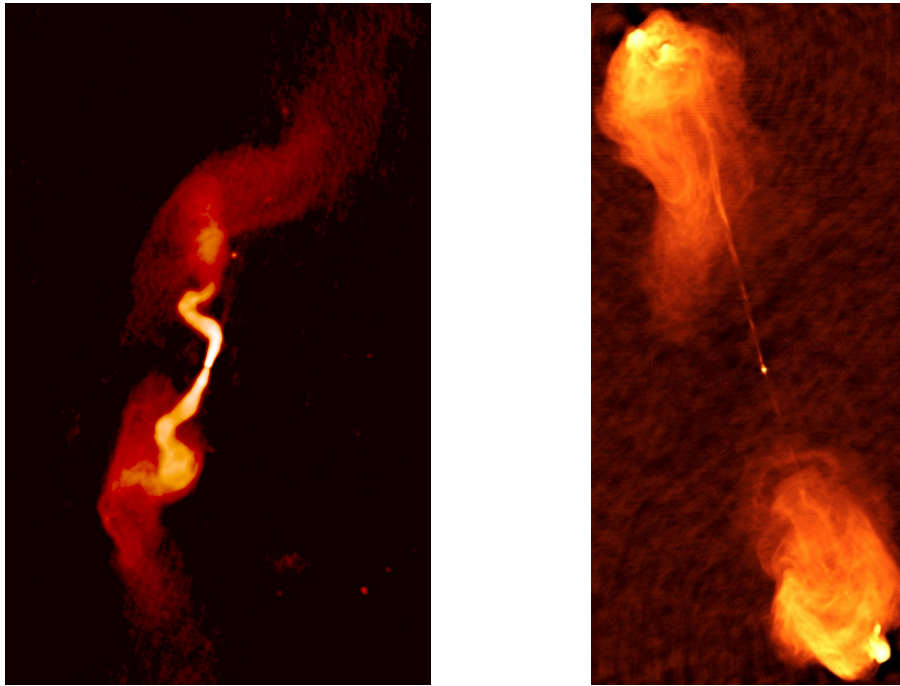


FIGURE 2.2: Example of Fanaroff-Riley radio galaxies. *Left*: FRI radio galaxy 3C31 (Laing et al., 2008). *Right*: FRII radio galaxy Cygnus A (Perley et al., 1984).

& Bridle, 2002a). The observed morphological differences result from several factors, namely the properties of the central engine and the interplay between jet power and environmental density. In fact, jets with the same power might remain relativistic and collimated in a poor host-galaxy environment, while decelerate and expand in a richer one (Ledlow & Owen, 1996). The two classes do not correspond instead to a division from the point of view of the optical spectroscopical properties of their host. Laing et al. (1994) defined *low* and *high excitation radio galaxies* (LERG and HERG, respectively) based on the ratios of specific diagnostic optical emission lines. It was observed that while the FRIs are predominantly LERG, the FRIIs are a mix of HERG and LERG (Hardcastle et al., 2007a; Buttiglione et al., 2010; Best & Heckman, 2012). The canonical FRI/II luminosity break was placed around radio luminosities $L_{150 \text{ MHz}} \sim 10^{26} \text{ W Hz}^{-1}$ (Fanaroff & Riley, 1974). However, deep radio surveys have recently revealed the existence of a population of low-luminosity sources with FRII morphology (Best, 2009; Capetti et al., 2017b; Mingo et al., 2019), showing that the FR dichotomy is less tied to a luminosity division than previously thought. Mingo et al. (2019), using a large sample from the LOw Frequency ARray (LOFAR) Two-Metre Sky Survey (LoTSS, Section 3.4.2), showed that these so-called *FRII-low* radio galaxies form a substantial fraction of the FRII population at $z < 0.8$.

A number of key studies related to the jets on kpc scales have been performed for both FRI and FRII radio galaxies (Laing, 2015, and references within), including, among the others, the velocity field, magnetic field structure, generation of relativistic particles and effects of the external environment. One of the more detailed empirical model to understand the jets in FRIs was developed by Laing and Bridle (2002c) and Laing and Bridle (2002b), considering the geometry and the velocity field of the jets. They assumed that the two oppositely-directed jets are axisymmetric, intrinsically symmetric and time-stationary, and that they can be divided into three parts. Firstly, a well-collimated *inner* region in which the central velocity is $0.8 - 0.9c$. This is followed by a rapid expansion region, referred as the *flaring* region, after which the jets recollimate. The boundary with the inner region

appears to mark a discontinuity (so-called *flaring point*, Parma et al., 1987) at which the emissivity increases abruptly. Finally, there is an outermost conical region. The on-axis velocity drops from $\sim 0.8 - 0.9c$ to $\sim 0.55c$ at the end of the flaring region, decreasing further outwards. The velocity at the edges of the jet are significantly lower with the deceleration of the jet being possibly due to entrainment from the external medium (Laing & Bridle, 2002b). The outflow speed at the jet edges are also slower than in the spine. The magnetic field is predominantly longitudinal close to the AGN, but predominantly toroidal after recollimation. For a sample of FRI jets, spectral flattening was observed with increasing distance from the nucleus. This spectral flattening occurs between the flaring point and the end of rapid deceleration as determined from the modeling of the jets as decelerating relativistic flows; thereafter the spectral index is constant until after the jets recollimate (Laing & Bridle, 2013). The range of observed spectral indices and the inferred dependence on velocity could result from first-order Fermi acceleration, but this would require shocks all along the volume of the jet. Alternatively, there may be two acceleration mechanisms operating at different distances from the core with different intensity.

The high efficiency of FRII jets, which maintain better collimation over longer scales than FRI due to their jet speed and environment, combined with strong viewing angle effects, makes this type of study challenging and necessitates high resolution observations. Collimation of jets has been probed by examining their structure, e.g. the variation of width transverse to the jet axis with distance from the core (Bridle & Perley, 1984), or the variation of hotspot size with projected linear size (Hardcastle et al., 1998). The correlation of jet-sidedness with lobe depolarization, known as the *Laing-Garrington effect* (Laing, 1988; Garrington et al., 1988), demonstrates that the prominent jets are on the approaching side. This is consistent with relativistic beaming being a viable explanation of jet asymmetry/one-sidedness. Although extended radio jets may start off with highly relativistic velocities, these, on average, slow down with increasing distance from the nucleus (Bridle et al., 1994).

Observationally, at radio frequencies, the FRI are characterized by a decreasing surface brightness moving from the core towards the jets, which are both visible because of the jet deceleration and consequent loss of collimation. Most of the emission in the FRIIs comes instead from the hotspots, where electrons are accelerated, and lobes, where they are deposited and age. Both FRIs and FRIIs are usually characterized by radiative ages of $10^7 - 10^8$ yr due to synchrotron and IC emission from the jets and, for the FRIIs, also from the hotspots.

Recently, the FR0 nomenclature has been introduced to the classical FRI/FRII discussion. FR0 are characterized by core luminosity similar to that of FRI sources, but the extended emission is weaker by a factor ~ 100 , a higher core dominance, poorer Mpc-scale environment and smaller (sub-kpc scale, if resolved) jets than FRIs (Baldi & Capetti, 2009; Sadler et al., 2014; Baldi et al., 2015; Baldi, 2023). However, FR0s share similar host and nuclear properties with FRIs. Despite the discussion about this terminology (Hardcastle & Croston, 2020), FR0s represent the most abundant class of radio galaxies in the local Universe, meaning that they are of great importance for our understanding of radio galaxy life cycles and AGN feedback.

2.2 Radio galaxies in galaxy clusters

2.2.1 Tailed radio galaxies

The environment plays a major role in shaping galaxy evolution. Galaxies inhabiting rich clusters are predominantly quiescent and relaxed systems, while those located in the field are star-forming, late-type objects (Dressler, 1980; Whitmore et al., 1993; Dressler et al., 1997). At the same time, late-type systems inhabiting dense regions are generally gas-poor and with a reduced star formation

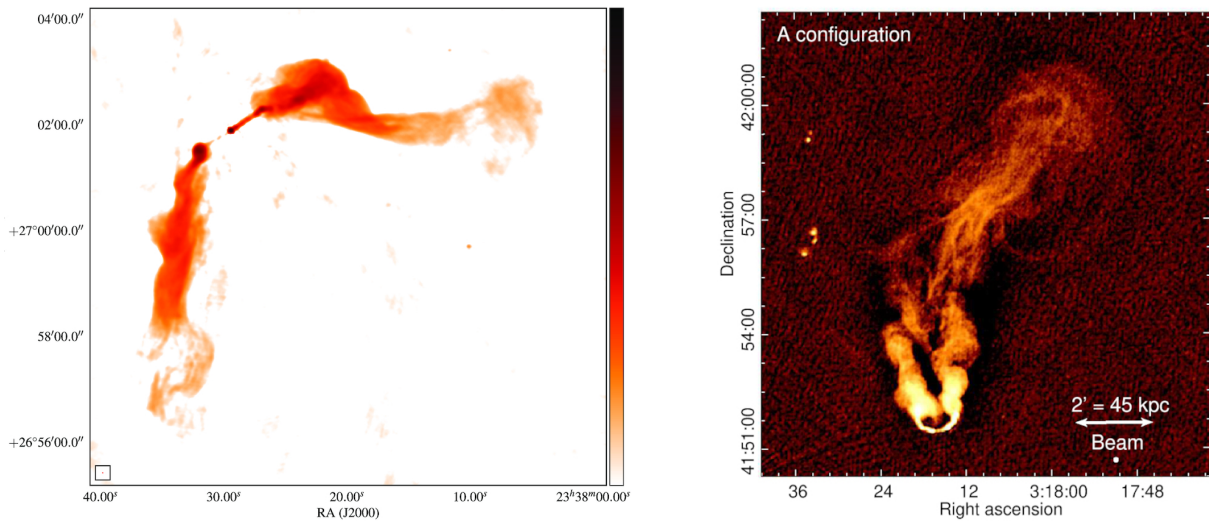


FIGURE 2.3: Examples of bent-tail radio galaxies. *Left*: the WAT 3C 465 in the cluster Abell 2634 (Bemping-Manful et al., 2020). *Right*: the NAT NGC 1265 in the Perseus cluster (Gendron-Marsolais et al., 2020).

activity (e.g., Boselli & Gavazzi, 2006, for a review). Hydrodynamic interactions can also occur between the cold interstellar medium (ISM) of galaxies and the surrounding hot ICM of the cluster. These include heat conduction between the two media at different temperatures (thermal evaporation, Cowie & Songaila, 1977), mixing in the instabilities formed at the interface between the galaxy ISM and the surrounding ICM (e.g., viscous stripping, Nulsen, 1982), the end of infall of fresh gas once a galaxy becomes a satellite of a larger system (e.g., starvation, Larson et al., 1980), and the pressure exerted by the ICM on galaxies moving at high velocity ($500 - 1000 \text{ km s}^{-1}$) within it (*ram pressure stripping*, Gunn & Gott, 1972).

Radio galaxies are no exception, with the cluster environment playing a significant role in shaping their morphological properties. The majority of radio galaxies do not reside in galaxy clusters. However, the small fraction that does show a range of morphological properties caused by the dense surrounding ICM (Miley, 1980; Owen & Ledlow, 1997; Burns, 1998). It is commonly stated that FRI radio galaxies preferentially reside in dense environments, such as clusters or groups of galaxies, whereas FRII are found in less dense environments. There are, however, exceptions, such as Cygnus A (Figure 2.2) or the Double (presented later in this Thesis, Section 4.3.1). The interaction with the cluster environment often distorts the morphologies of radio galaxies: these distorted radio galaxies are generally referred to as *bent-tail* sources. Further separation can be made based on the angle between the direction from the central source to the lobes: as it progressively departs from 180° , we distinguish the *wide-angle tail* (WAT, Owen & Rudnick, 1976) and the *narrow-angle tail* (NAT, or *head-tail*, HT, when resembling a cometary appearance, Ryle & Windram, 1968; Hill & Longair, 1971). Examples of these two categories are shown in Figure 2.3. Despite the large number of observations, the details of such interactions are not fully disentangled yet. This historical classification, uniquely based on the observed radio morphology, is not rigorous, as ambiguous and irregular morphologies can arise from limited instrument sensitivity and dynamic range or from projection effects. The framework is further complicated by the discovery of new and complex classes revealed by the enhanced resolution and sensitivity of modern telescopes (e.g., X-shaped radio galaxies, Giri et al., 2024, and references within), for which novel classification approaches have been proposed (e.g., Rudnick, 2021).

The tails of radio galaxies are constituted by relativistic electrons deposited by the activity of the

host galaxy. These have reached pressure equilibrium with the ambient gas and are losing energy essentially through synchrotron radiation and IC. Since the radio emitting electrons are expected to be older at greater distance from the nucleus, the variation of the physical conditions with distance is related to the time evolution of the radio plasma. As a consequence, a decline in surface brightness, as well as a steepening of the spectral index, is commonly observed moving from the core towards the tail (Feretti et al., 1998). The spectral steepening is stronger at high-frequencies, due to the spectral curvature usually observed above 1 GHz (Alexander & Leahy, 1987). Throughout the years, several aging models have been proposed to reproduce the spectral index trends for the extended emission (see some examples in Figure 2.4). These will be used later in this Thesis for the spectral index analysis of a NAT and its associated filaments (Chapter 5). Consider an electron energy distribution $N(E) = N_0 E^{-\delta}$, a power-law usually observed in non-thermal electron populations, where $\delta = 2\alpha_{\text{inj}} + 1$. α_{inj} is the injection spectral index, and is the initial spectral index of the synchrotron emitting electron population as injected by the core. Synchrotron and IC radiation losses change the electron energy distribution over time at rate

$$-\frac{dE}{dt} = -\xi E^2 = -(\xi_{\text{syn}} + \xi_{\text{IC}})E^2. \quad (2.2)$$

$\xi_{\text{IC}} = (2/3)c_2 B_{\text{CMB}}^2$ parametrizes the IC losses, where $c_2 = 2e^4/3m_e^4 c^7$ is a constant (as defined in Pacholczyk, 1970) and $B_{\text{CMB}} = 3.25(1+z)^2$ is the equivalent magnetic field of the cosmic microwave background in μG . ξ_{syn} can instead be expressed in different ways depending on the pitch angle of the synchrotron emitting electrons. The Jaffe-Perola (JP, Jaffe & Perola, 1973) model takes into account that the pitch angles are continuously isotropized on a timescale shorter than the radiative timescale

$$\xi_{\text{syn}} = \frac{2}{3}c_2 B^2. \quad (2.3)$$

For the Kardashev-Pacholczyk (KP, Kardashev, 1962; Pacholczyk, 1970) model, the pitch angle of the electrons θ remains in its original orientation with respect to the magnetic field

$$\xi_{\text{syn}} = c_2 B^2 \sin^2 \theta. \quad (2.4)$$

Both models assume a uniform magnetic field and a single injection event that produces a power-law

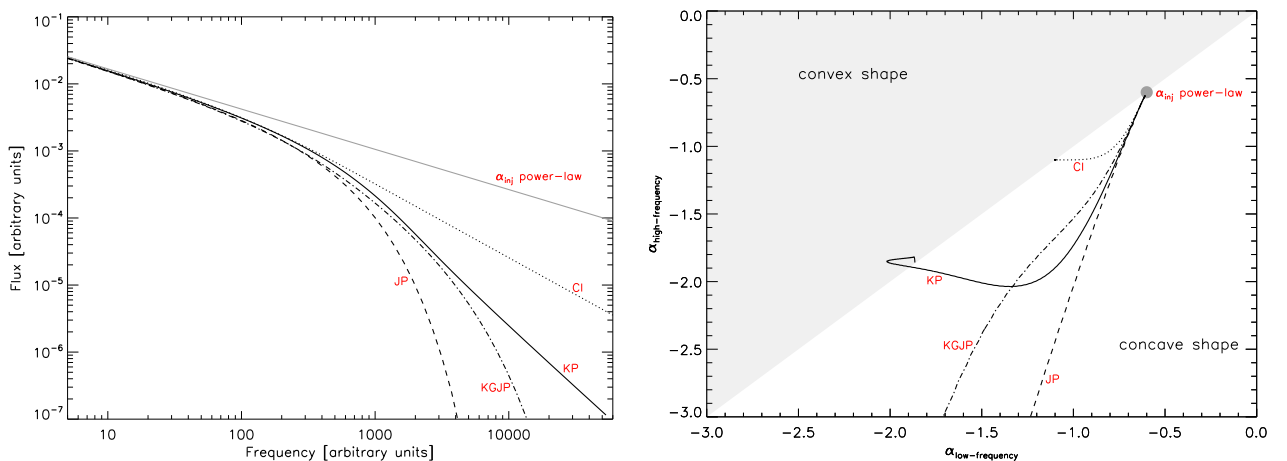


FIGURE 2.4: Spectral aging models, partially described in Section 2.2.1 (van Weeren et al., 2012). *Left*: synchrotron spectra for different spectral models, all having an injection spectral index $\alpha_{\text{inj}} = 0.6$. *Right*: corresponding color-color diagram (Katz-Stone et al., 1993, described in Section 5.3.3).

electron energy distribution. The JP model is more realistic from a physical point of view, as an anisotropic pitch angle distribution will become more isotropic due to changes in the magnetic field strength between different regions and scattering by self-induced Alfvén waves (e.g., Carilli et al., 1991; Tribble, 1993; Slee et al., 2001). At some time t , due to radiative losses, the energy distribution of electrons becomes $N(E) = N_0 E^{-\delta} (1 - \xi E t) E^{\delta-2}$. The result is that the energy losses for both models cause the radio spectrum to steepen above a *break frequency* ν_b

$$\nu_b \propto \frac{B}{[(B^2 + B_{\text{CMB}}^2)t]^2} . \quad (2.5)$$

JP spectra have an exponential high-frequency cut-off above ν_b . KP spectra steepen to a power-law with a slope $(4/3)\alpha_{\text{inj}} + 1$ above ν_b , because there are always some high energy electrons with low pitch angles to radiate at high frequencies in the KP case. Some variations of these models, widely used in the literature, are the Tribble-Jaffe-Perola (TJP, Tribble, 1993), based on the JP one and introducing Gaussian spatial fluctuations of the magnetic field around a central value (B_0), the continuous injection (CI, Pacholczyk, 1970) model, for which a fresh supply of particles is continuously injected, and the so-called KGJP or KGKP models (Komissarov & Gubanov, 1994), where particles are injected for a fixed period of time after which the supply of newly injected electrons is switched off.

NATs

NAT sources are usually associated with galaxies moving at large velocities ($\sim 600 \text{ km s}^{-1}$, Venkatesan et al., 1994) in the gravitational potential of the cluster (Miley, 1980). The main effect acting on the radio jets is the ram pressure due to the motion of the host galaxy within the dense ICM (Begelman et al., 1979; Jones & Owen, 1979). The ram pressure is quantified $P = \rho_{\text{ICM}} v^2$, where ρ_{ICM} is the mass density of the ICM and v the velocity of the host galaxy relative to it. The pressure bends the jets backwards, warping them and leaving a tail of cosmic ray electrons along its wake. In agreement with this idea, the optical counterparts of NATs are not the bright dominant or central dominant galaxies, usually located at the center of the cluster and at rest in the cluster potential well, but rather galaxies with fainter optical magnitude and lower radio luminosity (Rudnick & Owen, 1976; Valentijn, 1979). NAT radio galaxies have the same characteristics both in rich and poor clusters in terms of jet radii of curvature, jet opening angles, internal ram pressures within the jets, jet luminosity as a fraction of total source luminosity, and ICM densities (Venkatesan et al., 1994). An ICM density typical of that found in poor clusters ($\sim 10^{-4} \text{ cm}^{-3}$) and a galaxy velocity typical of the rich clusters ($\sim 600 \text{ km s}^{-1}$) provide sufficient ICM ram pressure to bend radio jets into NAT morphologies. However, in some cases, the host galaxies of NATs have velocities similar to those of typical cluster member, rather than moving with the high peculiar velocity expected in the ram pressure scenario (Venkatesan et al., 1994). Therefore, it has been suggested that the jet bending could also be partially due to the bulk motions in the ICM induced by the cluster-subcluster(s) mergers (e.g., Bliton et al., 1998; Giacintucci & Venturi, 2009). The NATs show a wide variety of opening angles between the two jets (O’Dea & Owen, 1985) and tail length (from 30 kpc to $\sim 1 \text{ Mpc}$, O’Dea & Owen, 1985; Srivastava & Singal, 2020; Botteon et al., 2020b). The jets exhibit regions of faster and slower expansions with distance from the core, and wiggles as it traverses outward, possibly due to the development of Kelvin-Helmholtz instabilities (O’Dea & Owen, 1985; O’Dea & Owen, 1987). New sensitive observations, especially at low frequencies, are also revealing that tails often exhibit longer extensions than expected from the radiative lifetime of relativistic electrons (Sebastian et al., 2017), and frequently display disturbed morphology, especially at their terminal ends, where the tail structure breaks (van Weeren et al., 2012; Srivastava & Singal, 2020; Wilber et al., 2018; Botteon et al., 2021; van Weeren et al., 2021; Ignesti et al., 2022; Venturi et al., 2022; Lusetti et al., 2024).

Spectral index values are usually $\alpha \sim 0.3 - 0.5$ at the core, and may reach $\alpha \sim 2.0 - 4.0$ down the tail (Cuciti et al., 2018). This has been observed for most of the tails (e.g., top panel of Figure 2.5, Bruno et al., 2024), confirming the aging scenario with progressively older (and least energetic) electrons found at larger distances from the core. This trend, however, is not homogeneous: high-resolution observations are indeed showing the presence of multiple sub-structures in the tails, which reflect also in the spectral index map, proving the high complexity of these objects and their associated phenomena (Lal & Rao, 2004; Gendron-Marsolais et al., 2020).

Since their first observations, NAT radio galaxies were found to be polarized. Miley (1973) noticed that the polarization distribution of head–tail galaxies become more ordered and also the polarization fraction increases as one moves along the tail away from the host galaxy. This property was observed in most of the NATs (e.g., Miley et al., 1975; Fanti et al., 1981; Robertson, 1981; O’Dea & Owen, 1986; Mack et al., 1993; Feretti et al., 1998; Govoni et al., 2006; Govoni et al., 2010; Pizzo et al., 2011; Sebastian et al., 2017; Müller et al., 2021), and is mainly due to the interaction between radio jets and the ICM, which causes the magnetic field to be ordered with the direction of the tail. Fractional polarization values are usually around a few percent at the core, and can increase up to $\sim 60\%$ in the tail at GHz frequencies (Miley, 1973; Miley et al., 1975; Klamer et al., 2004; Murgia et al., 2016). The equipartition magnetic field estimated along the tail varies between $1 - 10 \mu\text{G}$ (O’Dea & Owen, 1987; Lal & Rao, 2004; Sebastian et al., 2017; Lal, 2020; Bushi et al., 2025).

WATs

WATs are known to have a narrow range of radio luminosity of $10^{42} - 10^{43} \text{ erg s}^{-1}$ integrated over the frequency range 10 MHz - 100 GHz (e.g., O’Dea & Baum, 2023, and references within). Consistent with the current radio source framework, described in Section 2.1.1, it is suggested that there is a minimum radio luminosity required to produce the straight, fast, well-collimated jets that extend to several tens of kpc from the core. Similarly, there is also a maximum radio luminosity required to allow the jet disruption mechanism to cause the jet-tail transition. In WATs, ram pressure effect alone cannot explain the observed curvatures, due to the very low peculiar velocities of their optical counterparts (Bird, 1994; Pinkney et al., 2000). It is then necessary to invoke alternative scenarios to explain the bent shape of WATs. Many studies suggested that the necessary ram pressure may be provided during cluster mergers, which induce large-scale bulk flows in the ICM (Pinkney et al., 1994; Roettiger et al., 1996; Sakelliou et al., 1996; Gomez et al., 1997; Sakelliou & Merrifield, 2000; Smolčić et al., 2007; Giacintucci & Venturi, 2009). Also buoyancy forces (Gull & Northover, 1973; Burns & Balonek, 1982) can play a role, especially at larger distances from the cluster center (Sakelliou et al., 1996). If the jet density is lower than the density of the surrounding medium, buoyancy forces will drag the jets toward regions of the ICM where the densities are equal.

The sudden jet-tail transition observed in the WATs is a well-known problem. Hardcastle and Sakelliou (2004) suggest that the jet-tail transition is independent from the problem of bending the tails, both because there are sources which do not show overall bending (e.g., O’Donoghue et al., 1990; Hardcastle, 1999; Jetha et al., 2005; Taylor et al., 1990) and a few WATs show bending that occurs before the jet-tail transition (e.g., Robertson, 1984; O’Dea & Owen, 1985; Burns et al., 1986; Smolčić et al., 2007). Moreover, some jets show a hot-spot at the transition, and others do not. Nevertheless, in nearly all cases, the jets are bent either at the jet-tail transition or beyond it, suggesting that the transition makes the jets easier to bend. After the jet has propagated for several tens of kpc, which is near the expected transition between the host ISM and the ICM (Sakelliou & Merrifield, 1999; Hardcastle et al., 2005; Jetha et al., 2005), the jet disruption occurs (O’Donoghue et al., 1990). Possibilities to explain this include the development of instabilities in the jet (e.g., Kelvin-Helmholtz instability, Leahy, 1984; Sakelliou & Merrifield, 1999), the transition from a high-density ISM to a lower-density ICM (Burns & Balonek, 1982; Sakelliou & Merrifield, 1999), the transition from a cool

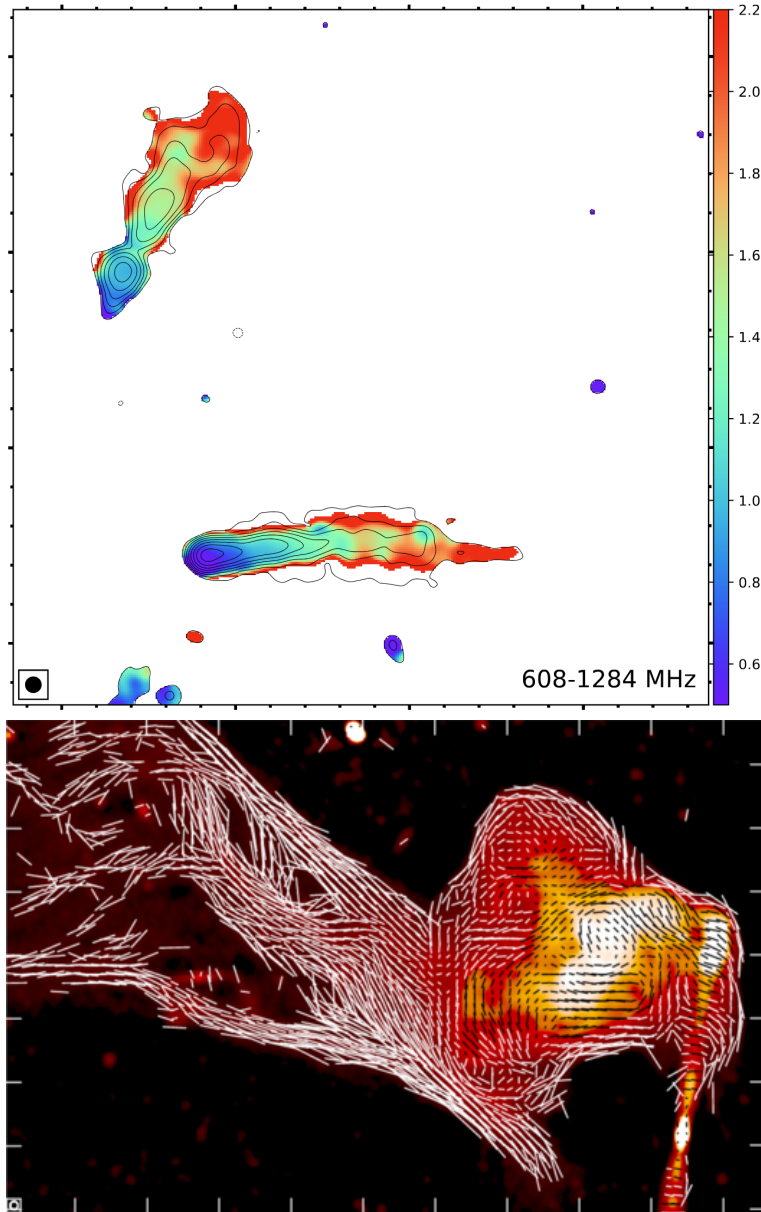


FIGURE 2.5: Polarization and spectral properties of tailed radio galaxies. *Top*: spectral index map between 608 and 1284 MHz obtained for two NAT radio galaxies in Abell 2142 (Bruno et al., 2024). *Bottom*: northern plume of the WAT radio galaxy J1712 – 2435 with Stokes I shown in color and fractional polarization B vectors showing the orientation of the magnetic field (Cotton et al., 2025).

ISM to hotter ICM (Jetha et al., 2005), the passage through a sharp pressure drop (Burns et al., 1986) or a shock (Norman et al., 1988; Loken et al., 1995). We refer to O’Dea and Baum (2023) for a complete review on these processes.

WAT show spectral steepening moving from the jets ($\alpha \sim 0.5 - 0.6$) towards the tails ($\alpha \sim 0.7 - 1.2$, O’Dea & Baum, 2023, and references within). The spectral index often does not vary in a linear fashion with distance but can have jumps in value, and regions of relatively constant spectral index. Spectral age analyses of the tails of some WATs suggest that the particle lifetimes are too short to account for the surface brightness and spectral index behavior (e.g., Feretti et al., 1985; O’Donoghue et al., 1990; O’Donoghue et al., 1993; Bempong-Manful et al., 2020). This suggests that there is jet

flow down the tails, i.e., the tail material does not just sit passively in the ICM. The jet flow can be a source of either fresh particles and/or the energy required to provide particle re-acceleration as apparently needed in the tails of some WATs. Note that the inferred jet flows do not seem to persist all the way down to the ends of the tails (Feretti et al., 1985; Katz-Stone et al., 1999). This suggests that the jets dissipate their energy along the way and likely re-accelerate particles. The deceleration of jet flow in the tails may allow buoyancy to dominate at the ends of the tails. The fractional polarization tends to be higher in the tails (tens of percent) and increases along the tails and also from the central brightness ridge to the sides of the tails, consistent with the magnetic field becoming more ordered (Burn, 1966; Cioffi & Jones, 1980). The field orientation in the jets is usually consistent with what is seen in FRI sources. An example is shown in the bottom panel of Figure 2.5 (Cotton et al., 2025). The field is usually either predominantly perpendicular to the jet axes or has a combination of perpendicular and parallel components (e.g., Bridle & Perley, 1984; Saikia, 2022, for reviews).

2.2.2 Astrophysical uses of radio galaxies for studying cluster environment

Galaxy clusters and groups tracers

Due to the role of the ICM in bending the jets of radio galaxies and the ease of detection in short exposure large radio surveys, tailed radio galaxies have been used by multiple studies to trace galaxy groups and clusters (Blanton et al., 2003; Giacintucci & Venturi, 2009; Norris & the EMU Team, 2011; Wing & Blanton, 2011; Dehghan et al., 2014; Paterno-Mahler et al., 2017). Unlike many other cluster-finding methods, whose mass limit depends on the survey depth in the cluster mass observable (such as the Sunyaev-Zel'dovich effect), bent, double-lobed radio sources can be found in associations over a wide mass range, from lower-mass groups to the most massive clusters. They are also found in a wide variety of environments, from clusters that are actively undergoing mergers (e.g., Douglass et al., 2011) to clusters that are highly relaxed on large scales (e.g., Paterno-Mahler et al., 2013). The presence of tailed radio galaxies in the local ($z \leq 0.1$) Universe is at a rate of 1-2 per cluster (Mao et al., 2009), and there is growing evidence that such associations carry on as far as redshift $z \sim 2$, at the limits of cluster detection (Dehghan et al., 2014). Based on the estimates coming from the Square Kilometre Array (SKA) pathfinders and precursors (e.g., in the area of the Australia Telescope Large Area Survey of the Chandra Deep Field-South, Dehghan et al., 2014), the future SKA will detect around 1 million NAT/WAT sources (Johnston-Hollitt et al., 2015).

Cluster magnetic field

Cluster (and group) magnetic field distribution provides important constraints on ICM transport processes and on models for the origin and evolution of their magnetic fields. An effective way to measure the cluster magnetic field strength is by using the polarization properties of both embedded radio galaxies, and radio galaxies located beyond the cluster but along a line of sight that passes through the cluster, through the so-called *Faraday rotation* effect.

This effect appears during the propagation of linearly polarized electromagnetic waves (e.g., synchrotron) in a magnetized plasma (e.g., the ICM). A linearly polarized wave can be decomposed into opposite-handed circularly polarized components. The right-handed (R) and left-handed (L) circularly polarized waves propagate with different phase velocities within the magneto-ionic material. This effectively rotates the plane of polarization of the electromagnetic wave (e.g., Govoni & Feretti, 2004). According to the dispersion relation, for a wave of angular frequency $\omega = 2\pi\nu$, the

refractive index of a magnetized dielectric medium can take two possible values

$$n_{L,R} = \left(1 - \frac{\omega_p}{\omega^2 \pm \omega \Omega_e} \right)^{1/2}, \quad (2.6)$$

where $\omega_p = \sqrt{4\pi n_e e^2 / m_e}$ is the plasma frequency, with e and m_e being the electron charge and mass, respectively, and $\Omega_e = eB / m_e c$ is the cyclotron frequency. Different refractive indices mean different propagation velocities for the left- and right-handed circularly polarized waves. Therefore, after the transition across the medium, the two circular components are out of phase with respect to those of the original radiation: the global effect, for a linearly polarized wave propagating in a magnetized plasma, is a change in the polarization angle.

The radio frequencies dominate the values of ω_p and Ω_e obtained for typical magnetic fields ($B \sim \mu G$) and gas densities ($n_e \sim 10^{-3} \text{ cm}^{-3}$) in the ICM. In the limit $\omega \gg \Omega_e$, Equation 2.6 can be approximated as

$$n_{L,R} \approx 1 - \frac{1}{2} \frac{\omega_p^2}{(\omega^2 \pm \omega \Omega_e)}, \quad (2.7)$$

thus, the difference in time of the two opposite handed waves to travel a path length dl results

$$\Delta t \approx \frac{\omega_p^2 \Omega_e dl}{\omega^3 c} = \frac{4\pi e^3}{\omega^3 m_e^2 c^2} n_e B dl \quad (2.8)$$

and the phase difference between the two signals is $\omega \Delta t$. Therefore, traveling along the cluster path length L , the intrinsic polarization angle χ_0 will be rotated by an angle $\Delta\chi = \frac{1}{2}\omega \Delta t$, resulting

$$\chi(\lambda) = \chi_0 + \Delta\chi = \chi_0 + \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^L n_e(l) B_{\parallel}(l) dl, \quad (2.9)$$

where $B_{\parallel}$ is the magnetic field component along the line of sight and λ the radiation wavelength. Usually, $\chi(\lambda)$ is written in terms of *Faraday depth* ϕ

$$\chi(\lambda) = \chi_0 + \lambda^2 \phi, \quad (2.10)$$

where

$$\phi = \frac{e^3}{2\pi m_e^2 c^4} \int_0^L n_e(l) B_{\parallel}(l) dl, \quad (2.11)$$

or, in practical units (Carilli & Taylor, 2002),

$$\phi = 0.812 \int_0^L \frac{n_e}{\text{cm}^{-3}} \frac{B_{\parallel}}{\mu G} \frac{dl}{\text{pc}} \text{ rad m}^{-2}. \quad (2.12)$$

By convention, Faraday depth is positive (negative) for a magnetic field directed toward (away) the observer. The *rotation measure* (RM) is defined as

$$\text{RM} = \frac{d\chi(\lambda^2)}{d\lambda^2}, \quad (2.13)$$

where

$$\chi = \frac{1}{2} \tan^{-1} \frac{U}{Q}. \quad (2.14)$$

The Faraday depth equals the RM at all wavelengths if there is only one source along the line of sight, which in addition has no internal Faraday rotation. Throughout the Thesis, the terms RM

and Faraday depth are used interchangeably to refer to the same physical quantity. The position angle of the polarization plane $\chi(\lambda)$ is an observable quantity, therefore, the Faraday depth of radio sources can be derived either by a linear fit to Equation 2.10 (using, at least, three frequencies, to avoid the so-called $n\pi$ ambiguity, e.g., Rand & Lyne, 1994) or by more advanced techniques, such as the *rotation measure synthesis technique* (RM synthesis, Burn, 1966; Brentjens & de Bruyn, 2005) or the *QU fitting* (O’Sullivan et al., 2012). In particular, the RM synthesis will be used later in this Thesis for polarization analysis (Chapter 5).

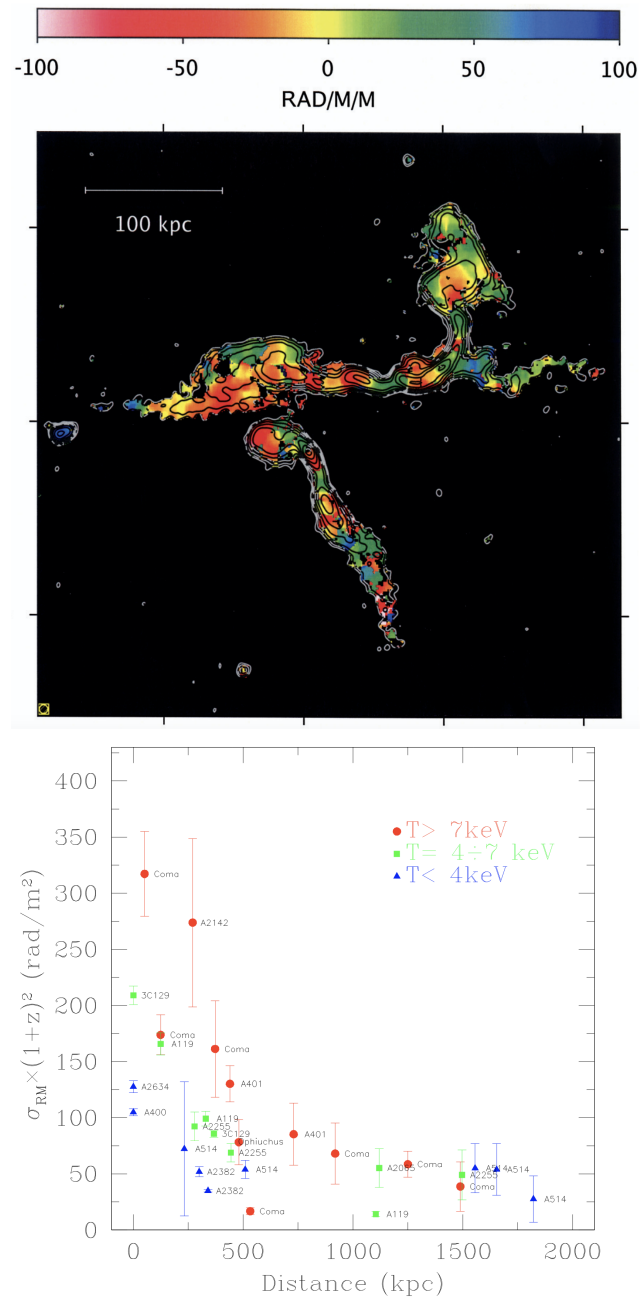


FIGURE 2.6: *Top*: rotation measure map computed using the polarization Q and U maps at the frequencies 1.46, 1.66, 4.83, and 4.88 GHz with a resolution of $5''.3$ (Guidetti et al., 2008). *Bottom*: radial profile of rotation measure distribution dispersion for different galaxy clusters (Govoni et al., 2010).

From Equation 2.12, Faraday depth of radio sources together with a model for the ICM (e.g.,

Equation 1.3) can provide important information on the cluster magnetic field responsible for the Faraday rotation effect. Faraday rotation studies of cluster-center radio galaxies in rich, cooling flow clusters found them to have high rotation measures (100s rad m^{-2} , e.g., Carilli et al., 2002, and references within). Studies of background radio galaxies have also been used to measure cluster magnetic field strengths and distributions, as well as to investigate the relationships between the cluster thermodynamic conditions and magnetic fields (e.g., Figure 2.6, Perley & Taylor, 1991; Clarke et al., 1992; Clarke et al., 2001; Murgia et al., 2004; Govoni et al., 2006; Bonafede et al., 2010; Govoni et al., 2010; Govoni et al., 2017; Anderson et al., 2021; Osinga et al., 2022; Anderson et al., 2024; Osinga et al., 2025; Pagliotta et al., 2025). The polarization properties of the jets and tails in resolved radio galaxies can also be used to probe the cluster magnetic field. Several works have used these objects to constrain the coherence length of magnetic fields in clusters on smaller scales, using Faraday rotation analysis (e.g., Figure 2.6, Feretti et al., 1995; Feretti et al., 1999; Taylor et al., 2001; Eilek & Owen, 2002; Vogt & Enßlin, 2003; Govoni et al., 2006; Guidetti et al., 2008; Laing et al., 2008; Bonafede et al., 2010; Pizzo et al., 2011; Pratley et al., 2013). Based on the estimates in Johnston-Hollitt et al. (2015), approximately 5 to 10 percent of the tailed radio galaxies to be detected with SKA should have sufficient polarization detected for such studies, and so to be used to probe the ICM magnetic field.

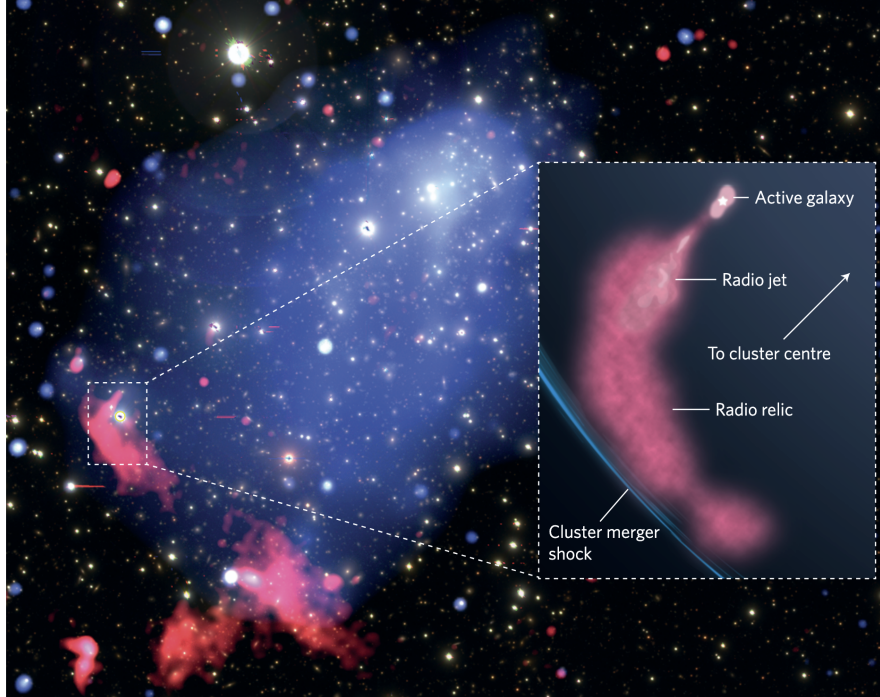


FIGURE 2.7: Composite image of cluster Abell 3411–3412 (background) and an illustration of the proposed configuration between radio galaxy and relic (van Weeren et al., 2017; Johnston-Hollitt, 2017).

Seeding of cosmic ray electrons

The evidence of diffuse radio emission in galaxy clusters, generated from a non-thermal particle population, requires the presence of fossil seed electrons to produce the observed diffuse structures (see Section 1.2, Feretti et al., 2012; van Weeren et al., 2019, for reviews). Jets from radio galaxies can store the majority of their internal energy in the form of non-thermal components (relativistic particles and magnetic fields). New, highly sensitive observations, mainly at low frequencies, are revealing

complex morphologies of remnant plasma, injected by radio galaxies and in different stages of mixing with the surrounding environment, and often in conjunction with diffuse cluster radio sources. Examples include radio halos (e.g., Wilber et al., 2018; de Jong et al., 2022; Botteon et al., 2022; Riseley et al., 2022; Gendron-Marsolais et al., 2021; Velović et al., 2023), radio relics (e.g., Bonafede et al., 2014; Shimwell et al., 2015; Botteon et al., 2016; van Weeren et al., 2017; Di Gennaro et al., 2018; Stuardi et al., 2019; Bonafede et al., 2022, Figure 2.7), and radio phoenixes (Owen et al., 2014; Duchesne et al., 2020; Mandal et al., 2020; Hodgson et al., 2021; Pandge et al., 2022; Pasini et al., 2022; Riseley et al., 2022; Raja et al., 2024). This supports the idea that the fueling of relativistic electrons from cluster radio galaxies is a key process to regulate the non-thermal energy budget of the ICM: shocks (Fermi I processes) and turbulence (Fermi II), either induced by cluster-cluster mergers or by sloshing or by the wake of a fast-moving radio galaxy, can re-accelerate these particles and generate diffuse radio emitting sources (see Brunetti & Jones, 2014; Hardcastle & Croston, 2020; Vazza & Botteon, 2024, for reviews). As pointed out in Section 2.2.1, tails often display structure breaking, providing a seeding mechanism of mildly relativistic electrons in the ICM that can be re-energized. Theoretical and numerical models suggest that present and past activity by a typical population of radio galaxies in the ICM can explain the total number of electrons required to power diffuse radio sources (Vazza & Botteon, 2024). The timescales and efficiency of the dynamics responsible for the transport of cosmic rays across the ICM are now subjects of investigation, utilizing novel numerical methodologies. Observationally, the advent of LOFAR2.0 and SKA-LOW will soon make it possible to recover the emission from older populations of cosmic ray electrons in the ICM, allowing the investigation of highly inefficient re-energization processes sustaining particle lifetimes in the ICM.

2.3 Non-thermal filaments

In a wide variety of astrophysical environments, non-thermal radio emission can be observed in the form of thin, elongated filaments. Radio filaments are not new: they have been known for years to be prominent in radio galaxy lobes (Perley et al., 1984; van Breugel et al., 1984; Owen, 1986; Hines et al., 1989; Owen et al., 2000), in radio relics (Owen et al., 2014), in the radio halos (Govoni et al., 2005; Pizzo et al., 2011), in the inner few hundred parsecs of our galaxy (e.g., Yusef-Zadeh et al., 1984; Lang et al., 1999; Yusef-Zadeh et al., 2004), and in supernova remnants (Milne, 1995). The increased sensitivity of current-generation radio interferometers (such as the SKA pathfinders and precursors) has led to a rise in the detection frequency of such features, which have become ubiquitous in radio maps. A short collection is shown in Figure 2.9. Spectacular examples are represented by the hundreds of filaments detected in the Galactic center by MeerKAT observations (Heywood et al., 2019; Heywood et al., 2022; Yusef-Zadeh et al., 2022b; Yusef-Zadeh et al., 2022a) or by the ones filling radio relics (e.g., Di Gennaro et al., 2018; Rajpurohit et al., 2020; de Gasperin et al., 2022; Rajpurohit et al., 2022c, and shown in Figure 1.5). For the aim of this Thesis, our interest resides in the filaments associated to the radio galaxies, especially in the galaxy clusters and groups environment. Filaments in the surrounding of radio galaxies have been observed for several objects, e.g. ESO 137 – 006 (Ramatsoku et al., 2020) and ESO 137 – 007 (Koribalski et al., 2024) in Abell 3627 (bottom left and right panels of Figure 2.9), Abell 1314 (van Weeren et al., 2021), IC 4296 in Abell 3565 (center right panel of Figure 2.9, Condon et al., 2021), 3C40B in Abell 194 (top left panel of Figure 2.9, Rudnick et al., 2022), NGC 507 (Brienza et al., 2022), J1331 – 3141 in Abell 3562 (Giacintucci et al., 2022). Filaments are also found in lobes, e.g. Fornax A (Maccagni et al., 2020), Centaurus A (Wykes et al., 2014), 3C 34 and 3C 320 (Mahatma et al., 2023), and tails of radio galaxies, e.g. J1712 – 2435 in Group 6489 (Figure 2.5, Cotton et al., 2025), PKS 2130 – 538 in Abell 3785 (Velović et al., 2023), NGC 741 (Rajpurohit et al., 2024), NGC 1265 in Perseus (right panel in Figure 2.3, Gendron-Marsolais et al., 2020), in buoyant AGN bubbles, e.g. NEST200047 (top

right panel of Figure 2.9, Brienza et al., 2021; Brienza et al., 2025), and also within diffuse radio emission, such as in Perseus (Figure 1.4, van Weeren et al., 2024) and Abell 2255 (Botteon et al., 2022). Finally, these filaments have been observed also in radio phoenixes, e.g. Abell 85 (center left panel of Figure 2.9, Raja et al., 2024), Abell 2593, SDSS-C4-DR3-3088, and Abell 2048 (Mandal et al., 2020).

Despite the large (and increasing) number of observations, there are some common properties among the filaments in cluster/group environments. They have lengths ranging between 10s to 100s kpc, and widths from a few kpc down to 350 – 500 pc (as observed in Perseus cluster, van Weeren et al., 2024). Spectral index is usually steep ($\alpha > 1.3$), showing, in some cases, spectral gradients along their lengths and widths, possibly due to electron aging (e.g., Ramatsoku et al., 2020; Rudnick et al., 2022; Velović et al., 2023; van Weeren et al., 2024; Brienza et al., 2025). A peculiar feature of many of these filaments is to be strongly polarized at GHz frequencies, up to 50 – 70% (e.g., Condon et al., 2021; Rudnick et al., 2022), indicating very ordered magnetic fields, usually well aligned along the filament. Several studies have also investigated the relationship between the filaments and the thermal ICM combining radio and X-rays observations. Giacintucci et al. (2022) observed the filament emerging from the tailed radio galaxy J1331 – 3141 to be parallel to an X-ray cold front, claiming that the filament forms where the tail of the radio galaxy touches the front. The fast tangential gas flow under the front can stretch the parcel of plasma enriched with cosmic-ray electrons into a narrow filament. Rudnick et al. (2022), instead, observed an X-ray dip overlapping with the filaments (Figure 2.8), indicating that shear-amplified magnetic fields, and possible accompanying cosmic-ray acceleration, in the filaments can build up pressures that could be comparable to those in the thermal ICM, and thus plausibly exclude the thermal plasma. Still, more radio and X-rays combined observations are required to clarify the relationship between these filaments and the thermal ICM.

Filamentary structures represent new opportunities for studying the physical properties and processes in the ICM, including their magnetic structure and the evolution of cosmic rays. In merger-driven flows, they can serve as probes of shear motions, which are otherwise invisible, and reveal the driving and dissipation scales of dynamic structures as the cluster evolves. Isolated filaments may also provide another site for cosmic ray acceleration in galaxy clusters. CRe re-acceleration is already required for diffuse radio structures, such as radio halos or radio relics (Section 1.2). Re-acceleration in magnetic field tubes in the backflows of radio galaxies, which would appear as filamentary features, was examined by Bell et al. (2019). They concluded that repeated encounters with weak shocks in such tubes could accelerate electrons to extremely high energies, illustrating the possibility that these mechanisms might play an important role. The seed electrons upon which the re-acceleration operates likely come from past AGN activity. Major open issues include determining whether specific filaments are linked to individual radio galaxies or the remnant of a dissipated lobe, if multiple AGN contribute to a mixed-background seed population, or if both play a role (Rudnick et al., 2022, and references within).

The origin of these structures is not yet fully understood. Nevertheless, given the wide variety of physical conditions in the filament environments, there is wide consensus that the filament formation is a natural result of dynamic magnetized astrophysical plasmas. Simulations show that extended bundles of filaments are ubiquitous in turbulent MHD flows in high- β_{pl} environments, where β_{pl} (not to be confused with β in Equation 1.3) is the plasma beta parameter defined as

$$\beta_{\text{pl}} = \frac{P_{\text{gas}}}{P_{\text{B}}} = \frac{8\pi P_{\text{gas}}}{B^2}, \quad (2.15)$$

with P_{gas} being the gas pressure, P_{B} the magnetic pressure, and B the magnetic field intensity. For

the weakly-magnetized ICM, typical values are $\beta_{\text{pl,ICM}} \sim 10^2 - 10^3$. In such environments, the transverse magnetic field pressure gradients can be balanced by the ambient pressure gradients (Porter et al., 2015). The strongest fields tend to be separated into distinct bundles of fibers, held together by the tension along the field lines: their widths can provide information about the resistivity scales in the plasma, so they are likely smaller than a kpc (Zhuravleva et al., 2019), while their lengths reflect the driving scales of the local turbulent flow (Porter et al., 2015; Vazza et al., 2018). When the turbulence is driven by highly non-isotropic dynamics, as expected in merging clusters, these structures can reach cluster scales (Vazza et al., 2018). The fiber bundles extend to increasingly larger scales via shear stretching, until at saturation the magnetic stresses approach the dynamical turbulent stresses. In this case, we expect the field strengths to scale as $\rho v^2/l$, where ρ is the density of the turbulent plasma, with a characteristic velocity v on the driving scale l . For a turbulent Mach number of 0.5, commonly assumed for the ICM (Porter et al., 2015), the maximum magnetic pressures would then be several times lower than the ICM pressure (e.g., Porter et al., 2015; Miniati & Beresnyak, 2015). The filaments are then supported by strong magnetic fields, amplified by shear stretching, and the beta plasma of the filaments $\beta_{\text{pl,f}}$ approaches unity (Rudnick et al., 2022; Churazov et al., 2026). The amplified magnetic fields have a strong impact on the propagation of relativistic electrons along the filaments. The Alfvén velocity $v_{\text{A,ICM}} = c_{\text{s,ICM}}/\beta_{\text{pl,ICM}}^{1/2}$ limits the propagation speed of electrons relative to the ICM, such that GHz-emitting electrons can travel only ~ 10 kpc relative to the underlying plasma. Yet, filaments spanning hundreds of kpc or even a few Mpc have been observed, requiring either re-acceleration mechanisms or other formation channels. Recent work by Churazov et al. (2026) argues that filaments supported by non-thermal pressure, due to the enhanced magnetic field, have Alfvén velocities $v_{\text{A,f}} = c_{\text{s,f}}/\beta_{\text{pl,f}}^{1/2} \gg v_{\text{A,ICM}}$, providing a valuable possible scenario. Along quasi-stationary filaments, electrons can propagate without experiencing adiabatic losses and with times shorter than the radiative cooling time. This implies that the energy spectrum of relativistic electrons can be largely independent of the distance from the initial source of electrons. The emission from such filaments should also be strongly polarized, due to the magnetic field being ordered along these structures.

In galaxy clusters, filaments with such properties can be formed in several ways. An example are the AGN-inflated bubbles in cool-core clusters. Observations in radio and X-rays show that these bubbles are bright in radio and dim in X-rays, suggesting that magnetic fields and relativistic particles are present, while the density of thermal plasma is significantly lower inside the bubbles (e.g., Boehringer et al., 1993); these represent then good candidates for plasma reservoirs. These bubbles evolve under the action of buoyancy (e.g., Gull & Northover, 1973; Churazov et al., 2000), and move radially in cluster atmospheres down the pressure gradient and/or due to large-scale motions of ambient thermal plasma. Buoyancy naturally produces subsonic motions (Zhang et al., 2018), and can also stretch magnetic field lines that are anchored to the bubble and the gas in the core (Churazov et al., 2026). This scenario can be relevant to objects like M87 or Nest200047. Another possibility is that filaments originate in the flows from one or more cluster non-central AGN; for example, in tailed radio galaxies such as the ones in Abell 2255 presented and discussed further in this Thesis in Chapters 4 and 5. The AGN is responsible for producing the initial volume of magnetized plasma, but the motion of the host galaxy relative to the ICM deposits the plasma in the wake of the radio galaxy. The field becomes more ordered in the far tail (Section 2.2.1), while in the vicinity of the source it might remain turbulent and tangled (similarly to the original model of Jaffe & Perola, 1973). In case of merging cluster, the turbulence can affect the relativistic plasma deposited by the radio galaxy, stretching the tangled magnetic field lines. Moreover, the galaxy motion also induces turbulence, which adds to the cluster one.

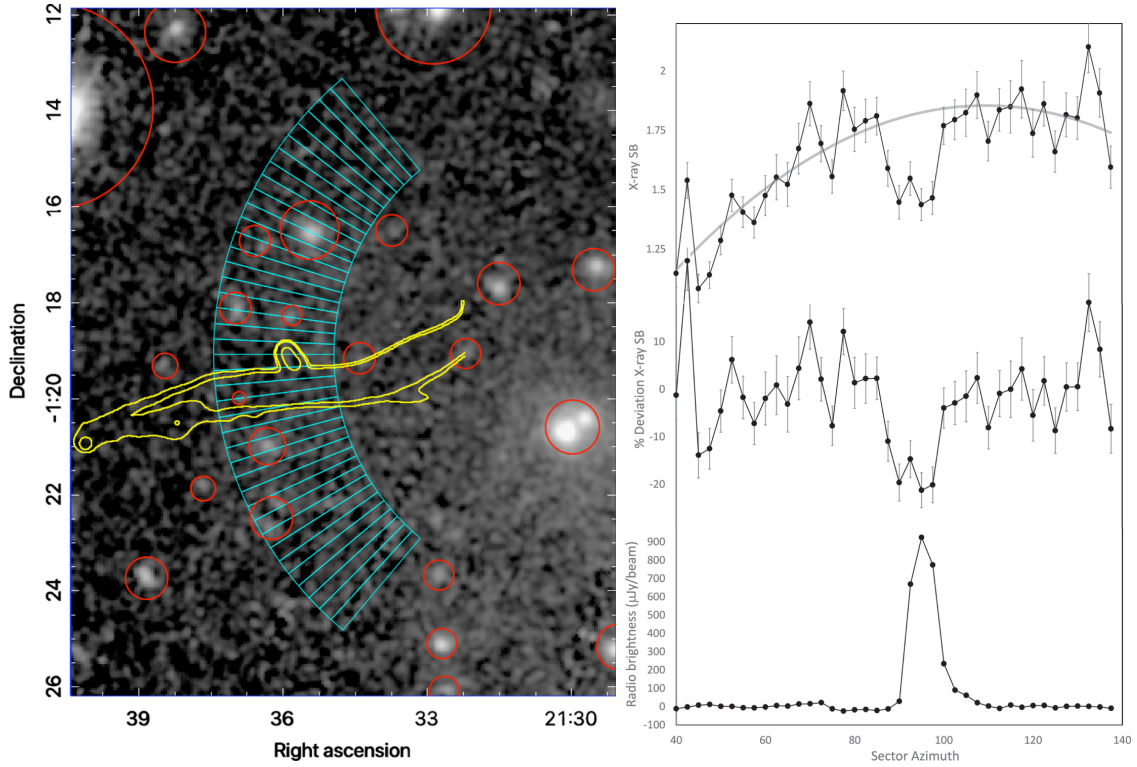


FIGURE 2.8: X-ray dip overlapping with the filaments position in Abell 194 (Rudnick et al., 2022). *Left*: XMM-Newton image overlapped with MeerKAT radio contours (in yellow). *Right*: X-ray surface brightness profile using the cyan sectors on the *left* and radio profile. A dip of $19 \pm 2\%$ in the X-ray surface brightness is coincident with the peak in the radio.

There are also other possible formation scenarios. For example, for the so-called *collimated synchrotron threads* (CSTs) in ESO 137 – 006 two different models were proposed. According to Gopal-Krishna and Biermann (2024), return currents in conjunction with a time-varying relativistic jet induce a varying electric current in the jets: this triggers the formation of zones of enhanced electric potential along the twin jets and, consequently, discharges which generate the threads observed between the radio tails. This model predicts both a magnetic field oriented along the filaments, as well as the production of ultra-high energy cosmic ray particles and high-energy neutrinos. Alam et al. (2025), instead, suggest that the CSTs (as well as many filaments in radio galaxies) most probably represent the forward shock of the AGN cocoon, either generated due to the turbulent motion at the lobe or the forward shock itself.

The formation of filaments is still an open question, and significant progress can be made from multiple perspectives. Observationally, it would be crucial to obtain polarization information for more objects, to disentangle between the formation scenarios and to better understand the magnetic field developing in cluster of galaxies. Resolution is also a key: as we proved throughout this Thesis, high-resolution (down to sub-arcsecond, Chapter 4) is important to disentangle thin filamentary structures, e.g. in tailed radio galaxies. LOFAR-VLBI represents a great tool for this, given the unique combination of high-resolution at low-frequency, with the latter required given the steepness of the filaments. MeerKAT has proven to be an excellent tool for detecting filaments, even at GHz frequencies, due to its high sensitivity. This capability is significant because most of the successful polarization observations of these filaments have only been possible with MeerKAT. The upcoming SKA-low and SKA-mid will provide exquisite sensitivities to detect these structures in a larger

number of radio galaxies and clusters, especially in polarization, even at GHz frequencies. On the other side, advanced MHD simulations are starting to reproduce the observed filaments and threads in tails (O'Neill et al., [2019a](#); O'Neill et al., [2019b](#)) and jets (Meenakshi et al., [2023](#); Upreti et al., [2024](#)) of radio galaxies. However, a detailed treatment of the ambient medium is needed (e.g., its magnetic field distribution, Cotton et al., [2025](#)), making the understanding of the mechanisms behind the formation of elongated filament-like structures a frontier topic of research.

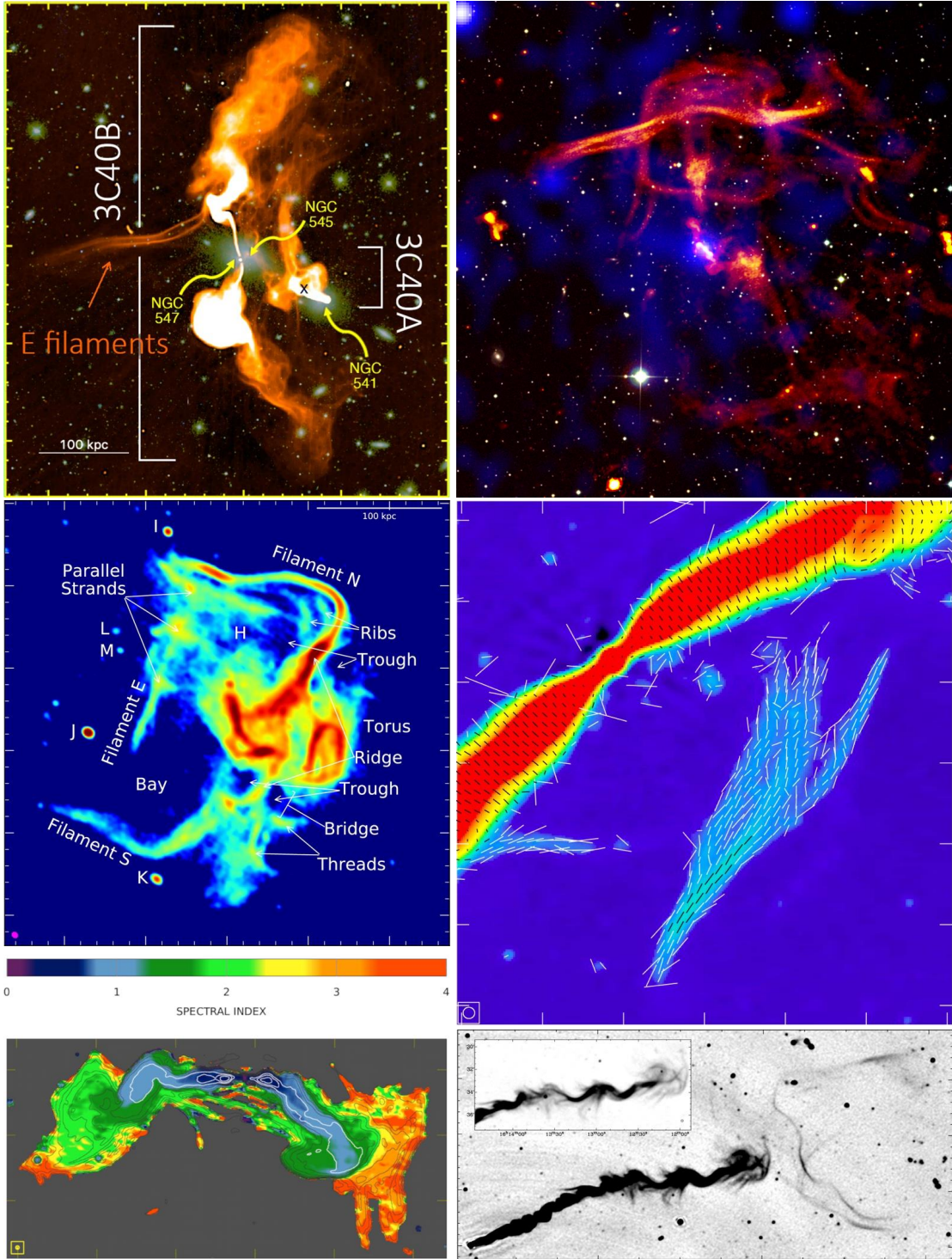


FIGURE 2.9: Examples of non-thermal radio filaments. From top left to bottom right. 3C40B in Abell 194 (Rudnick et al., 2022); the galaxy group Nest200047 (Brienza et al., 2021; Brienza et al., 2025); the radio phoenix in Abell 85 (Raja et al., 2024); fractional polarization vectors superimposed on the threads in the radio galaxy IC 4296 in Abell 3565 (Condon et al., 2021); spectral index map of the collimated synchrotron threads (CSTs) in the WAT ESO 137 – 006 in Abell 3627 (Ramatsoku et al., 2020); the helical radio tail of the Corkscrew Galaxy (ESO 137 – 007) in Abell 3627 (Koribalski et al., 2024).

Chapter 3

Radio interferometry and the International LOFAR Telescope

In this Chapter, we summarize the main theoretical principles of radio interferometry which represent the base of the whole work presented in this Thesis. After a brief description of the calibration routine, we focus on the imaging main algorithms, highlighting the mathematical formalism, which is a core step for both our scientific (Chapters 4 and 5) and computational (Chapter 6) work. We introduce then the main telescope used throughout this Thesis, namely the International LOw Frequency ARray (LOFAR) Telescope (ILT), describing its structural properties as well as the main calibration steps to generate images using its international stations.

3.1 Antenna and interferometry theory

A radio telescope works differently than any other wavelength. While at higher frequencies photons are sufficiently energetic to induce photoelectric on conventional detectors (such as a charge-coupled devices), radio telescopes exploit the wave nature of the radiation. In fact, the light is recorded as a *signal* by an antenna, a passive device that converts electromagnetic radiation into electrical currents. Given the extremely low intensities of the celestial radio signals, radio telescopes often deploy large reflectors to collect and focus power onto their antennas. The easiest example is given by a *single dish*, which is often constituted by a parabolic-shaped collecting area to focus the plane wave from a distant point source onto a single focal point. Considering a reflector antenna with an aperture D (representing its projected diameter), the angular distribution of the instrumental response is defined the *power pattern* of the antenna. For a uniformly illuminated aperture, the power pattern $P(\theta)$ can be written as the square of the field pattern

$$P(\theta) = \left(\frac{D}{\lambda}\right)^2 \text{sinc}^2\left(\frac{\theta D}{\lambda}\right). \quad (3.1)$$

Here θ indicates the direction of the point source and λ the observing wavelength. The complete derivation of this relationship is described in Condon and Ransom (2016). Notably, its derivation involved a series of approximations and theorems. These foundational principles, though not reiterated in this Thesis, are integral to the concepts that will be explored from this point forward.

- **Reciprocity theorem.** An antenna can be treated either as a receiving device, or as a transmitting device. This is true because of the time reversibility of Maxwell's equations.
- **Huygens-Fresnel principle.** The aperture can be treated as a collection of small elements which act individually as small antennas.

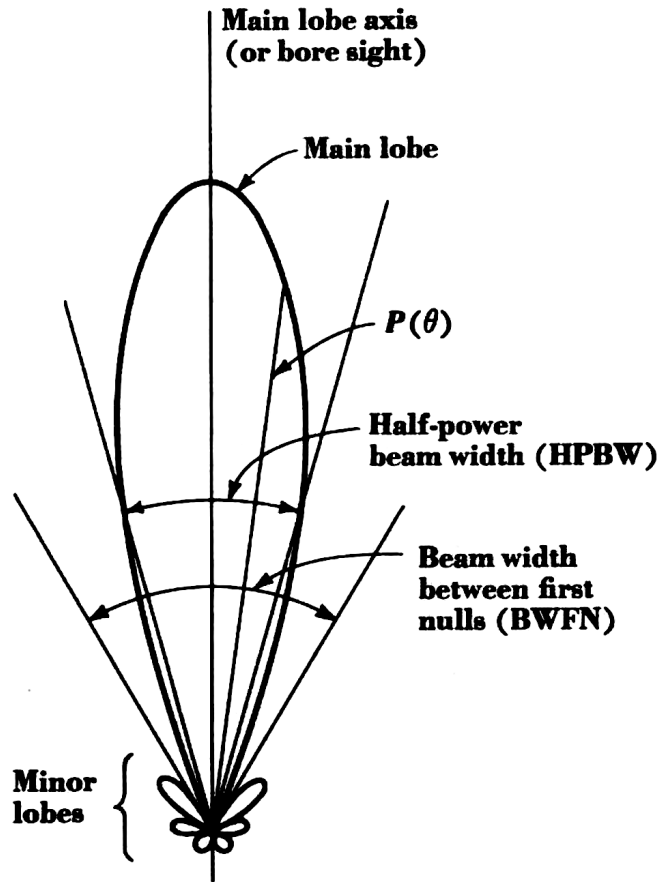


FIGURE 3.1: Example of point-source response (Kraus, 1966).

- **Far-field approximation.** The distance of the point source is much greater than the far-field distance $R_{\text{ff}} \approx \frac{2D^2}{\lambda}$, defined by requiring that the maximum departure from a plane wave is $\Delta < \lambda/16$. In this approximation, we can consider the received electromagnetic waves to be nearly planar across the reflector.

Generalizing Equation 3.1, we can state that in the far field approximation, the electric field pattern of an aperture antenna is the Fourier transform (FT) of the electric field distribution illuminating the aperture. This can be further extended in 2D, for both rectangular and circular apertures. For the latter case, the power pattern is also known as the Airy pattern. The analogue of the power pattern for a receiving antenna is called the *point-source response*. An example of point-source response is represented in Figure 3.1. The central peak between the first nulls is called main beam. The angular extent of the main beam is usually described by the half-power beamwidth (HPBW), which is the angle between points of the main beam where the normalized power pattern falls to 1/2 of the maximum (Wilson et al., 2009). This sets the angular resolution limit for the radio telescope.

$$\theta_{\text{HPBW}} \propto \frac{\lambda}{D} \quad (3.2)$$

Single dishes are diffraction-limited instruments: even an ideal aperture antenna has a finite resolving power due to the spreading of rays passing through a finite aperture. Engineering and economical limits avoid the construction of arbitrarily large dishes. Interferometry represents then a powerful solution to overcome these limitations. Combining multiple antennas, it is possible to simulate an arbitrarily large aperture, improving the resolution as well as the sensitivity of the system with

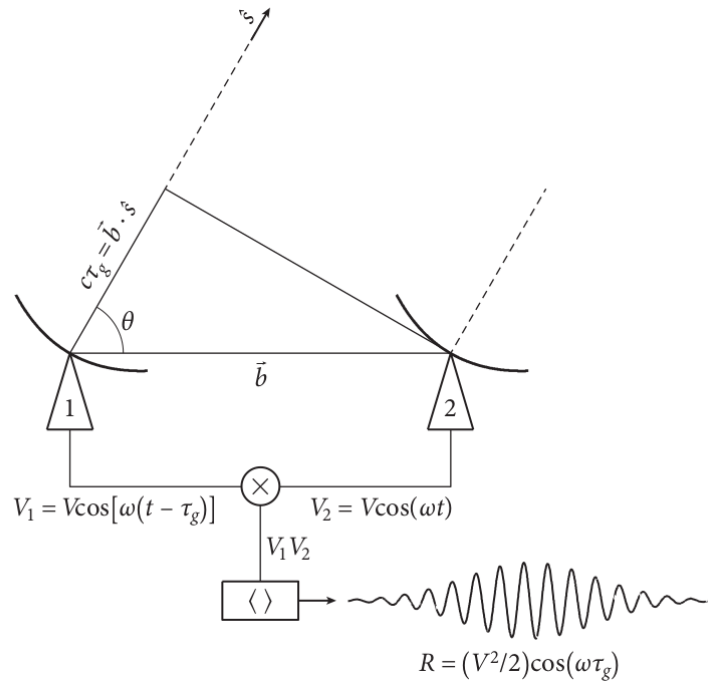


FIGURE 3.2: Example of a two element interferometer (Condon & Ransom, 2016).

respect to a single dish. The application of interferometric techniques in astronomy dates back to the late 19th and early 20th centuries, with the first optical measurements of nearby objects (Michelson, 1891; Michelson, 1920; Michelson & Pease, 1921). The use of interferometry in radio astronomy began in 1946, with the aim of measuring the radio emission coming from the Sun (Pawsey et al., 1946; Ryle & Vonberg, 1946). To formulate the fundamentals of radio interferometry, we consider hereafter the simplest example of an interferometer made by a pair of radio telescopes whose voltage outputs are correlated (two-element interferometer). Even the largest interferometers, made by N antennas, can be treated as $N(N - 1)/2$ independent two-element interferometers. Conceptually, a two-element interferometer can be seen as performing a double slit experiment on the incoming wavefront with the antennas being the slits. Figure 3.2 shows two identical dishes separated by the *baseline* vector $\vec{b}$, of length b , that points from antenna 1 to antenna 2. Both dishes point towards the same direction, specified by the unit vector $\hat{s}$, and θ is the angle between $\vec{b}$ and $\hat{s}$. Plane waves from a distant point source must travel an extra distance (with respect to antenna 2) in order to reach antenna 1, and this causes a delay in time called *geometric delay* τ_g

$$\tau_g = \frac{\vec{b} \cdot \hat{s}}{c} \quad (3.3)$$

The two output voltages of antennas 1 and 2 at time t can be written as

$$V_1 = V \cos[\omega(t - \tau_g)] \quad ; \quad V_2 = V \cos(\omega t). \quad (3.4)$$

A correlator multiplies and time averages the two outputs. The resulting output voltage of the correlator can then be approximated to

$$R = (V^2/2) \cos(\omega \tau_g) ; \quad (3.5)$$

it varies sinusoidally with the Earth's rotation, which changes the source direction relative to the

baseline vector. These sinusoids are called *fringes*. For the convolution theorem, the response R of a two-element interferometer is given by a cosinusoid multiplied by the product of the voltage patterns of the individual antennas. In case of identical antennas, this product is the power pattern of the individual antennas (sinc^2 function) and is called the *primary beam* of the interferometer; it defines the field of view of the interferometer and is equivalent to Equation 3.2, meaning that it is set by the single antenna diameter D . The angle between the fringes is the inverse of the length of the baseline (in unit of λ) projected onto a plane normal to the direction of the source

$$\theta_{\text{FWHM}} \approx \frac{\lambda}{b \sin \theta} . \quad (3.6)$$

It measures the full-width at half-maximum (FWHM) of the *synthesized beam* and defines the angular resolution of the interferometer. Long baselines have a narrower angular fringe spacing projected on the sky, meaning that their response is sensitive to very compact objects; on the other hand, shorter baselines have a larger angular fringe spacing, being sensitive to extended objects. The array minimum projected baseline defines the *largest angular scale* (LAS) that can be detected. A multi-element interferometer with N antennas has $N(N-1)/2$ unique responses. The instantaneous synthesized beam projected on the sky is then the arithmetic mean of the individual responses of its component two-element interferometers. The synthesized beam, that approaches a Gaussian with increasing number of responses (so the number of antennas), is also known as *dirty beam*.

So far, we have considered for simplicity only a cosine correlator (R_C). To derive the full power of a source we need to compute also the sine correlator output (R_S). The combination of cosine and sine correlators is called *complex correlator*. The complex visibility is defined as

$$V \equiv R_C - iR_S = Ae^{-i\phi} \quad (3.7)$$

$A = \sqrt{R_C^2 + R_S^2}$ is the visibility amplitude, and $\phi = \tan^{-1}(R_S/R_C)$ is the visibility phase. If the source is slightly extended, with a sky brightness distribution $I_\nu(\hat{s})$ at frequency ν , the response is obtained by treating the extended source as the sum of independent point sources. As a result, we can write the response of the interferometer with a complex correlator to any source as the Fourier transform of the sky brightness distribution

$$V_\nu = \int I_\nu(\hat{s}) \exp(-i2\pi \vec{b} \cdot \hat{s}/\lambda) d\Omega , \quad (3.8)$$

with $d\Omega$ representing the solid angle subtended by a small element of the radio source in direction $\hat{s}$. This relationship is a direct consequence of the van Cittert-Zernike theorem (Born & Wolf, 1999). The sine and cosine correlators represent the polarization of the instrument, which can usually be linear (X and Y , such as in LOFAR) or circular (R and L).

3.2 Calibration

For a multi-element interferometer, data from each antenna pair are recorded. We refer to these as *observed visibilities* and use the symbol $\tilde{V}_{ij}$, where i and j represent the antenna pair to which the visibility refers. The observed visibilities usually differ from the *true visibilities*, identified with V_{ij}^{true} , for a multitude of reasons. To measure and remove these effects, which are mainly instrumental and atmospheric, a process known as *calibration* is required.

The basic relationship between $\tilde{V}_{ij}$ and V_{ij}^{true} , also known as *radio interferometry measurement equation* (Hamaker et al., 1996), is linear and can be written as

$$\tilde{V}_{ij} = G_{ij}(t)V_{ij}^{\text{true}}(t) + \epsilon_{ij}(t) + \eta_{ij}(t) , \quad (3.9)$$

where t is the time of the observation, $G_{ij}(t)$ is the baseline-based *complex gain*, $\epsilon_{ij}(t)$ is a baseline-based complex offset, and $\eta_{ij}(t)$ is a stochastic complex noise (Fomalont & Perley, 1999). The complex gain term encompasses all the effects that corrupt the true visibilities. The term G_{ij} is also known as *Jones matrix* (Jones, 1941), and can also be factored into the sequence of specific corrupting effects, each having their own particular (relative) importance and physical origin, which determines their unique algebra. Most of the effects contained in (indeed, the most important of them) are antenna-based, i.e., they arise from measurable physical properties of (or above) individual antenna elements in a synthesis array. Including the most commonly considered effects and assuming the terms $\epsilon_{ij}(t)$ and $\eta_{ij}(t)$ to be zero, Equation 3.9 can be written as

$$\tilde{V}_{ij} = K_{ij}B_{ij}J_{ij}D_{ij}E_{ij}P_{ij}T_{ij}F_{ij}V_{ij}^{\text{true}} . \quad (3.10)$$

Here:

- K_{ij} baseline-based correlator (non-closing) errors.
- B_{ij} *bandpass* (frequency-dependent) response, such as that introduced by spectral filters in the electronic transmission system.
- J_{ij} electronic amplitude and phase gain response due to components in the signal path between the feed and the correlator.
- D_{ij} instrumental polarization response, describe the polarization leakage between feeds.
- E_{ij} antenna voltage pattern.
- P_{ij} parallactic angle.
- T_{ij} tropospheric effects.
- F_{ij} ionospheric Faraday rotation.

Quantitatively, we can see then the calibration as the procedure to calculate all these complex terms constituting G_{ij} to invert Equation 3.10 and derive the true visibilities V_{ij}^{true} . To accomplish this, we can use fundamental assumptions.

- Most of the aforementioned effects (apart from K_{ij}) are antenna-based, hence the cross-correlation between antennas i and j can be safely ignored, i.e. $G_{ij} = G_i G_j^*$.
- temporal and frequency dependence are only slightly coupled, so their variations can be determined independently, namely $B_i(\nu, t) = B_i(\nu)$ and $J_i(\nu, t) = J_i(t)$.

As shown in Equation 3.7, visibilities are complex numbers characterized by an amplitude A and a phase ϕ . Gain terms also have amplitudes a and phases θ . For a multi-element interferometer having N antennas, Equation 3.9 yields $N(N-1)/2$ equations, meaning that the system is solvable. Considering first the phase relationships from Equation 3.9, we can write

$$\tilde{\phi}_{ij} = \theta_i - \theta_j + \phi_{ij}^{\text{true}} . \quad (3.11)$$

For three antennas i, j, k , the phase closure relationship is

$$\tilde{\phi}_{ij} + \tilde{\phi}_{jk} + \tilde{\phi}_{ki} = \phi_{ij}^{\text{true}} + \theta_i - \theta_j + \phi_{jk}^{\text{true}} + \theta_j - \theta_k + \phi_{ki}^{\text{true}} + \theta_k - \theta_i \quad (3.12)$$

$$= \phi_{ij}^{\text{true}} + \phi_{jk}^{\text{true}} + \phi_{ki}^{\text{true}}. \quad (3.13)$$

The combination of the three correlator output phases constitutes an observable quantity that depends only on the phase of the visibility (Jennison, 1958). We need then to define a reference antenna, whose phase for both polarization is arbitrarily fixed to zero. An amplitude closure relationship involves four antenna pairs, for which four antennas i, j, k , and l are required

$$\frac{\tilde{A}_{ij}\tilde{A}_{kl}}{\tilde{A}_{ik}\tilde{A}_{jl}} = \frac{a_i a_j A_{ij}^{\text{true}} a_k a_l A_{kl}^{\text{true}}}{a_i a_k A_{ik}^{\text{true}} a_j a_l A_{jl}^{\text{true}}} = \frac{A_{ij}^{\text{true}} A_{kl}^{\text{true}}}{A_{ik}^{\text{true}} A_{jl}^{\text{true}}}. \quad (3.14)$$

The first corrupting effects that need to be corrected are thus introduced by the observing system. This is achieved by observing bright calibrator sources whose spatial structure, flux density, and (if required) polarization properties are well known. Typically, such a source is referred to as *primary calibrator* or *bandpass calibrator*. The practical idea is based on the fact that the true visibilities for such sources have been previously modeled V_{ij}^{model} , so that

$$\tilde{V}_{ij} = G_{ij} V_{ij}^{\text{model}}; \quad (3.15)$$

since $\tilde{V}_{ij}$ and V_{ij}^{model} are known, we can derive G_{ij} , required to solve Equation 3.9.

Before reaching the telescope, radio waves are already distorted by terrestrial effects. At gigahertz frequencies this is mainly absorption from water vapor, while at lower frequencies the ionospheric effects become dominating (de Gasperin et al., 2018). The correction for these effects is done through so-called *phase referencing*. An ideally point-like source, close to the target of interest, is used to calibrate the visibility phases: this is based on the assumption that the atmosphere equally affects the phase calibrator and the target, given that the two sources are close in the sky plane. This source is usually known as *secondary calibrator* or *phase calibrator*. For mechanical telescopes, such as the *K. Jansky Very Large Array* (VLA) or the *upgraded Giant Meterwave Radio Telescope* (uGMRT), both used further in this Thesis (Chapter 5), this means occasionally pointing this source. For telescopes such as the International LOFAR Telescope (ILT, van Haarlem et al., 2013), the field of view is so large that the phase reference easily fits within the primary beam. The phases of the target are corrected by interpolating the phase solutions of the phase calibrator at the time of the scan on the target.

3.3 Interferometric imaging

The natural Cartesian coordinate system for expressing Equation 3.8 is the so-called uv plane (Figure 3.3). This is perpendicular to the source direction $\hat{s}_0$ (*phase center*), and represents the distribution of the projected baselines (in units of λ) as seen from a source at infinity. The baseline vector $\vec{b}$ has components (u, v, w) in a right-handed coordinate system, where w is chosen to be in the direction of the phase center. The arbitrary unit vector $\hat{s}$ has components (l, m, n) , which are *direction cosines*. Here, $n = \cos \theta = \sqrt{1 - l^2 - m^2}$. On Fourier transformation, the phase reference position becomes the origin of the derived intensity distribution $I(l, m)$, where l and m are measured with respect to the axes u and v . In terms of these coordinates, we can write then the three-dimensional

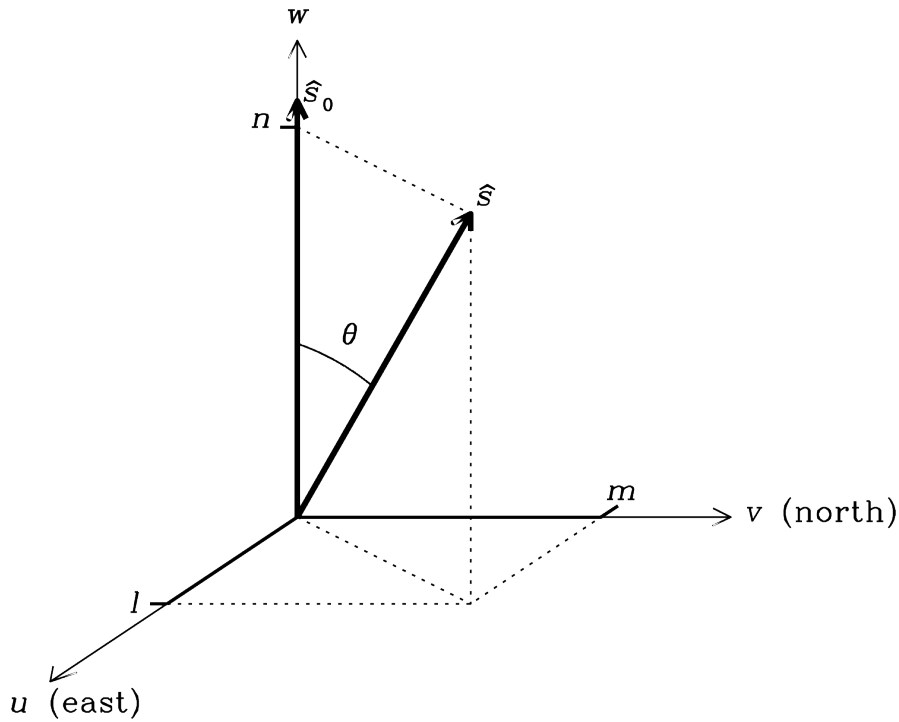


FIGURE 3.3: The (u, v, w) coordinate system for interferometers. The w -axis points in the reference direction $\hat{s}_0$ usually containing the source to be imaged. Projected onto the plane normal to the w -axis, u is the east–west baseline in wavelengths and v is the north–south baseline in wavelengths. l , m , and n are projections of the unit vector $\hat{s}$ onto the u -, v -, and w -axes, respectively. (Condon & Ransom, 2016).

generalization of Equation 3.8

$$V_\nu(u, v, w) = \iint \frac{I_\nu(l, m)}{\sqrt{1 - l^2 - m^2}} e^{-i2\pi[ul + vm + w(\sqrt{1 - l^2 - m^2} - 1)]} dl dm \quad (3.16)$$

The complete description of the transformations and relationships between the coordinates can be found in Thompson et al. (2017). Inverting this relationship, we see how it is possible, from the sampled visibility function, to obtain the distribution of surface brightness on the plane of the sky. In the following, we examine the practical computational approach to reconstruct it. A brief schematic view is shown in Figure 3.4.

3.3.1 Gridding

Multi-element arrays, especially the more modern ones, are capable of sampling millions to billions of visibilities. Using a direct FT approach, given these enormous numbers, is computationally expensive. For this reason, the preferred method requires interpolating the data onto a regular grid, so that a fast Fourier transform (FFT, Cooley & Tukey, 1965) algorithm can be used¹. This interpolation is known as *gridding* (Briggs et al., 1999). One disadvantage of this operation is that the sampled visibilities are not naturally displaced on a regular grid. This grid, similar to pixels in an image, consists of cells $\Delta u \times \Delta v$ in size, within which visibilities are grouped to a single value. There are many ways to achieve this interpolation (Thompson & Bracewell, 1974), and a complete description is beyond the scope of this Thesis. The best approach is to convolve the

¹For a grid $N \times N$, the number of operations goes as $\mathcal{O}(N^4)$ for direct FT, while for an FFT algorithm is only $N^2 \log_2 N$

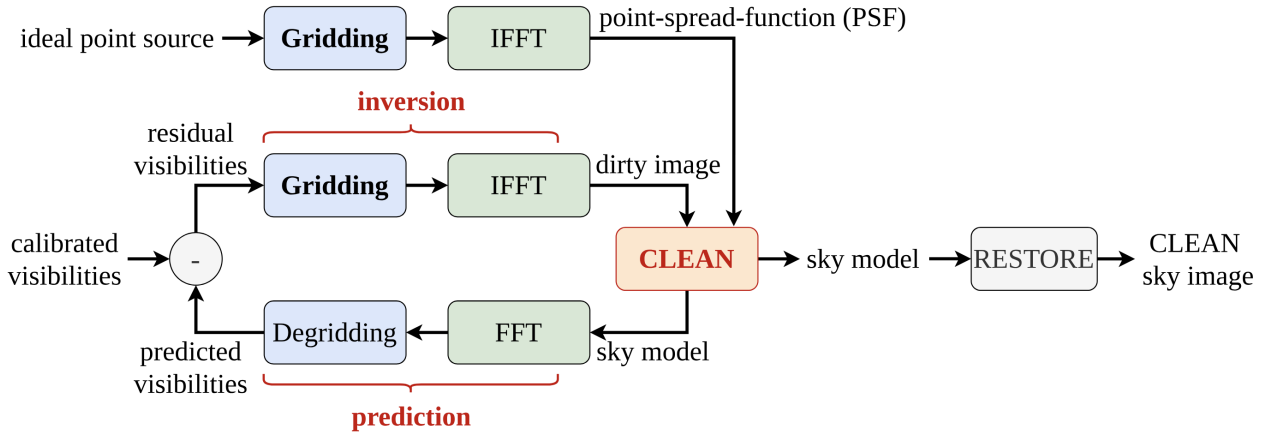


FIGURE 3.4: High-level schematic of the radio-astronomical imaging step. The three main phases, inversion, prediction, and deconvolution (or CLEAN) are highlighted in red. The critical kernel, the gridding, is included in the inversion step (highlighted in bold, Corda et al., 2022).

sampled visibilities with a function $C(u, v, w)$. This function is usually chosen to have a FT that drops off very rapidly beyond the edge of the image: examples are a truncated sinc (O’Sullivan, 1985), a Gaussian, or a Kaiser-Bessel (Jackson et al., 1991) function.

3.3.2 The non-coplanar baseline effects and the w -stacking algorithm

For small fields of view, Equation 3.16 can be simplified by the approximation that $\sqrt{1 - l^2 - m^2} \sim 1$: the relationship between the sky brightness and the visibility function then becomes a two-dimensional Fourier transform (Cornwell & Perley, 1992)

$$V_\nu(u, v) \approx \iint I_\nu(l, m) e^{-i2\pi[ul+vm]} dldm \quad (3.17)$$

When this assumption does not hold it is not possible to estimate the sky brightness by simple Fourier inversion of the sampled visibilities. In general, neglecting the phase term in w will always result in a phase error which degrades the quality of the image. To a first approximation, this error can be written as

$$\phi_w \sim \pi w(l^2 + m^2) \quad (3.18)$$

The w -term can be neglected, and two-dimensional imaging employed, if this phase error is much less than unity. This condition can also be seen as

$$\frac{\lambda b_{\max}}{D^2} \ll 1 \quad (3.19)$$

We note that this condition is not respected for longer wavelength, longer baselines or small antenna aperture (or wide FoV). For example, LOFAR is characterized by low-frequency observations with large FoV (Section 3.4.1), requiring a full three-dimensional treatment of the imaging problem (Equation 3.16). Many solutions have been proposed to approximate this problem, due to *non-coplanar baselines* (Cornwell & Perley, 1992). The conceptually simplest approach is to extend Equation 3.16 to a full 3D FT (Perley, 1999). This method allows the 3D shape of the visibility distribution to be maintained, enabling the data to be gridded into a visibility cube or even processed using a direct FT, which bypasses the need for gridding entirely (Smith et al., 2017). However, the main drawbacks are the necessity of three-dimensional deconvolution and the fact that for arrays characterized

by long baselines on a curved surface (such as the ILT), the discrete visibilities fill the visibility volume very sparsely, resulting in only a small number of non-zero gridded visibilities (Cornwell et al., 2008). Another approach is to divide the sky into small pieces where the local variation of w is negligible or acceptably small. This comprises the w -projection (Cornwell et al., 2008), the w -stacking (Humphreys & Cornwell, 2011; Offringa et al., 2014), or the w -gridder (Arras et al., 2021; Ye et al., 2022). Given its relevance for this Thesis work, we focus in particular on describing the w -stacking algorithm, which is used by the w -stacking CLEAN (WSCLEAN, Offringa et al., 2014; Offringa & Smirnov, 2017) as well as by our code (Section 6.3).

Differently from the w -projection (Cornwell et al., 2008), which uses a w -plane dependent convolution function, the w -stacking algorithm uses a w -dependent grid with samples being gridded to the grid corresponding to the nearest w -plane. We can re-write Equation 3.16 as

$$V_\nu(u, v, w) = \int \int \frac{I_\nu(l, m)}{\sqrt{1-l^2-m^2}} e^{-i2\pi w(\sqrt{1-l^2-m^2}-1)} \times e^{-i2\pi(ul+vm)} dldm \quad (3.20)$$

which can be inverted to get

$$\frac{I_\nu(l, m)}{\sqrt{1-l^2-m^2}} = e^{i2\pi w(\sqrt{1-l^2-m^2}-1)} \int \int V_\nu(u, v, w) e^{i2\pi(ul+vm)} dudv. \quad (3.21)$$

Integrating both sides over $w_{\min}$ to $w_{\max}$, minimum and maximum values of w respectively, results in

$$\frac{I_\nu(l, m)(w_{\max} - w_{\min})}{\sqrt{1-l^2-m^2}} = \int_{w_{\min}}^{w_{\max}} e^{i2\pi w(\sqrt{1-l^2-m^2}-1)} \int \int V_\nu(u, v, w) e^{i2\pi(ul+vm)} dudvdw. \quad (3.22)$$

Through gridding, the parameters u , v , w are discretized, so that the integration over u and v can become an inverse FFT and the integration over w becomes a summation. The discretization of w defines the number of w -layers that need to be processed. Recalling Equation 3.19, we request that the phase difference between two subsequent discretized values, w_A and w_B , is less than one radian. This results in the constraint

$$|(w_A - w_B)2\pi(\sqrt{1-l^2-m^2}-1)| \ll 1, \quad (3.23)$$

suggesting that a uniform discretization in w is optimal, in contrast to Cornwell et al. (2008). Following this, the required number of layers can be derived and is given by

$$N_{w\text{-layers}} \gg 2\pi(w_{\max} - w_{\min}) \max_{l,m} (1 - \sqrt{1-l^2-m^2}). \quad (3.24)$$

Once gridding is complete, each plane is Fourier transformed separately, a direction-dependent phase correction is applied for that offset value of w , as $e^{i2\pi w(\sqrt{1-l^2-m^2}-1)}$, and finally all planes are summed. This has the benefit of decreasing from one to two orders of magnitude the gridding operations, at the cost of increased memory usage and the need to perform a greater number of Fourier transforms, one for each w specific grid.

3.3.3 Deconvolution

Interferometric observations can sample only a finite number of visibilities, due to the limited number of antennas (and therefore baselines), limited bandwidth, or finite observing time, meaning that the synthesized beam will be degraded, far from a Gaussian. The image produced by inverting Equation 3.16 (or, for w -stacking algorithm, from Equation 3.22), is also known as the *dirty image*, and will be contaminated by the sidelobes of the synthesized beam (also known as *dirty beam*). The

simplest form of the dirty beam is obtained by considering a *sampling function* expressed in terms of the 2D Dirac delta function

$$S(u, v) = \sum_{k=1}^M \delta(u - u_k, v - v_k) . \quad (3.25)$$

This function defines the distribution of sampled visibilities on the uv plane, so-called *uv coverage*. We can then write the *sampled visibility function* as $V^S(u, v) \equiv S(u, v)V(u, v)$. Substituting the sampled visibility function in Equation 3.17 we find

$$I_\nu^D = \iint S(u, v) V_\nu(u, v) e^{i2\pi(ul+vm)} dudv , \quad (3.26)$$

highlighting the Fourier transform relationship between the sampled visibility function and the dirty image I^D . By the convolution theorem

$$I^D = \mathcal{F}(SV) = \mathcal{F}(S) \otimes \mathcal{F}(V) , \quad (3.27)$$

where $\otimes$ denotes convolution and $\mathcal{F}$ the Fourier transform operator. We can then see the observed brightness I^D as the true brightness I (FT of the true visibility function) convolved with the dirty beam B^D , which is the FT of the sampling function. One way to improve the sampling function, and thus the dirty beam, is to use the Earth-rotation aperture synthesis. Each projected baseline corresponds to a couple of points on the uv plane (considering also its complex conjugate): the Earth's rotation varies the projected baseline coverage of the interferometer elements, resulting then in more sampling.

Still, the finite sampling of the uv plane, and the consequent presence of sidelobes in the dirty beam, imply unavoidable confusion over the true distribution of any emission in the dirty image, which can be resolved only either by making further observations (mostly implausible) or by introducing a priori information. *Deconvolution* tackles this issue, aiming at removing the sidelobe structures introduced by B^D . A simple, but still widely used, approach in radio interferometry is the CLEAN algorithm (Högbom, 1974). After making the dirty image, the idea is to iteratively subtract a scaled version of the dirty beam to build up a model of the sky, which is then *restored* using a *clean beam* (or *restoring beam*). We summarize in the following the main steps; a visual representation of some of these quantities is found in Figure 3.5.

1. Find strength and position of the peak in the dirty image I^D at position (x, y) .
2. Subtract from the dirty image, at the position of the peak, the dirty beam B^D multiplied by the peak strength and a factor $\gamma \leq 1$, usually termed the *loop gain*.
3. Record the position and magnitude of the point source subtracted in a model. These are called *clean components* I^C .
4. Go to (1) unless any remaining peak is below some user-specified threshold. The remainder of the dirty image is now termed *residuals* I^R .

$$I^R(x, y) = I^D(x, y) - \gamma B^D(x, y) \otimes I^C(x, y) \quad (3.28)$$

5. Convolve the point source model with an idealized clean beam B^C , usually an elliptical Gaussian fitted to the central lobe of the dirty beam.

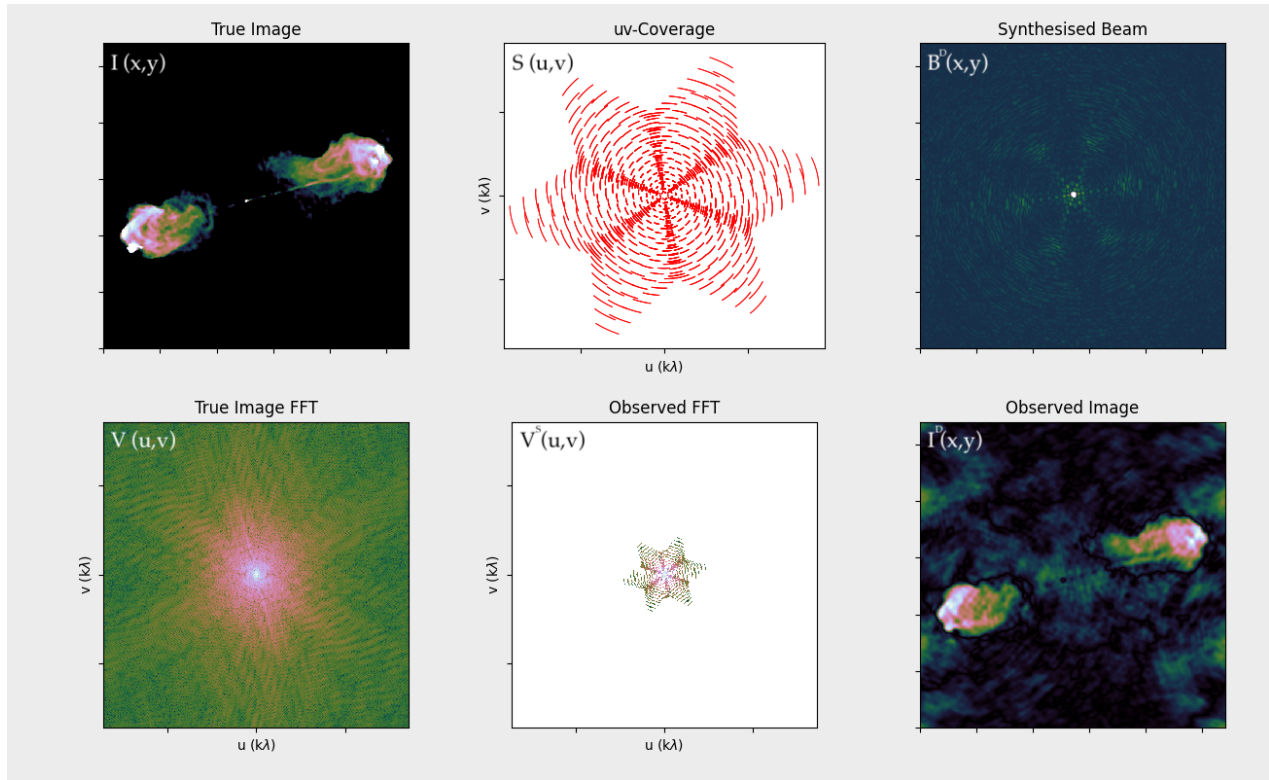


FIGURE 3.5: Representation of the relationship between the observed visibilities and the brightness distribution. Example for a simulated 1 hour observation with VLA (A-configuration, 1520 MHz) of Cygnus A. From *top to bottom*, from *left to right*. True image $I(x, y)$; sampling function $S(u, v)$; dirty beam $B^D(x, y) = \mathcal{F}(S(u, v))$; dirty image $I^D(x, y) = \mathcal{F}(S(u, v) V(u, v))$; sampled visibility function $V^S(u, v) = S(u, v) V(u, v)$; visibilities corresponding to the true image $V(u, v) = \mathcal{F}(I(x, y))$. Credits: THE FRIENDLY VIRTUAL RADIO INTERFEROMETER ².

6. Add the residuals of the dirty image to the CLEAN image formed in (5) (*restoration* step).

$$I(x, y) = I^C(x, y) \otimes B^C(x, y) + I^R(x, y) \quad (3.29)$$

This algorithm was then expanded by Clark (1980) introducing two cycles, a *major* and a *minor* cycle. In the minor cycle, a classic Högbom CLEAN is performed for several iterations. Then, in a major cycle, the point source model found in the minor cycle is transformed via an FFT, multiplied by the sampling function, transformed back, and subtracted from the dirty image. Further developments came from (Schwab, 1984), with a variant of the Clark algorithm in which the major cycle subtraction of CLEAN components is performed on the ungridded visibility data, accommodating direction-dependent effects (DDE) CLEANing simultaneously separate but proximate fields. Multiscale CLEAN (Bhatnagar & Cornwell, 2004; Cornwell et al., 2008; Offringa & Smirnov, 2017) was developed to deal with extended objects, where extended sources are recovered using extended components instead of Dirac components. The idea is to convolve the dirty image with scaling functions having a finite extension in order to be able to use CLEAN boxes. A paraboloid is generally preferred as a scaling function. Alongside CLEAN, other algorithms have been or are being explored as well; more details are provided in Section 6.2.

3.3.4 Self-calibration

After calibrating a data set using the observed calibrator sources (Section 3.2), there may be residual phase and/or amplitude errors in the calibrated data of the target source that degrade the image quality. Calibration of the visibility amplitude is usually accurate to a few percent or better, but phase errors may be much larger, sometimes as a result of ionospheric or tropospheric variations, often dominating the overall variation of the antenna gains. Hence, the effects on $g_i(t)$ cannot be completely removed and residual errors remain. *Self-calibration* is the process of using a model of the target source to reduce the phase and amplitude errors in the visibilities of the same target source. The basic principle of self-calibration is to allow the antenna gains to be free parameters and to use the source itself to bootstrap the calibration (Pearson & Readhead, 1984; Cornwell & Fomalont, 1999). The whole procedure can be summarized in an iterative scheme.

- Create an initial model of the target source, either from deconvolution or from other constraints. Ideally, the source should have enough signal-to-noise ratio: it is suggested to have at least $S/N > 3$ for phase-only self-calibration, and $S/N > 10$ for amplitude self-calibration.
- Calibrate the data against this model. One convenient method (Schwab, 1980) is to minimize, by adjusting the complex element gains g_i and g_j (recalling Equation 3.9), the sum of squares of residuals

$$S = \sum_k \sum_{i \neq j} |V_{ij}(t_k) - g_i(t_k)g_j^*(t_k)\mathcal{F}(I_{ij}^C)(t_k)|^2, \quad (3.30)$$

where V_{ij} are the calibrated visibilities and $\mathcal{F}(I_{ij}^C)$ is the Fourier transform of the clean components. t_k is the data averaging time used to obtain the values of g .

- Image the corrected data and create a new model.
- Go to (2), unless satisfied with the current model.

3.4 International LOFAR Telescope calibration and imaging technique

The work in this Thesis is mainly based on data from the ILT. In this Section, we define the main properties of LOFAR and briefly detail the calibration and imaging strategies that have been developed in the past decade to deal with low-frequency observations, and that were used for this Thesis. Special attention will be paid to the LOFAR's more distant stations, which provide a unique, sub-arcsecond resolution at such low-frequencies. Calibrating and imaging these data for cluster radio galaxies, as well as exploiting the subsequent scientific outcome, has been the primary goal of my work.

3.4.1 The International LOFAR Telescope

LOFAR is a pan-European interferometer that operates in the low-frequency regime. It currently consists of 52 stations spread throughout Europe (Figure 3.6). 38 stations are in the Netherlands: 24 *core* stations (CS) are located within 4 km of the array center in Exloo, and another 14 *remote* stations (RS) with baselines up to 120 km. 14 *international* stations (IS) are located in several European countries: six of which are in Germany, three are in Poland, and one each is in the UK, France, Sweden, Ireland and Latvia (Morabito et al., 2022). Furthermore, two additional stations are planned to be constructed in Italy and Bulgaria, improving the sensitivity and uv coverage. Data calibration and imaging using the LOFAR IS will be the main topic of the Thesis. Each LOFAR station is equipped with two sets of antennas: the Low Band Antennas (LBA), operating between 10

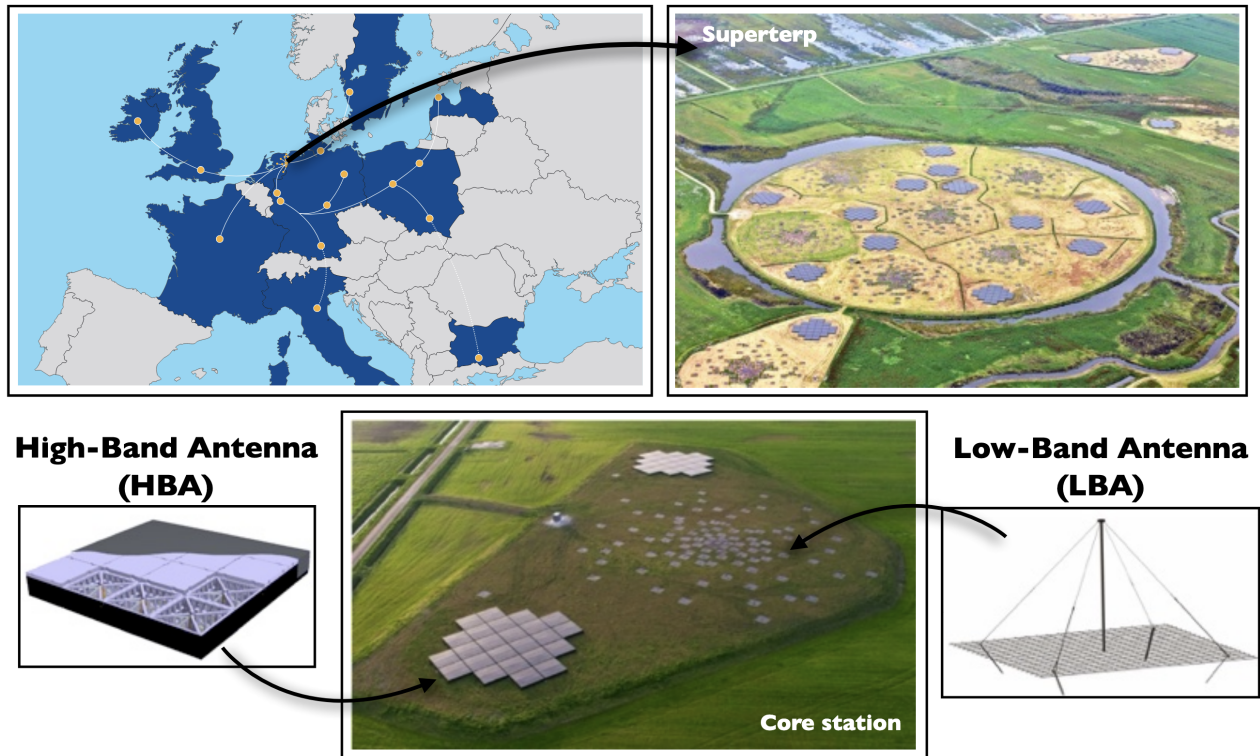


FIGURE 3.6: Global view of the LOFAR telescope. *Top left*: distribution of the LOFAR stations, identified with yellow points on the map. *Top right*: the *Superterp*, center of the LOFAR telescope located in Exloo (the Netherlands). *Bottom*: example of a LOFAR core station, with a high-band antenna (HBA, on the left) and a low-band antenna (LBA, on the right).

and 90 MHz, and the High Band Antennas (HBA), operating between 110 and 250 MHz. Given that our work was based on LOFAR data in HBA, we will avoid covering the topics related specifically to the LBA. Each station can have different number of antenna tiles: Dutch stations (both CS and RS) have 48 antenna tiles, while IS have 96. The effect of this difference will be underlined later on this Section. Following Equation 3.6, the Dutch stations (CS+RS) provide an angular resolution of $\sim 6''$ at 144 MHz while, including also the IS, baselines increase up to 1989 km, yielding an angular resolution of $0.27''$ at 150 MHz. LOFAR makes use of the phased-array technology (Herd & Conway, 2016), where signals from many individual dipoles are combined electronically, allowing LOFAR to point any direction in the sky by introducing time delay in the data, but without physically moving the antennas. Electronic beam-forming techniques make the system agile and allow for rapid re-pointing of the telescope as well as the simultaneous observation of multiple, independent areas of the sky (e.g., in HBA, up to 488 simultaneous beams can be created, van Haarlem et al., 2013). At 144 MHz, the field of view of the Dutch stations (Equation 3.2) is greater than 10 deg^2 (Shimwell et al., 2017), while including also the IS it reduces down to 6 deg^2 (Sweijen et al., 2022): this is due to the fact that IS are double the size, having double the number of antenna tiles (96 against 48) than the CS and RS. Wide-field and high-sensitivity ($\sim 70 \mu\text{Jy beam}^{-1}$ at $6''$ resolution for a typical target field observation of 8 hours, Shimwell et al., 2019) make LOFAR a very powerful tool to perform surveys over large sky areas. The best example is LoTSS (Shimwell et al., 2017; Shimwell et al., 2019; Shimwell et al., 2022, Shimwell et al. *in preparation*), which, at its upcoming third data release, covers 89% of the Northern sky between 120 – 168 MHz using the Dutch stations, with a median sensitivity of $92 \mu\text{Jy beam}^{-1}$. It catalogs 13,664,379 radio sources at $6''$ resolution, representing the largest radio wavelength survey ever carried out in terms of number of source detected.

3.4.2 Dutch stations calibration in the HBA

In this Section, we will briefly describe the calibration routine for the Dutch stations in the HBA. To achieve high dynamic range and resolution, low-frequency data reduction employs complex schemes aimed to track and correct a number of systematic effects (van Weeren et al., 2016; Tasse et al., 2018). In a high signal-to-noise ratio (S/N) regime, a brute-force calibration that has no assumptions concerning the systematic effects that it aims to correct for is satisfactory. However, at low frequency, the sky temperature is high and observations are plagued by systematic corrupting effects mainly caused by ionospheric disturbances (de Gasperin et al., 2019). These variations are time, frequency, and direction dependent; therefore, in the low S/N regime, calibration of these effects is challenging. An effective way to tackle this problem is to reduce the number of free parameters in the calibration by incorporating the (i) time, (ii) frequency, (iii) polarization, and (iv) spatial coherency of the systematic effects for which we aim to solve. A fundamental step in this process is to identify as many systematic effects as possible by understanding the response of the telescope when observing bright, unresolved, and well-characterized sources; we refer to these as primary calibrators. At LOFAR frequencies only a handful of sources meet these requirements, namely 3C 48, 3C 147, 3C 196, and 3C 295. Once identified, these effects can be physically characterized to determine their frequency dependence, time/space coherency scale, and polarization properties. The effects can then be isolated and removed to facilitate the characterization of higher order effects. The primary calibrator is usually observed before and after the target fields, for around 10 minutes: in this case, all effects that are time and direction independent can be corrected on the target field using the high S/N calibrator solutions; this is a conventional approach in radio astronomy. Solutions from the primary calibrator can be used for all the generated beams.

Hereafter, we briefly describe all the systematic effects that affect low-frequency radio observations with their properties, following de Gasperin et al. (2019).

- **Clock drift.** Each LOFAR station is equipped with a global positioning system (GPS) corrected clock. All the CS are connected to the same clock, while RS and IS have their own clock. Clocks drifts, even if being periodically realigned, create a time-dependent delay between all the CS (assumed as a reference) and any other station. Clock errors are equivalent to time delays, therefore, their effect is proportional to frequency.
- **Polarization alignment.** In LOFAR stations, the X and Y polarizations data streams are formed independently, and different calibration tables are applied to the data streams. This can imprint an artificial constant delay offset between the two data streams.
- **Ionosphere.** The ionosphere is a major source of systematic corruptions in low-frequency observations (de Gasperin et al., 2018). Its major effect is an introduction of a time- and direction-dependent propagation delay (Intema et al., 2009), caused by the variation of the refractive index n of the ionospheric plasma along the wave trajectories. Expanding n in powers on ν^{-1} , we have two relevant terms for the HBA frequencies: a dispersive-delay ($\propto \nu^{-1}$) which depends on the density of free electrons along the line of sight (also known as total electron content, TEC), and a second order term ($\propto \nu^{-2}$) that causes Faraday rotation.
- **Beam.** Inaccuracies in the modeling of the LOFAR dipole beam (the common beam shape that each dipole in a LOFAR station has) can contribute to small variations of the beam array in time.
- **Bandpass.** The LOFAR bandpass in the HBA is shaped by different effects, such as a ripple in the band due to the cable connecting the tiles to the electronics and improper removal of the correlator conversion to the frequency domain. Unmodeled differences among the X and Y dipoles create deviations from the ideal case.

In practice, these effects are corrected using the LOFAR Initial Calibration (LINC³) pipeline, previously known as PREFACTOR (van Weeren et al., 2016; Williams et al., 2016; de Gasperin et al., 2019). This pipeline, written in the Common Workflow Language (CWL) standard, takes care of deriving and correcting for all these systematics in the HBA. It is divided into two workflows, one for the primary calibrator and one for the target field. For the primary calibrator, LINC corrects for polarization alignment, Faraday rotation, bandpass, and ionosphere effects over the ensemble of LOFAR stations (Dutch and International). Then, direction-independent corrections for the primary calibrator are applied to the target field, and a first direction-independent phase-only calibration against a sky model is performed; the sky model is based on the TIFR GMRT Sky Survey Alternative Data Release (TGSS ADR, Intema et al., 2017) or on the Global Sky Model (GSM). LINC produces, as final output, 24 measurement sets (MS, Wieringa & Cornwell, 1996; Kemball & Wieringa, 2000) of 2 MHz each, with resolution in time and frequency of 4 s and 48.82 kHz, respectively, covering a total bandwidth of 48 MHz.

To reach thermal noise limited images, it is also necessary to correct for DDE, such as the complex beam patterns or the ionosphere. These corrections not only depend on direction but also on time, frequency, and antenna, and must be derived from the visibilities and applied during imaging. The standard approach applied for the LoTSS is to use the faceting on the image plane (Tasse et al., 2018) deploying the DDF-PIPELINE⁴ (Shimwell et al., 2017; Tasse et al., 2021), which uses KILLMS⁵ (Tasse, 2014; Smirnov & Tasse, 2015) and DDFACET⁶ (Tasse et al., 2018) for the calibration and imaging routines, respectively, required for the DDE correction. The workflow described in this Section follows, in its main parts, the one adopted for the two LoTSS data releases in total intensity (Shimwell et al., 2019; Shimwell et al., 2022), and represents the starting point for the IS calibration described in the next Section.

International stations calibration in the HBA

As previously stated, LOFAR is equipped with 14 stations dislocated in Europe, which provide sub-arcsecond resolution at 150 MHz. This capability will remain unparalleled, even with the advent of the SKA, positioning LOFAR as a unique array to achieve numerous scientific objectives at an unrivaled resolution. Throughout this Thesis, we will refer to this system (LOFAR including IS) as LOFAR-VLBI.

For many years, the IS have seen very limited use due to the challenging calibration and the large data volume involved. The ionosphere, which already plays a huge role in corrupting radio signal for the Dutch stations over a relatively small radius (120 km, Section 3.4.2), becomes even more variable when considering the wide spread of IS. Another issue is that although LOFAR is technically a connected interferometer (all stations have fiber feeds to the correlator), the RS and IS have independent clocks: offsets in the clock values introduce delays in the phase structure of the data. Then, as already stated in Section 3.4.1, IS stations have double the number of tiles with respect to the Dutch ones, meaning that they are twice as sensitive and have smaller fields of view (also reduced by bandwidth and time-smearing effects). The number of suitable calibrators represents another important issue. In Section 3.4.1 we underlined the importance of observing bright, unresolved, and well-known sources. With increasing resolution, the number of sources that have truly compact structure drops drastically, as the extended emission gets resolved out. This has several effects: (i) the sky density of sources decreases; (ii) there is less total flux on compact scales and we move into a lower signal-to-noise regime; and (iii) resolved sources have increasingly complicated

³<https://linc.readthedocs.io/en/latest/>

⁴<https://github.com/mhardcastle/ddf-pipeline>

⁵<https://github.com/saopicc/killms>

⁶<https://github.com/saopicc/DDFacet>

Preparation

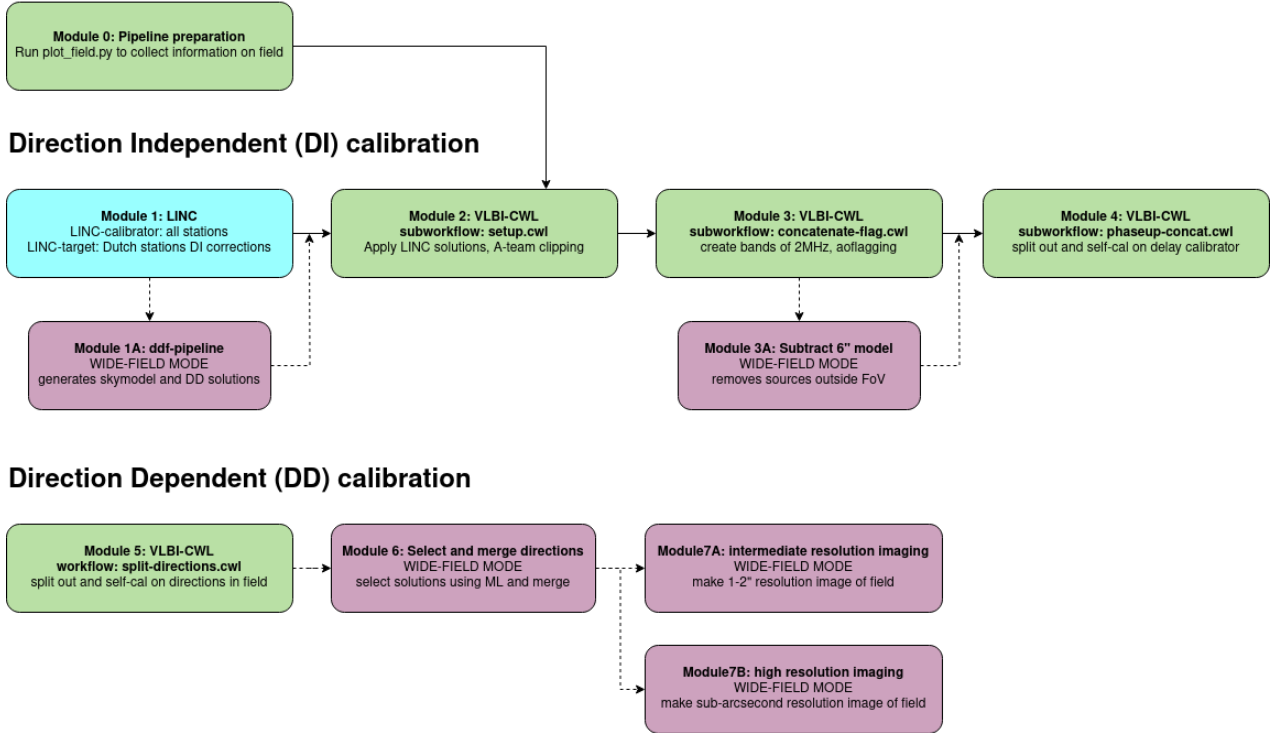


FIGURE 3.7: Flowchart showing the philosophy of the LOFAR-VLBI pipeline. Different colors indicate mandatory (green) or optional (purple) steps.

visibility information and suitable models are necessary to drive self-calibration to convergence. A so-called *delay* or *in-field* calibrator is required for correcting direction-independent *dispersive delays*, which are frequency-dependent effects introduced by the ionosphere. The Long Baselines Calibrator Survey (LBCS, Moldón et al., 2015; Jackson et al., 2016; Jackson et al., 2022) was completed for this scope, selecting all the sources having enough correlated flux density ($\gtrsim 50 - 100$ mJy) at frequencies of 110-190 MHz on scales of a few hundred milliarcseconds. Finally, the data volume required to calibrate LOFAR IS can increase up to a factor four with respect to the size of the raw data (which are around 4.2 TB with default averaging and DYSCO compression, Offringa, 2016).

Recently, a calibration strategy for LOFAR-VLBI was described by Morabito et al. (2022): although some modifications have been made since its initial release⁷, it remains the default routine for exploiting LOFAR-VLBI data in the HBA. We detail hereafter the main steps of the LOFAR-VLBI pipeline, which are also represented in the flowchart in Figure 3.7.

- **Pipeline preparation.** First, it is crucial to check the presence of suited delay calibrators in the field, cross-matching the LBCS and LoTSS catalogs to look for the best suited sources. Ideally, the target and the delay calibrator should be within 1.25 degrees from the pointing center and within around 1 degree of distance from each other. The script automatically ranks the best delay-calibrator combining information about the flux density, the distance from the pointing center, and the signal-to-noise in the Fourier transformed data.

⁷This pipeline was recently upgraded to a new version which implements the CWL and which has become the new standard for LOFAR-VLBI data (van der Wild, in prep., <https://git.astron.nl/RD/VLBI-cwl>).

- **Setup.** direction-independent effects (DIE) solutions from LINC and, optionally, DDE solutions from DDF-PIPELINE are applied to the raw data of the target field. These solutions, evaluated only on the Dutch stations, are applied also to the IS. Then, there is the clipping of the so-called *A-team* sources. These are the four persistent radio sources in the northern sky with the highest flux density at meter wavelength, namely Cassiopea A, Cygnus A, Taurus A, and Virgo A (de Gasperin et al., 2020).
- **Concatenate and flag.** The DIE (and optionally DDE) corrected measurement sets are concatenated into sub-bands of 2 MHz each, usually covering the frequency range from 120 to 166 MHz, and radio-frequency interferences (RFIs) are removed using AOFLAGGER (Offringa et al., 2012).
- **Delay calibration.** The concatenated datasets are averaged down to 390.56 kHz and 32 s in frequency and time, respectively, then phase-shifted towards the direction of the selected delay-calibrator and further concatenated in frequency to a single measurement set. Self-calibration is performed for the delay calibrator using FACETSELFAL (van Weeren et al., 2021). This script enables self-calibration routines using the *Default Preprocessing Pipeline* (DP3, van Diepen et al., 2018; Dijkema et al., 2023) for calibration and WSCLEAN for imaging. The default strategy for self-calibrating the delay calibrator exploits the following calibration operations (van Diepen et al., 2018; van Weeren et al., 2021; Dijkema et al., 2023)
 - **scalarphasediff:** derive a diagonal phase correction to eliminate any phase difference present between circular *RR* and *LL* (or linear *XX* and *YY*) polarizations as a function of time and frequency.
 - **scalarphase:** solving for phase errors as a function of time and frequency, independent of polarization.
 - **scalarcomplexgain:** solving for phase and amplitude errors as a function of time and frequency, independent of polarization.
 - **fulljones:** solving for phase and amplitude errors as a function of time and frequency for both diagonal and cross-hand polarization simultaneously, required for polarization.

The main end-products of this stage of the pipeline are, for each self-calibration round, maps of the delay calibrator, solution files (in hierarchical data format 5, h5parm) and relative inspection plots, and the final, calibrated measurement set.

- **Split directions.** The direction(s) of the target(s) is split-out, using the same averaging as the delay calibration, and self-calibration solutions from the delay calibrator are applied to the target field. Finally, self-calibration towards the target direction is possible, whether the target source is bright enough, and a final map for the target field is produced at sub-arcsecond resolution.

This procedure, also known as *postage stamp* mode, is useful and effective in imaging the bright and compact sources in the LOFAR-VLBI fields (typically up to ~ 100 sources in each observation). For this reason, progress is currently being made with reprocessing the archival LoTSS data using this pipeline. This project, known as LoTSS-High Resolution (LoTSS-HR), aims to publish cutout images of all sufficiently bright (> 10 mJy) radio sources at an angular resolution of $0.3''$ as well as full field of view images at an intermediate resolution of approximately $1.2''$ (Morabito et al., 2025). In recent years, many published studies have exploited LOFAR-VLBI for a wide variety of scientific cases, using the standard LOFAR-VLBI pipeline (see Morabito et al., 2025, for an overview on the scientific cases in which the ILT has been involved so far). For the sake of brevity, we report hereafter those regarding galaxy clusters and cluster member radio galaxies, aiming at studying the diffuse

emission (van Weeren et al., 2024; HLavacek-Larrondo et al., 2025), the relationship with X-ray cavities (Timmerman et al., 2024; Ubertosi et al., 2024), the inner structures in a central dominant radio galaxy (Timmerman et al., 2022), and the high-redshift galaxies and protoclusters (Cordun et al., 2023).

Together with splitting-out the individual target, it is also possible to use the wide-field capabilities of LOFAR to image the whole LOFAR-VLBI field of view, including the IS, down to sub-arcsecond resolution. This was first enabled by Sweijen et al. (2022) for the Lockman Hole field, imaged at $0.3''$ resolution (Figure 3.8). Then the ELAIS-N1 field, imaged both at intermediate ($1.2''$, Ye et al., 2024) and full ($0.3''$, de Jong et al., 2024). The main calibration and imaging steps, required to

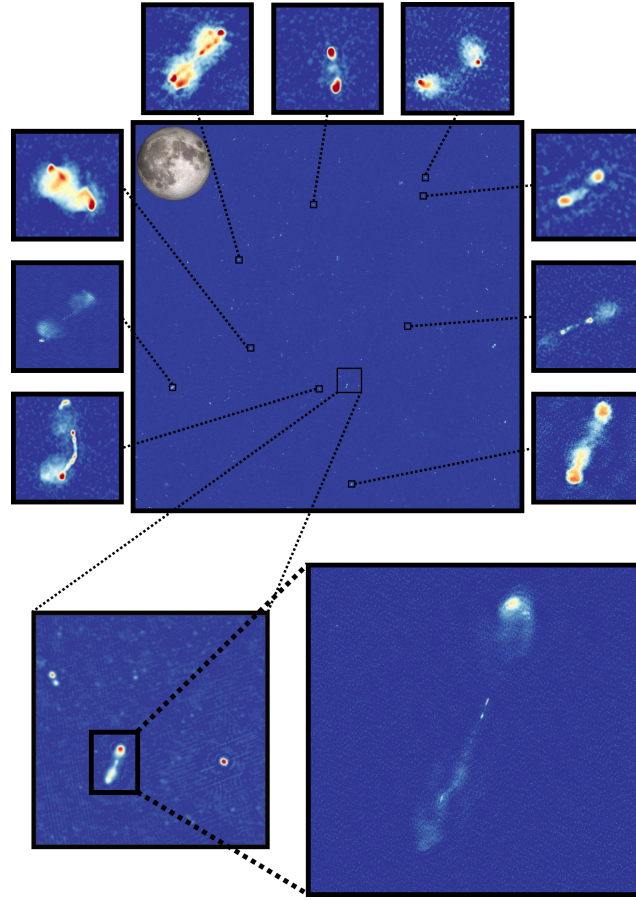


FIGURE 3.8: Image of the Lockman Hole at 144 MHz at $0.3''$ resolution using LOFAR-VLBI (Sweijen et al., 2022).

image the full FoV at sub-arcsecond resolution, are listed below.

- The $6''$ model generated from the DDF-PIPELINE is used to subtract the sources outside the FoV (which, for the ILT, is $2.5^\circ \times 2.5^\circ$).
- A number of direction-dependent calibrators is selected, to correct for residual DDE across the FoV, mainly due to the ionosphere and the errors in the beam model. Ideally, these sources should be compact and bright enough to enable self-calibration. A more quantitative selection criterion, involving the differences RR and LL polarizations, has been introduced by de Jong et al. (2024) (Sect. 3.3.1 in their paper). Basically, calibrators with a high S/N will have more similar phase corrections on both RR and LL polarizations: the circular standard deviation of the discrete difference along the frequency axis from the `scalarp phasediff` solutions is

used as a measure of the phase noise. Self-calibration made through FACETSELFAL produces calibration solutions for each of the DDE calibrator.

- For intermediate resolution imaging ($1.2 - 1.5''$), the DDE calibrators solutions can be directly applied to the data at the imaging step enabling the facet-based imaging (Williams et al., 2016; van Weeren et al., 2016). In this way, the FoV is divided in as many facets as the number of DDE calibrators, and the calibration solutions are applied to their resident facet.
- For full resolution imaging ($0.3 - 0.7''$), the image has to be made separately for each facet, using the intermediate resolution image as a model to subtract all the sources outside each facet (more details in de Jong et al., 2024). This is motivated by the large computational effort required to make, at this resolution, images up to 10^{10} pixels in a single instance.

All these steps have been recently automated and implemented in the LOFAR-VLBI pipeline. The main bottleneck of LOFAR-VLBI wide-field is represented by the imaging step, especially when increasing the amount of observations and/or the resolution. In case of multiple observations of the same target field, one possibility is to average the visibilities at similar baseline coordinates (so-called *sidereal visibility averaging*, Owen & Morrison, 2008; de Jong et al., 2025b). Still, as we will demonstrate later in this Thesis, a huge improvement can be achieved by developing efficient parallel and accelerated solutions for the interferometric imaging algorithms. All these recent improvements in developing an automated strategy for selecting DDE calibrators and speed-up the imaging will be crucial for the completion of the International LOFAR Two-metre Sky Survey (ILoTSS⁸), which will build on the LoTSS survey to be the first wide-area, sensitive ($30 \mu\text{Jy beam}^{-1}$), high resolution ($0.3''$) extragalactic radio survey.

In this Thesis, we present LOFAR-VLBI images obtained both for single targets at sub-arcsecond resolution, using the postage-stamp mode, and for the cluster's field of view at $1.5''$ resolution, using the wide-field mode. These images, derived by combining 56 hours of combined observations, constitute the deepest LOFAR-VLBI data obtained for a galaxy cluster to date.

⁸<https://lofar-surveys.org/ilotss.html>

Chapter 4

Revealing the intricacies of radio galaxies and filaments in the merging galaxy cluster Abell 2255. I. Insights from deep LOFAR-VLBI sub-arcsecond resolution images

¹In this Chapter, we aim to detect and characterize non-thermal filaments observed close or within the radio galaxies in Abell 2255 using deep LOFAR-VLBI observations at 144 MHz at sub-arcsecond resolution. Combining multiple observations, we produced the deepest images ever obtained with LOFAR-VLBI targeting a galaxy cluster, using 56 hours of observations, reaching a resolution of $0.3 - 0.5''$. We detail the calibration and imaging strategy for the different targets, as well as the multitude of morphological features discovered.

Thanks to the high-sensitivity of LOFAR-VLBI, we reveal an unprecedented level of detail for the main cluster radio galaxies, recovering in most cases their more extended structure as well, which can only be observed at such low frequencies. In particular, we focus on the Original Tailed Radio Galaxy (Original TRG) where we distinguish many filaments constituting its tail with varying lengths (80 – 110 kpc) and widths (3 – 10 kpc). The final radio images showcase the potential of deep, high-resolution observations for galaxy clusters. With such approach, we enable the study of these thin, elongated radio filaments. Following their discovery, these filaments now require spectral studies to determine their formation mechanisms (Chapter 5).

4.1 Introduction

In this Chapter, we use the ILT to observe the radio galaxies and filaments in the galaxy cluster Abell 2255 (hereafter A2255) at sub-arcsecond resolution. This is a merging galaxy cluster ($z = 0.0806$) exhibiting morphologically complex radio structures on multiple scales (see Botteon et al., 2020b; Botteon et al., 2022, and references therein for a more detailed description). Several optical and infrared studies reported a total number of confirmed member galaxies that range from 300 to 500 (depending on the radius selection criteria), using both spectroscopic and photometric techniques (Yuan et al., 2003; Shim et al., 2011; Tyler et al., 2014; Golovich et al., 2019). Miller and Owen (2003) focused in particular on the fraction of AGN. Using VLA data at 1.4 GHz, they found that A2255 has an abnormal abundance of radio galaxies compared to other clusters, which is

¹This Chapter is based on De Rubeis et al. (2025c)

possibly motivated by the cluster’s dynamical state, even if this is not yet clear from optical observations (Burns et al., 1995; Yuan et al., 2003). Radio galaxies in A2255 have been widely observed in the past (e.g., Harris et al., 1980; Burns et al., 1995; Miller & Owen, 2003; Govoni et al., 2006; Pizzo & de Bruyn, 2009; Pizzo et al., 2011; Terni de Gregory et al., 2017; Botteon et al., 2020b; Botteon et al., 2022). Four tailed radio galaxies reside in the cluster: following the nomenclature introduced by Harris et al. (1980), there are three NAT sources, namely: the Original Tailed Radio Galaxy (Original TRG), the Goldfish, and the Beaver, along with a WAT known as the Embryo. Together with these, there is also a FR II radio galaxy located, in projection, close to the cluster center called the Double. Observations for these sources were performed by Govoni et al. (2006) at high frequencies, using VLA in C- and X-band providing resolution of $2''$; they also studied the fractional polarization of these sources, finding mean values around 14% for the NATs. The Goldfish has been observed also with VLA at 15 GHz, reaching an angular resolution of $0.47'' \times 0.44''$ (Terni de Gregory et al., 2017) and revealing strong projection effects impacting its morphology. Together with observations of cluster radio galaxies, Govoni et al. (2005) discovered the presence of strongly polarized filaments (20 – 40% of fractional polarization) in the cluster radio halo at 1.4 GHz, with a rectangular shape and regions of ordered magnetic field of ~ 400 kpc in size. They were reported also subsequently using the Westerbork Synthesis Radio Telescope (WSRT) by Pizzo and de Bruyn (2009) and Pizzo et al. (2011). Recently, thanks to deep LOFAR observations (75 hours at 145 MHz, with rms noise of $43 \mu\text{Jy beam}^{-1}$, resolution of $4.7'' \times 3.5''$, as shown in Figure 4.1; 72 hours at 49 MHz, rms noise of $730 \mu\text{Jy beam}^{-1}$, resolution of $11.5'' \times 8.2''$), Botteon et al. (2020b) and Botteon et al. (2022) detected the presence of additional filamentary and distorted structures on different scales with a very steep spectrum ($\alpha > 2$) embedded in the radio halo, whose association with optical counterparts of the cluster radio galaxies is not trivial, considering also that these filaments are detectable only at LOFAR frequencies.

In this work, we aim to observe the tails and filaments that populate the cluster environment using the high-resolution, low-frequencies capabilities of the ILT. We produced radio maps at 144 MHz at sub-arcsecond resolution, targeting the brightest cluster member radio galaxies: using 56 hours of observations, this makes the deepest LOFAR-VLBI images ever targeting a galaxy cluster. Thanks to the high-resolution and sensitivity of LOFAR-VLBI we detected, for the first time, a multitude of substructures related to these radio galaxies; they are mostly filamentary and observable only at such low frequencies. Particular attention was given to the Original TRG, which revealed the presence of filaments related to its tail extending for almost 300 kpc presuming a complex origin scenario involving the turbulent environment which surrounds it. In this Chapter, we focus on the methodology used to produce the deep LOFAR-VLBI images and on a morphological study of the Original TRG. In the next Chapter, this analysis will be combined with high-resolution spectral index maps resulting from the combination of LOFAR-VLBI data with uGMRT and the VLA at higher frequencies.

At the redshift of Abell 2255, $1''$ corresponds to a linear scale of 1.512 kpc.

4.2 Data calibration and imaging

A2255 was first observed for 72 hours by LOFAR in the period June to November 2019 (project LC12_017, P.I. R.J. van Weeren). The cluster is located at about 5 degrees from the Euclid Deep Field North (EDFN), which made it possible to observe the two targets simultaneously using two different LOFAR beams (Bondi et al., 2024). After these first observations, A2255 was again observed for an additional 226 hours as the secondary target during the very deep EDFN observations carried out in the period 2022-2023 (project LT16_005, P.I. P.N. Best). For this work, we selected only

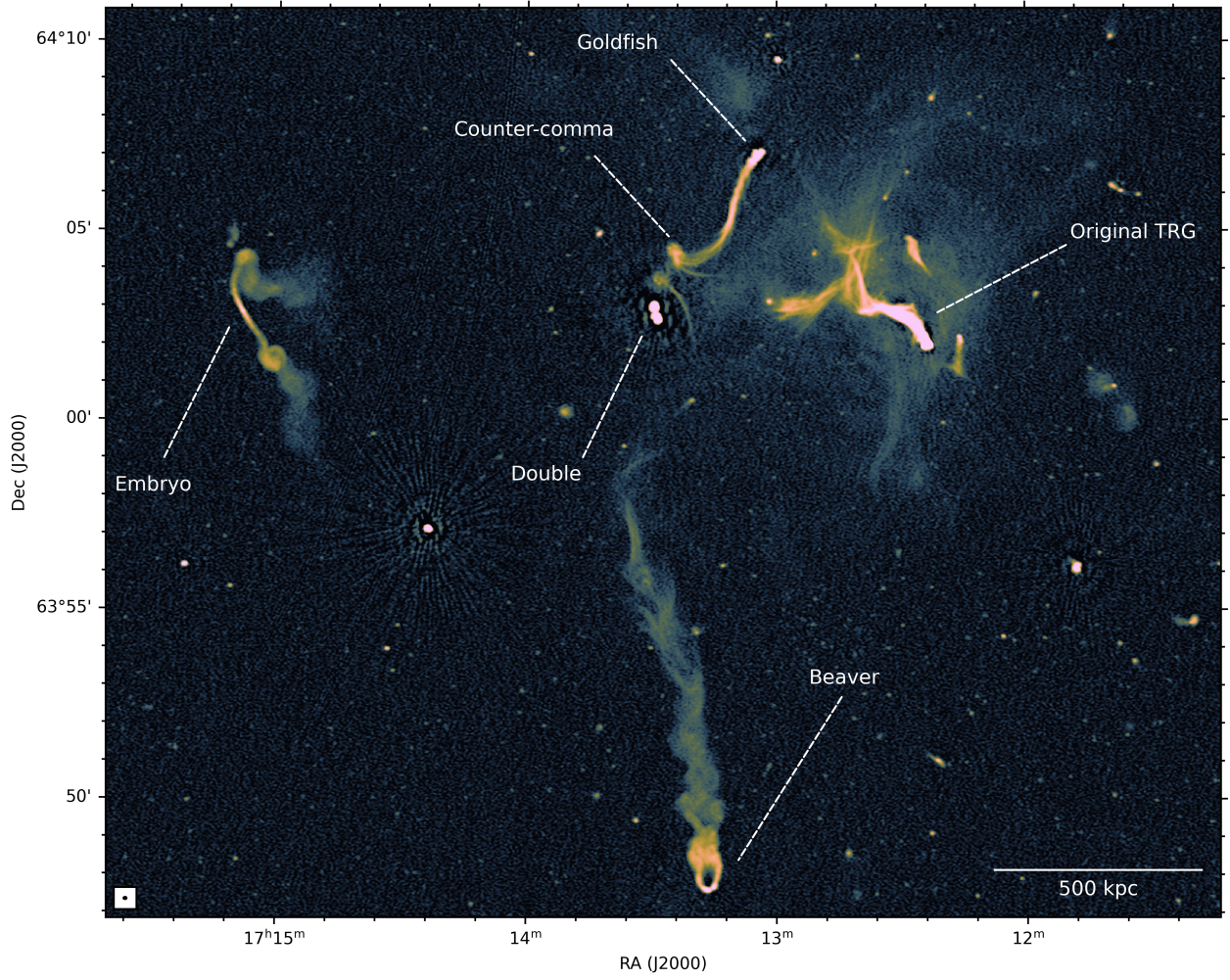


FIGURE 4.1: Zoom-in on Abell 2255's center at 145 MHz, resolution of $4.7'' \times 3.5''$, adapted from Botteon et al. (2022). The main cluster member radio galaxies that are the focus of this Chapter are highlighted in white and labeled the same as in Harris et al. (1980) and Botteon et al. (2020b). The restoring beam size is shown in the bottom-left corner.

Obs. ID	Obs. date [YYYY-MM-DD]	Stations (International)	$\sigma_{\text{rms},6}$ [$\mu\text{Jy beam}^{-1}$]
L720378	2019-06-07	51 (13)	89
L725454	2019-06-22	51 (13)	90
L726708	2019-06-28	51 (13)	85
L727110	2019-07-03	50 (12)	92
L733077	2019-08-09	48 (13)	97
L747613	2019-09-28	47 (11)	99
L751366	2019-10-04	50 (12)	93

TABLE 4.1: List of the LOFAR observations used in this and next Chapter. Column 1: ID of the observation. Column 2: date of the observation. Column 3: total number of stations (number of IS in brackets). Column 4: rms noise of the map output from DDF-PIPELINE using only Dutch stations.

observations coming from the first set of 72 hours, because the latest ones are still in the phase of processing. The 72 hours were split in 9 runs and each 8 hour observation was calibrated individually.

After describing the preliminary steps involved in the calibration of the Dutch stations, for both DIE and DDE effects, we detail the procedures on the IS: for their calibration strategy, we followed the procedures extensively described in Morabito et al. (2022) (and in Section 3.4.2), with different tailored adjustments, especially in the imaging step, required by the high-complexity radio morphology of the field containing A2255, with the combination of extended and structured radio galaxies overlapping the cluster radio halo.

4.2.1 Initial calibration of the Dutch stations

The first step provides calibration of the visibilities following the standard procedure used for the LoTSS (Section 3.4.2, Shimwell et al., 2017; Shimwell et al., 2019; Shimwell et al., 2022). After downloading data from the LOFAR Long-Term Archive (LTA), both for primary calibrator and target, for each observation, we used PREFACTOR (de Gasperin et al., 2019) solutions from Botteon et al. (2020b) and Botteon et al. (2022) on the primary calibrator, which was 3C48 for all the observations. This pipeline corrects for the polarization alignment, clock delays between stations, and bandpass, for both Dutch and international stations. PREFACTOR is used also for the target field (A2255) to correct for DIE on the Dutch stations. After applying the solutions found for the primary calibrator to the target, it calibrates the phases against a sky model from the TGSS (Intema et al., 2017).

We then further processed our data to correct for DDE using DDF-PIPELINE (Shimwell et al., 2017; Tasse et al., 2021), which uses KILLMS (Tasse, 2014; Smirnov & Tasse, 2015) for direction-dependent calibration and DDFACET (Tasse et al., 2018) to apply direction-dependent solutions during imaging. The output image of the target field at 6'' resolution, corrected for both DIE and DDE on the Dutch stations, has been used to assess the quality of the observation.

4.2.2 Calibration of the International stations

Once the Dutch array was fully calibrated, we proceeded with the calibration of the IS. Following the strategy described in Morabito et al. (2022), solutions from the Dutch array corrected for both DIE and DDE were transferred to the original measurement sets including also the IS. Then, after checking the contribution of bright, off-axis sources (so-called A-team sources, that were sufficiently far to avoid contaminating the target field), the datasets were concatenated into sub-bands of 1.95 MHz each. These sub-bands were phase-shifted toward the direction of an in-field calibrator for the calibration of the IS, required for correcting direction-independent dispersive delays, and concatenated in frequency into a single measurement set.

For our field, we searched for the best available in-field calibrator using the LBCS. The selected source was 4C +64.21 (RA: 17^h19^m59^s, Dec: 64°04'37'', Pilkington & Scott, 1965), a powerful radio source, compact on arcsec-scale, with flux density of ~ 4.87 Jy at 144 MHz. Given that it shows the presence of two components at 0.3'' resolution (and was observed at multiple frequencies throughout the radio spectrum), we built a sky model distributing the flux density among two Gaussian components, with the same flux ratio as the one in the full resolution map. To better reproduce the spectral index for the calibrator, we used flux density measures at multiple radio frequencies, following de Jong et al. (2024): in particular, the 8C survey at 38 MHz (Hales et al., 1995), the VLA Low-frequency Sky Survey at 74 MHz (VLSS, Cohen et al., 2007), the 6C survey at 151 MHz (Hales et al., 1990), the Westerbork Northern Sky Survey at 325 MHz (WENSS, Rengelink et al., 1997), the Texas Survey at 365 MHz (Douglas et al., 1996), and the NRAO VLA Sky Survey (NVSS, Condon et al., 1998)

at 1.4 GHz. With flux densities and frequencies we fitted a second-order logarithmic polynomial

$$\log S(\nu) = \log S_0 + c_0 \log \left(\frac{\nu}{\nu_0} \right) + c_1 \log \left(\frac{\nu}{\nu_0} \right)^2. \quad (4.1)$$

Using $\nu_0 = 144$ MHz as the reference frequency, we ended up with $c_0 = -0.013$ and $c_1 = -0.90$. These parameters, together with the position of the Gaussian subcomponents, made the initial sky model that we used for the in-field calibrator.

We used FACETSELFAL (van Weeren et al., 2021) to perform self-calibration. It allows us to correct phases and amplitudes, thereby minimizing the differences between the data and the sky model, namely by updating the latter in each self-calibration cycle. We followed the procedure adopted by de Jong et al. (2024) with some minor adjustments. In particular, during the self-calibration cycles, we solved for:

1. **scalarphasediff**: solution interval 128 s, frequency smoothness 4.0 MHz;
2. **scalarphase**: 32 s, frequency smoothness 1.0 MHz;
3. **scalarcomplexgain**: 53 min, frequency smoothness 4.0 MHz, one solution each 10 channels.

We ignored all the baselines shorter than $40,000\lambda$, corresponding to an angular scale of about $5''$ at 144 MHz, using the parameter `--uvmin`, to prevent possible incompleteness in the sky model. We phased up LOFAR's core stations to form a large, virtual, narrow FoV station, to reduce the interference from unrelated nearby radio sources especially at short baselines. Through FACETSELFAL, we also averaged the input data down to 32 s in time and 488 kHz in frequency and used a Briggs weighting with robustness of -1.5 for the imaging (Briggs, 1995). At the end of the self-calibration routine on the in-field calibrator, one hierarchical data format 5 (**h5parm**) solution file was produced for each calibration step and one containing all the solutions merged, with phases and amplitudes corrections. We performed 20 self-calibration cycles providing the best solutions for visibilities (Figure 4.2). Among the 9 available observations, two (namely L728074 and L746864) have been discarded because of the significantly higher image noise once including the IS (between 30 – 40% with respect to the other runs). We ended up with 7 runs (meaning 56 hours of observing time on target), that have been used for the long baselines calibration and imaging. The main characteristics of the selected observations are listed in Table 4.1.

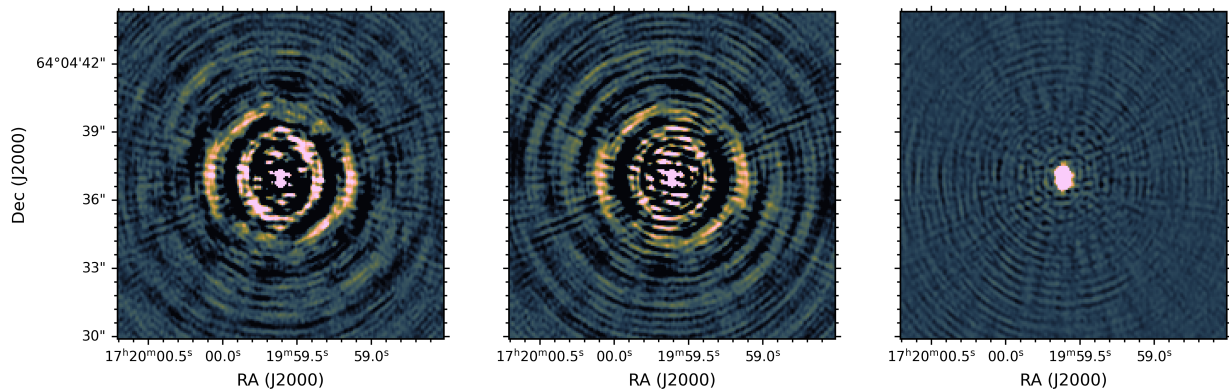


FIGURE 4.2: Self-calibration results on the delay calibrator 4C +64.21 for one observing run. From left to right: Self-calibration cycle 0 (sole imaging), cycle 1 (only **scalarphasediff** and **scalarphase** solutions), cycle 19 (final image, solving also for **scalarcomplexgain**).

Target	Redshift	Host galaxy coordinates [J2000]	Radio morphology	Robust	Resolution	rms noise [$\mu\text{Jy beam}^{-1}$]
Double	0.07844	$17^{\text{h}}13^{\text{m}}29^{\text{s}}.11; +64^{\circ}02'48''.74$	FRII	−0.5	$0.30'' \times 0.24''$	18
Original TRG	0.07981	$17^{\text{h}}12^{\text{m}}23^{\text{s}}.16; +64^{\circ}01'57''.09$	FRI-NAT	−0.5	$0.34'' \times 0.24''$	18
Goldfish	0.08092	$17^{\text{h}}13^{\text{m}}03^{\text{s}}.78; +64^{\circ}07'01''.67$	FRI-NAT	−0.5	$0.55'' \times 0.41''$	29
Beaver	0.08295	$17^{\text{h}}13^{\text{m}}16^{\text{s}}.00; +63^{\circ}47'37''.54$	FRI-NAT	−0.5	$0.54'' \times 0.40''$	27
Embryo	0.08001	$17^{\text{h}}15^{\text{m}}09^{\text{s}}.08; +64^{\circ}02'53''.51$	FRI-WAT	0.5	$0.55'' \times 0.40''$	40

TABLE 4.2: List of the target sources with the final map properties. Column 1: target name. Column 2: spectroscopic redshift from Ahn et al. (2012) (for the Double and the Original TRG) and Alam et al. (2015) (for the Goldfish, the Beaver, and the Embryo). Column 3: host galaxy coordinates from Alam et al. (2015) (for the Double) and Gaia Collaboration et al. (2021) (for all the others). Column 4: radio morphological classification following Fanaroff and Riley (1974) (FRI/FRII) and Miley (1980) (NAT/WAT). Column 5: robust parameter used for Briggs weighting during imaging. Column 6: beam size. Column 7: rms noise.

4.2.3 Self-calibration on target cluster radio galaxies

With the IS fully calibrated, we imaged the main cluster radio galaxies with LOFAR-VLBI at 144 MHz at sub-arcsecond resolution. For each of the 7 runs, the concatenated datasets produced by the LOFAR-VLBI pipeline were phase-shifted toward 5 targets and averaged. The selected targets correspond to the main cluster radio galaxies: the Double, the Original TRG, the Goldfish, and the Beaver. First, we applied the h5parm, DIE calibration solutions from the in-field calibrator to all the sources for each observation individually. Given the large distance of the in-field calibrator from the pointing center (0.8°) and the complex morphology of the targets, we used compact and bright sources closer to the cluster as additional calibrators to improve the calibration solutions on targets in a similar way to the faceting (van Weeren et al., 2016) or the wide-field direction-dependent calibration (de Jong et al., 2024). The radio source J171259+640931 was used as additional calibrator for the Double and the Goldfish. After performing the self-calibration, solving for `scalarphase` and `scalarcomplexgain`, and phasing-up the core stations, to reduce the FoV and so the effects from the nearby radio emission from the cluster center, we transferred the calibration solutions to the two targets and proceeded with self-calibration. For the Double, we solved for `tec`, `scalarphase`, and `scalarcomplexgain`, avoiding all the baselines below $10,000\lambda$ (corresponding to $\sim 20''$) and phased-up the core stations. For the Goldfish, we solved for `tecandphase` and `scalarcomplexgain` and phased-up the superterp stations, avoiding all the baselines below $5,000\lambda$ (corresponding to $\sim 41''$). The Double was also used as additional calibrator for the Original TRG: for the main tailed cluster radio galaxy, we solved for `tec`, `scalarphase`, and `scalarcomplexgain`, avoiding all the baselines below $10,000\lambda$ and phased-up the core stations. Including shorter baselines for these extended sources, with respect to what was done for the in-field calibrator, was required to add more large-scale signal during calibration. For Beaver and the Embryo instead, we used the radio source J171423+635707 as an additional calibrator. Given the dominant low surface brightness extended emission in these sources, self-calibration did not result in any improvement in the image quality: for this reason, we simply applied the solutions from J171423+635707 and imaged the two targets. After self-calibration (where possible), we imaged each source with WSCLEAN using `wgridder` (Arras et al., 2021; Ye et al., 2022), combining all the calibrated MS at once, using automatic masking and `multiscale` deconvolution (Offringa & Smirnov, 2017) to better deal with their extended structure.

4.3 Morphological analysis of cluster member radio galaxies

In this section, we present the final imaging results for the target radio galaxies, as well as their morphological detailing. Their main properties are listed in Table 4.2.

4.3.1 The Double

The Double, also known as J171329+640249 (Miller & Owen, 2002), is a FR II radio galaxy located, in projection, at about 600 kpc from the cluster center. It exhibits a double-lobed morphology with a total extent of almost 50 kpc ($\approx 35''$). Our new LOFAR-VLBI sub-arcsecond resolution image of the source is shown in Figure 4.3. We resolve the core and the two jets departing from it up to the hotspots. Both lobes show edge-brightening at their tips, possibly resulting from the shocks formed by the interaction with the ICM, and extend for about 21 kpc (north) and 23 kpc (south), measured above the $3\sigma_{\text{rms}}$. At this detection level, the source has a flux density of 0.95 ± 0.10 Jy at 144 MHz. Assuming a spectral index $\alpha = 0.65$ (Botteon et al., 2020b), the source has a rest-frame luminosity $L_{144} \sim 1.48 \times 10^{25} \text{ W Hz}^{-1}$: the classical FRI – II luminosity break is around $L_{150} \sim 10^{26} \text{ W Hz}^{-1}$ (Fanaroff & Riley, 1974; Ledlow & Owen, 1996), so the Double can be classified as *FR II-Low* (Mingo et al., 2019). The southern hotspot is shifted with respect to the initial direction of the jet, which ends up into another bright spot in the same lobe: this may suggest the presence of

multiple hotspots (Hardcastle et al., 1997). In the southern hotspot there is also a narrow arc-like structure (labeled in Figure 4.3) which, as for other similar objects, could represent a well-collimated backflow (Leahy et al., 1997). The northern hotspot is instead surrounded by a ring-shaped radio brightness enhancement (labeled in Figure 4.3). These rings are unusual, but not unique: they were already observed in other radio galaxies, for instance, in the western hotspot of Hercules A (Dreher & Feigelson, 1984; Timmerman et al., 2022), in 3C 310 (Morrison & Sadun, 1996), or in 3C 219 (Perley et al., 1980). Several scenarios can explain the formation of the rings (Saxton et al., 2002; Gizani & Leahy, 2003), involving mainly the shocks and the inner lobes model. In the former, the rings are shocks with circular geometry, caused by backflows in the cocoon, which introduce adiabatic compression and particle acceleration. In the latter, instead, rings arise from material deposited by new jets in the lobe and separated from it by a contact discontinuity. From the sole radio map, disentangling the correct one is non-trivial. The presence of rim-brightening, observed in the ring around the northern hotspot in the Double, favors the shock model because it is the only one that can explain such feature, as also shown in simulations (Meenakshi et al., 2023). Additional information, such as the spectral index, is still required to reliably discriminate between the proposed models or (if necessary) to motivate new ones. Further investigation of all these aspects is beyond the scope of this work.

4.3.2 The Original TRG

The Original TRG, also known as 7C 1712+6406 (Hales et al., 2007), is a NAT radio galaxy, classified as a FRI by Capetti et al. (2017a). Previous studies at higher frequencies (VLA L-, C-, and X-band, Govoni et al., 2005; Govoni et al., 2006) reported a source extension of about $2.5'$ with a mean fractional polarization of up to 14%. Our deep and high-resolution map provided by LOFAR-VLBI is presented in Figure 4.4. We reveal several new substructures along the tail, which otherwise would have been considered as a unique, continuous component. First, we precisely identified the host galaxy (red cross in Figure 4.4) and the ejection location of the two relativistic jets. Following the tail extension in the north-east direction, we observed three turbulent eddies at distances between 10 and 30 kpc from the host galaxy, evenly spaced from each other (~ 9 kpc). We note that they possibly arise from the instabilities developed in the downstream of the radio galaxy. Interestingly, the entire tail seems to depart only from the northern jet: the southern one, instead, seems to interrupt abruptly, as also observed at higher frequencies by Govoni et al. (2006). Thanks to the combination of high-sensitivity and resolution we also detect, for the first time, multiple filamentary structures that constitute the tail of the radio galaxy. At 144 MHz we reveal the presence of an extended filament at the lower bound of the main tail, labeled F1 and which follows its shape, just after an emission gap of around 10 kpc from the southern jet termination. This may suggest that some event could have prevented the development of a tail from the southern jet for a fixed amount of time during the host galaxy motion. However, the lack of the southern tail can also result from projection effects, where it can be bent and hidden behind the northern one. The southern jet is connected to a bright emission patch, having a flux density of ~ 80 mJy beam $^{-1}$ (at $10\sigma_{\text{rms}}$), via two tethers similar to the ones observed in the radio galaxy IC711 in Abell 1314 (van Weeren et al., 2021) or in the MysTail in Abell 3266 (Rudnick, 2021). Along with F1, we detected a horizontal filament at the north-east end of the main tail and a vertical filament that departs from this last one toward the north. Between the upper end of the main tail and the west side of the horizontal filament there is another filamentary feature that emerges, labeled as F2 in Figure 4.4. Despite resembling the F1 filament, it is attached directly to the horizontal filament, which would suggest a plausibly different origin and that is might be more connected to what is happening above the horizontal filament. A more quantitative description of the filaments, including their lengths and widths, is presented in Section 4.4.

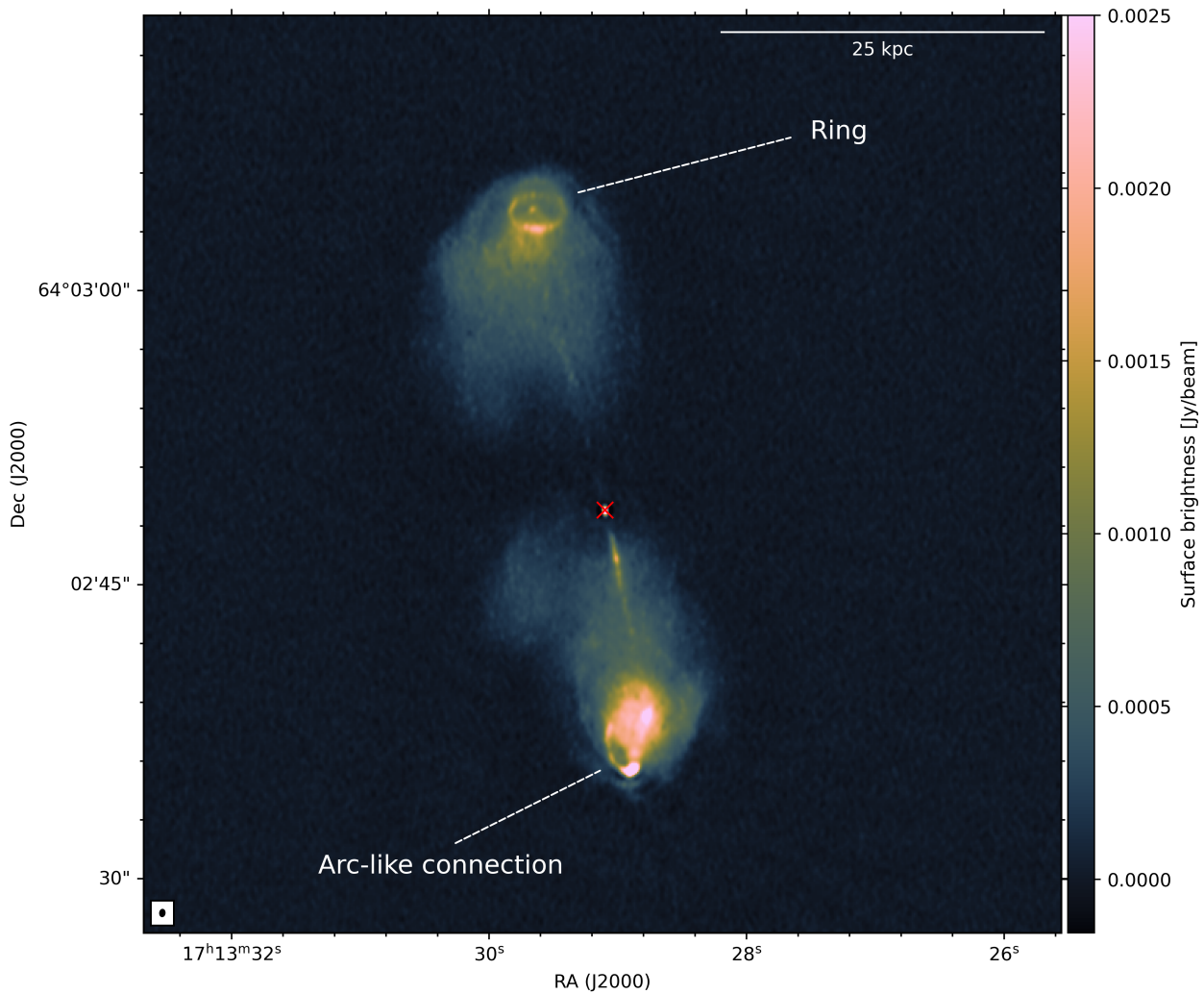


FIGURE 4.3: The Double at 144 MHz; resolution $0.30'' \times 0.24''$, rms noise $18 \mu\text{Jy beam}^{-1}$. This image was obtained using Briggs weighting, robust = -0.5 , and multiscale. The restoring beam size is shown in the bottom-left corner. The red cross identifies the optical position of the host galaxy as listed in Table 4.2.

The characteristics of plasma in the main tail and in the filaments cannot be determined solely on the basis of a morphological analysis, but from a spectral index analysis instead. This analysis will be presented the next Chapter, where we discuss images of the Original TRG and its filaments obtained at 144, 1260, and 1520 MHz with a resolution of $1.5''$. Spectral index information between 49 and 145 MHz from Botteon et al. (2022) ($12.5''$ resolution) on the Original TRG reports nuclear values around $\alpha \sim 0.5 - 0.6$, with signs of spectral aging along the tail up to $\alpha \sim 2$, corresponding to what we identified as the vertical filament. The combination of low-resolution and low-frequency implies a significant contribution of the diffuse emission from the radio halo in which this radio galaxy is situated; this motivates a follow-up at higher frequency and resolution, to extract the intrinsic spectral properties of the radio galaxy.

At almost $50''$ from the Original TRG there is the Sidekick radio galaxy ($z = 0.071436$, Miller & Owen, 2003), another cluster member radio galaxy for which we resolve its double-jetted structure, which extends for ~ 3.6 kpc and then ends up into a tail that goes south for around 80 kpc.

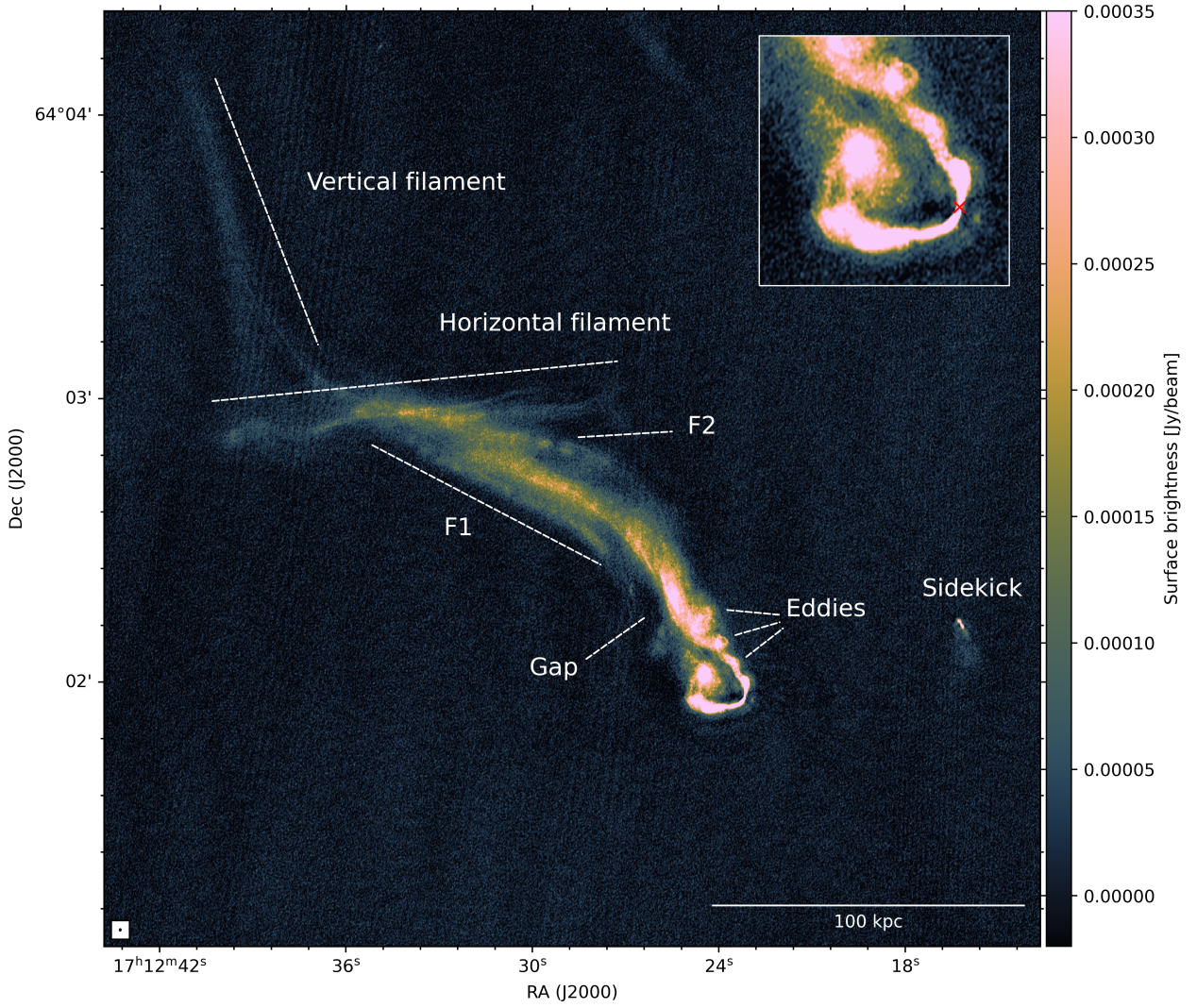


FIGURE 4.4: The Original Tailed Radio Galaxy (Original TRG) at 144 MHz; resolution of $0.34'' \times 0.24''$, rms noise of $18 \mu\text{Jy beam}^{-1}$. This image was obtained using Briggs weighting, robust = -0.5 , and multiscale. The restoring beam size is shown in the bottom-left corner. Top-right corner: Zoom-in (22 kpc) on a region close to the host galaxy, whose optical position (listed in Table 4.2) is identified with a red cross.

4.3.3 The Goldfish

The Goldfish, also known as 7C 1713+6407a (Hales et al., 2007), is a NAT radio galaxy classified as FRI. A deep LOFAR image made with the Dutch array (Figure 4.1) revealed an extended head and a narrow tail of ~ 300 kpc length that ends up mixing with a diffuse feature, known as Counter-comma (Botteon et al., 2020b), whose origin is still unclear. High-resolution, high-frequency observations (in the L-, C-, and Ku-band) resolved the head of the radio galaxy, with two jets that depart from the core with a gap of $1.5''$ observed for both of them (Owen & Ledlow, 1997; Terni de Gregory et al., 2017). From a deep LOFAR-VLBI map (presented in Figure 4.5), we resolved the core and the region immediately close to the head (within 50 kpc from the host), where the ram pressure effects on the jets can be observed; this is the case, in particular, for the northern one, which is deflected by almost 90 degrees as soon as it leaves the core region. At sub-arcsecond resolution, we also detect the tail emission up to the connection with the Counter-comma, with the presence

of a region of increased surface brightness at around 170 kpc from the core. Interestingly, the tail presents a helical morphology right after the head region, as if the two jets are spiraling around each other before linking back into a single tail that then extends southwards. This wobbling, similar to what happens for the Beaver radio galaxy (Section 4.3.4, but on smaller scales), can be due to different reasons related to the motion of the host galaxy or the instabilities developed behind it.

4.3.4 The Beaver

The Beaver, also known as 7C 1712+6352 (Hales et al., 2007), is a NAT radio galaxy placed at ~ 1.5 Mpc from the cluster center. Low-frequency observations made with LOFAR Dutch array at 144 MHz have revealed a twisted tail that extends for more than 1 Mpc, before fading into the cluster radio halo (Figure 4.1). Deep LOFAR-VLBI map is shown in Figure 4.6 (left panel). At sub-arcsecond resolution, we mainly resolved the core region and the two jets departing from it and also the first, brighter part of the tail up to the point at which the two jets get close for the first time along the tail, before developing its characteristic corkscrew feature (fully depicted in Figure 4.1). The rest of the tail was not detected because of the lower surface brightness and the time and bandwidth smearing effects, reducing the intensity far from the pointing center (Bridle & Schwab, 1999).

4.3.5 Embryo

The Embryo, also known as GB6 B1714+6405 (Gregory et al., 1996, $z = 0.08001$), is a WAT radio galaxy located, in projection, at about 1.5 Mpc from the cluster center. Its radio emission at 144 MHz extends for ~ 600 kpc, considering the more diffuse emission generated by ram pressure effects in correspondence of the lobes. The deep, sub-arcsecond resolution map is shown in Figure 4.6 (right panel). As for the Beaver, we resolve the core region with the inner jets; the southern jet is brighter than the northern one by a factor of 2, considering the $5\sigma_{\text{rms}}$ emission within a projected distance of 10.5 kpc from the core. Moreover, there are multiple bright spots along the northern jet, possibly hinting at the central black hole's duty cycle. The jets are maintained collimated (3.5 – 6 kpc) before experiencing the effects of the ICM and becoming bent. Following Equation 1 in Laing et al. (1999), and assuming isotropic emission in the source rest-frame and a spectral index $\alpha = 0.5$ (from Botteon et al., 2020b), we can constrain the angle to the line of sight to be $\theta \leq 60^\circ$ and the jet velocity to be $\geq 0.5c$. The morphology of the Embryo suggests possible hints for the kinematics of the host galaxy within the ICM: the slight bending of the northern jet can be caused by the motion of the host galaxy toward the north-east direction, with the southern jet which is not affected by such dynamics.

4.4 Characterization of the filaments in the Original TRG

In this Section, we describe and discuss the properties related to the morphology and the emissivity of the filaments detected in the Original TRG, based on what we have observed at 144 MHz from LOFAR-VLBI. We distinguished several morphological features presented in Section 4.3.2 and highlighted in Figure 4.4. Projected lengths can be directly measured from the map. The main tail, which develops from the northern jet, extends for ~ 140 kpc before linking with the horizontal filament. The horizontal filament extends for about 110 kpc on the east-west direction, with a forking on the west side. The vertical filament's length is ~ 105 kpc. The F1 filament has length of ~ 83 kpc, measured from the gap to the horizontal filaments (where it ends up); F2 is instead more challenging to isolate with respect to the other features, given the tight connection with the horizontal filament and the upper end of the main tail. In this case, spectral index information will be helpful in determining the properties of its electron population and, thus, its origin. Overall, considering all

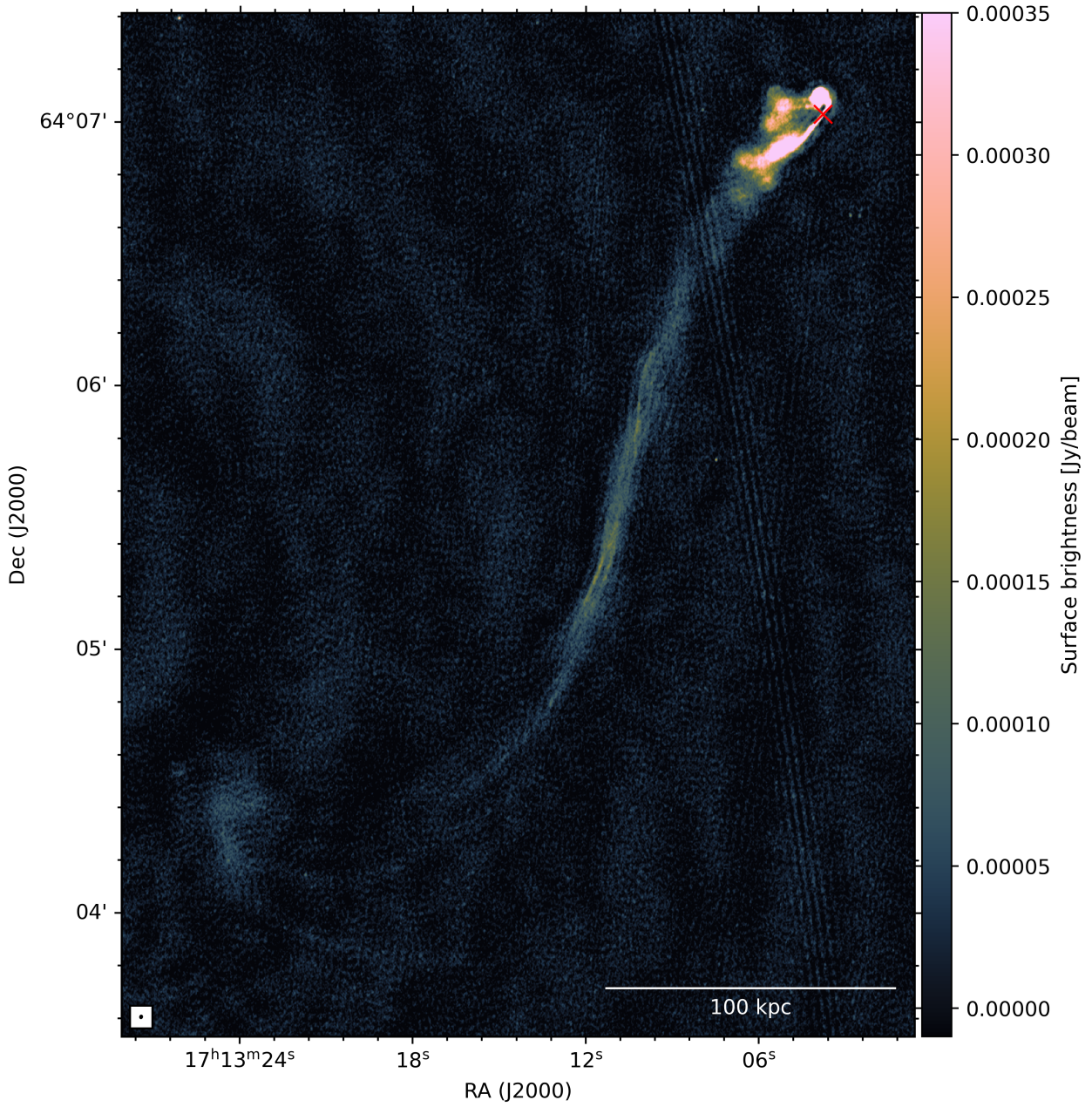


FIGURE 4.5: The Goldfish at 144 MHz; resolution of $0.55'' \times 0.41''$, rms noise of $29 \mu\text{Jy beam}^{-1}$. This image was obtained using Briggs weighting, robust = -0.5 , and multiscale. The restoring beam size is shown in the bottom-left corner. The red cross identifies the optical position of the host galaxy as listed in Table 4.2.

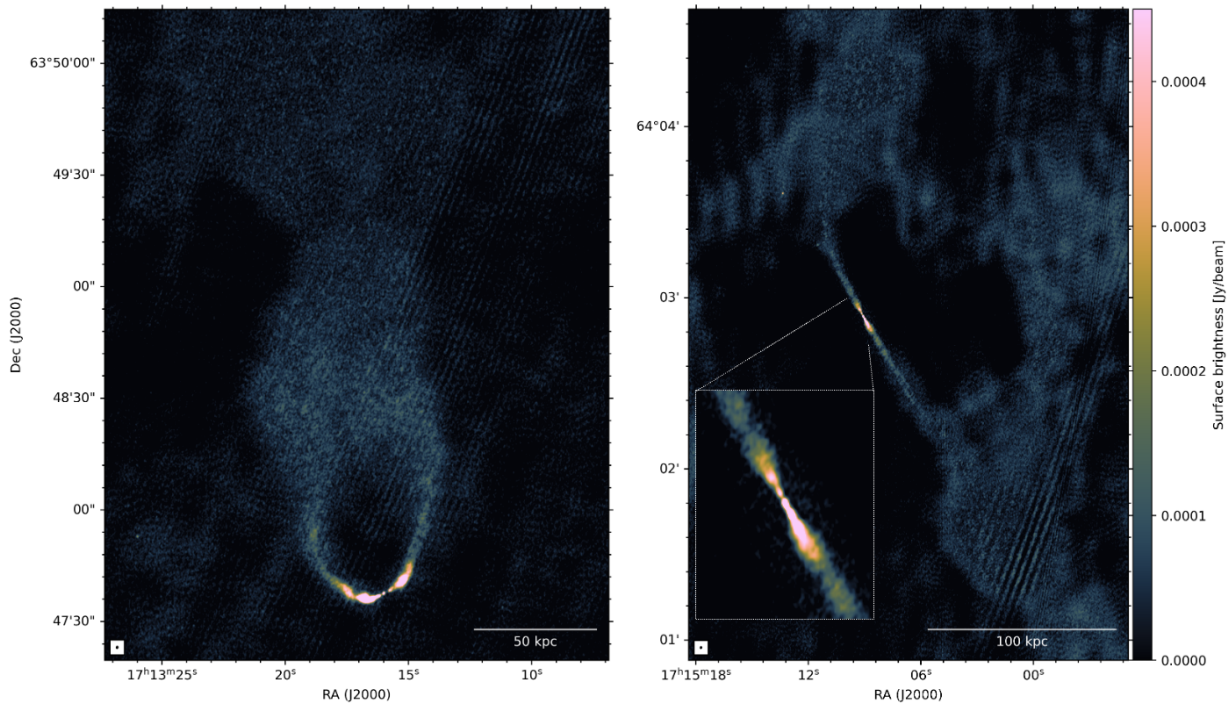


FIGURE 4.6: Left: the Beaver at 144 MHz, resolution of $0.54'' \times 0.40''$, rms noise of $27 \mu\text{Jy beam}^{-1}$. The image was obtained using Briggs weighting, robust = -0.5 , and multiscale. Right: the Embryo at 144 MHz, resolution of $0.55'' \times 0.40''$, rms noise of $40 \mu\text{Jy beam}^{-1}$. The image was obtained using Briggs weighting, robust = 0.5 , and multiscale. Bottom-left panel: Zoom-in view of approximately 32 kpc centered on the source. For both images, the restoring beam size is shown in the bottom-left corner.

three components (main tail, horizontal and vertical filament) the Original TRG complex extends for at least $\sim 3'$ (~ 270 kpc).

To measure the width of the filaments and the main tail, we traced multiple transversal cuts (as the one shown in Figure 4.7, dashed white arrow) across the Original TRG, obtaining a spatial surface brightness profile for each cut. The rms noise of the image was quadrature-subtracted to the brightness values and the resulting profiles were fitted with single or multiple Gaussian profiles. For the fit, we used the non-linear least squares method. The number of Gaussians of the model function was chosen by a visual inspection of the surface brightness profiles along the cuts. The amplitude, standard deviation, and center of each Gaussian were allowed to vary; as an initial guess, we used values of 1.0 for the amplitude and the standard deviation, while for the center we used equidistant values (depending on the number of Gaussians) distributed within the length of the cut. The beam-deconvolved full width at half maximum of the fitting Gaussian is then considered to be the width of the corresponding feature. An example of three-Gaussian fit for the central part of the Original TRG, which includes F1, the main tail, and F2, is shown in the bottom panel of Figure 4.8. The main tail has widths that start from 1.8 kpc (at the point where it starts developing from the northern jet) to 3.5 – 4.7 kpc between the eddies. Moving upward, the width ranges between 8 and 13 kpc: then, it mixes up with the horizontal filament. The F1 filament has width ranging between 3 and 4.2 kpc (from the gap upward); F2, instead, exhibits a width of 5 kpc. The horizontal filament, when observed at such high-resolution, is resolved into multiple substructures - rather than appearing as a single monolithic structure, as highlighted in the top panel of Figure 4.7. We measured its width in the central brighter part (where there is a high-enough signal-to-noise ratio),

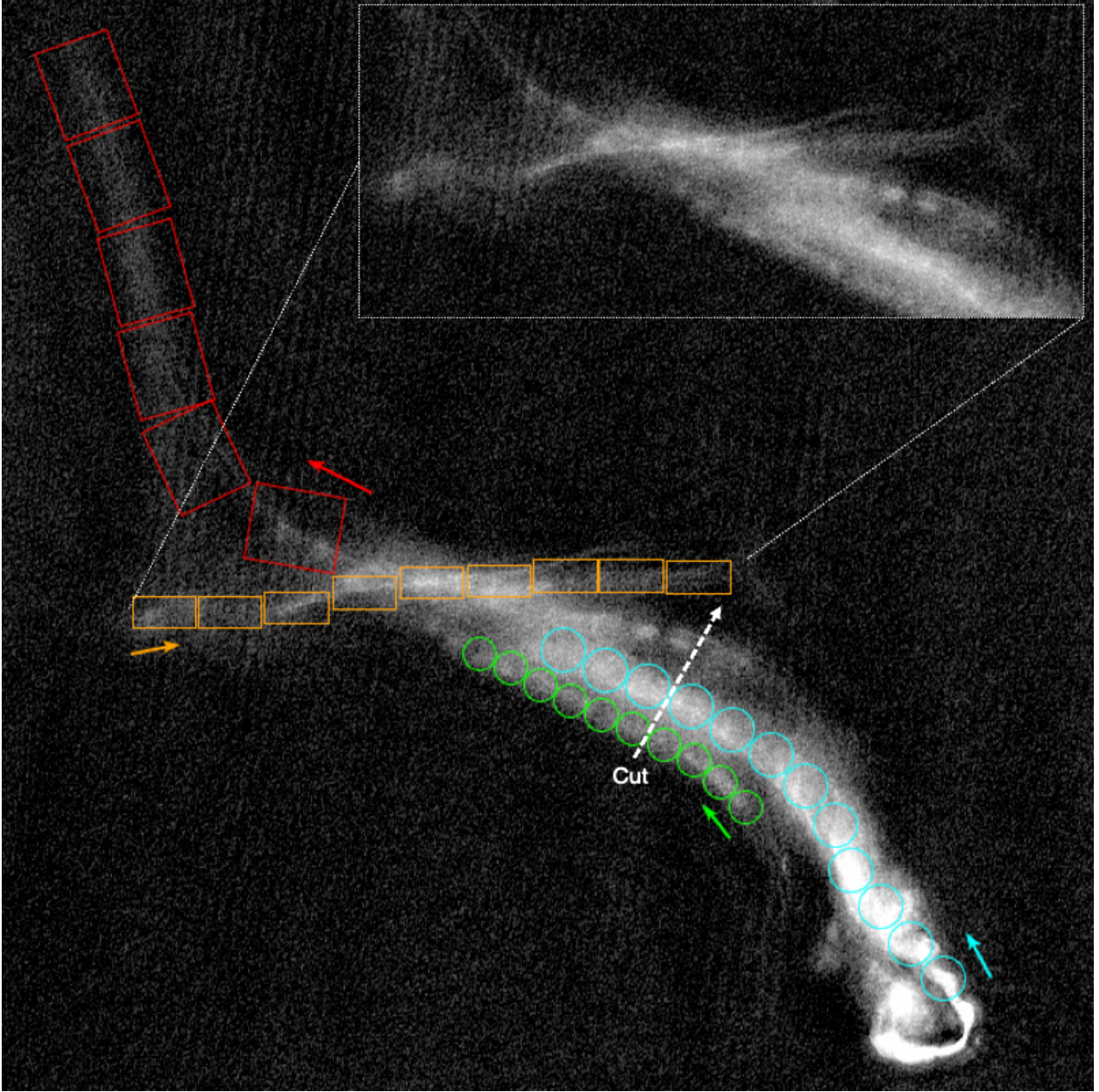


FIGURE 4.7: Same LOFAR-VLBI map for the Original TRG shown as in Figure 4.4 highlighting the regions used for determining the main morphological features associated to the radio galaxy using different colors. Arrow represent the direction of the transversal cut used to retrieve the filaments' widths depicted in the bottom panel of Figure 4.8. Top right corner: Details of the horizontal filament to highlight the main morphological patterns coexisting in this region.

to be $\sim 8 - 10$ kpc, even if there it is difficult to distinguish between the main tail, the horizontal filament and F2 as they are co-spatial. At the edges the detection is at the noise level. The vertical filament has almost constant width of about 4.5 kpc, with a forking at the bottom where it connects in two different parts to the horizontal one.

In Figure 4.8 we show also the flux density profiles along the main feature highlighted for the Original TRG in Figure 4.7: the main tail (in cyan), F1 (in green), the horizontal filament (in orange) and the

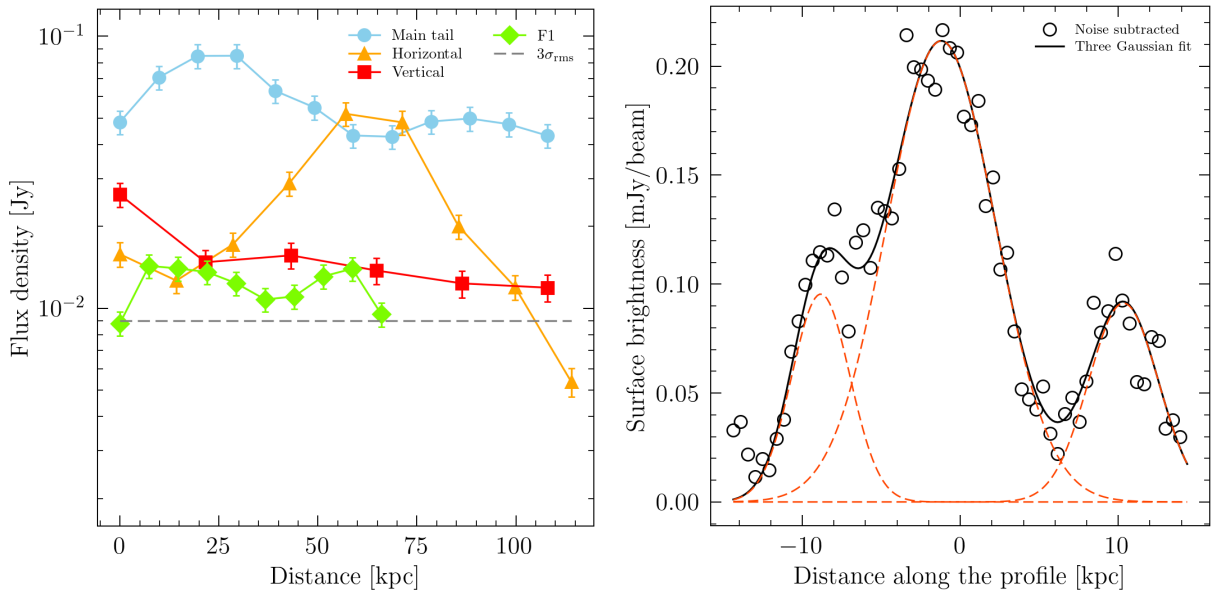


FIGURE 4.8: Spatial trends along the Original TRG and its filaments from regions highlighted in Figure 4.7. Top: Flux density along the main features of the Original TRG, highlighted in different colors. Error bars refer to the errors on flux densities, calculated assuming a 10% flux uncertainty (as for the LoTSS, Shimwell et al., 2022). Colored arrows indicate the direction followed by the spatial trends. Bottom: Profile across the Original TRG following the cut depicted in Figure 4.7. The noise-subtracted data are shown as open circles. The black solid line shows the total fit using three-Gaussian fit. The three Gaussians (individually shown with red dashed lines) correspond (from left to right) to F1, the main tail, and F2, respectively.

vertical one (in red). The brightness increase in the center of the horizontal filament is due, at least in part, to the overlap with the upper end of the main tail and (apparently) the F2 filament. At high angular resolution, filaments also show their non-thermal emission in multiple patches; this could indicate that their formation process does not act homogeneously along the filament’s extension and, instead, could have some local contribution that enhances the radio emission.

Having thin and long non-thermal filaments, with the horizontal and vertical ones that also show a particularly straight shape, may suggest a common formation scenario with the E-fils observed by Rudnick et al. (2022) in the radio galaxy 3C40B in Abell 194. In that case, the preferred formation scenario relied on the amplification of the magnetic field through shear stretching of magnetic field lines: the observed filaments would then be made by smaller bundles of illuminated and aligned fibers, held together by tension along the field lines. The thickness of the fibers should reflect the transverse resistivity scales, while their length reflects the driving scales of the local turbulent flow (Vazza et al., 2018). For A2255, given the presence of turbulence associated to the merging state of the cluster, this can reach the cluster scale. From the filament length we can evaluate its dynamical lifetime, which is essentially the cascading time of the turbulent eddy on scale L . Assuming a turbulence Mach number of $\mathcal{M} = 0.5$ and a characteristic ICM sound speed $c_s \sim 10^3 \text{ km s}^{-1}$ (Porter et al., 2015), we end up with

$$\tau_{\text{dyn}} \sim \frac{L}{\mathcal{M} \cdot c_s} \sim \frac{L}{0.5} \text{ Myr.} \quad (4.2)$$

Our filaments have lengths ranging between 80-110 kpc, resulting in $\tau_{\text{dyn}} \sim 160 - 220 \text{ Myr}$: this is comparable to the synchrotron radiative lifetimes ($10^7 - 10^8 \text{ yr}$), meaning that electrons have sufficient time to emit all their energy via synchrotron radiation before the filament gets dissipated

by the turbulence. The stretching of the magnetic field lines implies magnetic field amplification by a factor proportional to $\rho v^2/l$, where ρ is the density of the turbulent ICM, with characteristic velocity, v , on the driving scale, l . This causes enhancement in the magnetic field pressure $P_B = B^2/8\pi$, which becomes compatible with the thermal pressure, reducing the plasma beta of the filaments (Equation 2.15). We expect the filaments, given also their straightness, to have very low plasma beta (approaching unity), being high-magnetic pressure regions. In support of this scenario, some cases have shown an overlap between the presence of non-thermal radio filaments and the absence of thermal, X-ray emitting ICM (Rudnick et al., 2022).

4.5 Conclusions

In this work, we present LOFAR-VLBI observations at sub-arcsecond resolution of the brightest cluster radio galaxies in the merging cluster Abell 2255, obtained using 56 hours of observations. These images represent the deepest ones obtained to date using LOFAR-VLBI for a galaxy cluster. The unique resolution and sensitivity capabilities of LOFAR IS revealed unprecedented structures connected to the radio galaxies, particularly with respect to the Original TRG, where several filaments have been discovered around the tail and attached to its upper end. Despite being already observed in other galaxy clusters and groups, especially in the presence of a turbulent ambient medium, this represents the first time that these objects have been observed at such high resolution, demonstrating the potential of LOFAR-VLBI observations for these elongated, non-thermal filaments. They have lengths ranging from 80 to 110 kpc, with varying widths along their extension (3 – 10 kpc), as seen for other cases observed in other clusters (such as in Abell 194, Rudnick et al., 2022). Being thin and straight, there is the possibility that, as the ones in A194, they present very low plasma beta due to the amplification of magnetic field caused by shear stretching of field lines. One peculiarity observed is the patchiness of the radio emission along the filaments, which may suggest further hints about their formation scenario.

To constrain the nature and the origin of these filaments, in Chapter 5 we present observations at higher frequencies of the Original TRG using uGMRT (Band 5) and VLA (L-band). Providing a resolution of $1.5''$, these images allow for high-resolution spectral index analyzes of the filaments to constrain their radio spectral properties and disentangle multiple spectral components that are co-spatial in the Original TRG from lower-resolution studies. In addition, we also present additional filaments detected with LOFAR-VLBI at $1.5''$ resolution on larger scales extending for ~ 250 kpc east of the Original TRG, originally known as the Trail (Botteon et al., 2020b).

Chapter 5

Revealing the intricacies of radio galaxies and filaments in the merging galaxy cluster Abell 2255. II. Properties of filaments using multi-frequency radio data

¹In this Chapter, we aim to further analyze the filaments in Abell 2255 combining LOFAR data with uGMRT (1260 MHz) and VLA (1520 MHz) data to constrain the spectral shape of the filaments. This allows studying their morphological properties, required to understand their origin, at unprecedentedly high resolution (~ 2.3 kpc), crucial to disentangle the different cosmic ray components that populate the Original TRG.

We produced a LOFAR-VLBI map at $1.5''$ resolution using the wide-field technique with 56 hours of observations. This was the first time this technique was used for targeting a galaxy cluster, especially for such deep observations. uGMRT and VLA data have been calibrated and imaged to produce spectral index maps and to apply further techniques to extract additional information, such as the radiative ages of the filaments or their equipartition magnetic field. Polarization information was also obtained using VLA through the rotation measure synthesis technique.

Thanks to the LOFAR-VLBI wide-field image at 144 MHz, we revealed additional, very steep ($\alpha > 2$) filaments beyond those attached to the radio galaxy, extending for around 250 kpc and previously known as the Trail. Combining LOFAR-VLBI with uGMRT and VLA, we found integrated spectral values between 1.1 – 1.7 for the filaments. Spectral analysis revealed also that the Original TRG has a complex structure, showing overlapping features with distinct spectral indices that extend throughout its tail. Polarized emission emerges only from the tail and the brightest part of the filaments, with values up to 22%. Although there is no clear scenario regarding the formation of filaments, we highlight the importance of the Original TRG as the main driver of such structures, even at larger distances from the core.

5.1 Introduction

In Chapter 4, we presented deep (56 hours), ILT observations at 144 MHz of the main tailed radio galaxies in A2255. Thanks to the high-sensitivity and sub-arcsecond resolution ($0.3'' - 0.5''$), we resolved a wealth of filamentary emission (labeled in Figure 5.1 as in Chapter 4), especially surrounding the wake of the Original TRG, a NAT radio galaxy projected close to the cluster center.

¹This Chapter is based on De Rubeis et al. (2025d)

We characterized the morphological properties of these filaments, having lengths of 80 – 110 kpc and varying widths between 3 – 10 kpc. Given that their length is directly related to the driving scales of the turbulent flow (Vazza et al., 2018), we found that the dynamical lifetime of the filaments is comparable with the synchrotron radiative lifetime of electrons ($10^7 - 10^8$ yr), meaning that these can survive long enough to display radio emission before being dissipated by turbulence.

In this Chapter, we aim to study the physical properties of the filaments in A2255 combining LOFAR-VLBI image at 144 MHz with data from the uGMRT at 1260 MHz and the VLA at 1520 MHz. Data at higher frequencies are required to obtain spectral and polarization information on such structures, given that such structures have shown to be highly polarized in some cases (e.g., Condon et al., 2021; Rudnick et al., 2022; Cotton et al., 2025), while maintaining a sufficiently high angular resolution ($1.5''$) to disentangle all the various components already observed in Chapter 4. The emission from these filaments is expected to be strongly polarized due to the magnetic field being ordered along these structures. To improve the detection of the more extended filaments, linked to the upper end of the Original TRG and observable only at LOFAR frequencies (like the so-called Trail and T-bone, Botteon et al., 2020b), we used the LOFAR-VLBI wide-field technique (Section 3.4.2), which enables imaging a FoV up to $2.5^\circ \times 2.5^\circ$ using LOFAR international stations down to sub-arcsecond resolution with the HBA. After its first employment by Sweijen et al. (2022), to image the Lockman Hole field, this method was improved by recent works for the ELAIS-N1 (Ye et al., 2024; de Jong et al., 2024; de Jong et al., 2025a) and Boötes (Escott et al., *submitted*) fields. For A2255, we used an intermediate resolution of $1.5''$, required to match that of higher frequency observations, combining all the 56 hours of observations already used for Chapter 4, imaging a region of $1.5^\circ \times 1.5^\circ$ around the cluster. This resolution is optimal to recover the more extended emission (such as the one from the filaments, especially in the low signal-to-noise regime), and combined with smaller image size (with respect to previous works) allows to reduce the imaging computational time, which is the true bottleneck of the wide-field data processing (about 80% of the total time for full resolution imaging, as found in de Jong et al., 2024). This represents the first work in which this technique was used to target a galaxy cluster.

5.2 Data calibration and imaging

5.2.1 LOFAR HBA data

The calibration strategy used for the LOFAR-VLBI data at 144 MHz (observations listed in Table 5.1) is extensively described in Chapter 4. We refer the reader to it for a detailed description of the Dutch stations calibration, and will focus our discussion here on the calibration of the IS for the wide-field imaging. We followed the procedures described in Morabito et al. (2022) and de Jong et al. (2024), with different ad-hoc adjustments, especially in the imaging step, required by the highly complex morphology of A2255, with the combination of extended and structured radio galaxies overlapping the cluster radio halo.

Telescope	Obs. ID	Date [YYYY-MM-DD]	Band [MHz]	On-source time	Robust	Restoring beam, PA	σ_{rms} [$\mu\text{Jy beam}^{-1}$]
LOFAR	L720378	2019-06-07		8 h			
	L725454	2019-06-22		8 h			
	L726708	2019-06-28		8 h			
	L727110	2019-07-03	120 – 168	8 h	–1.5	$1.5'' \times 1.5'', 0^\circ$	38
	L733077	2019-08-09		8 h			
	L747613	2019-09-28		8 h			
	L751366	2019-10-04		8 h			
uGMRT	46_063	2024-07-23		9.33 h			
	48_082	2025-05-29		7.2 h			
	48_082	2025-07-01	1060 – 1460	8.5 h	–1.0	$1.5'' \times 1.5'', 0^\circ$	5
	48_082	2025-09-14		8.5 h			
VLA (C)	14B-165	2014-10-26		4.46 h			
VLA (B)		2015-02-28	1008 – 2032	6.27 h	–0.5	$1.3'' \times 1.2'', 94.5^\circ$	3
VLA (A)	24B-067	2024-12-28		8.65 h			

TABLE 5.1: List of the observations used in this work and final maps properties. Column 1: telescope. Column 2: ID of the observation. Column 3: date of the observation. Column 4: observing band. Column 5: time on source. Column 6: robust parameter used for Briggs weighting during imaging. Column 7: restoring beam size. Column 8: final rms noise.

Direction-independent calibration of the ILT

Solutions from the Dutch array corrected for both DIE and DDE were transferred to the IS. Then, the datasets were concatenated into sub-bands of 1.95 MHz. Given that we aimed to image only the cluster field, and that the IS have a reduced FoV with respect to the Dutch stations because of the larger number of antenna tiles (Morabito et al., 2022), we subtracted all the sources outside a box region of $1.5^\circ \times 1.5^\circ$ using the sky model provided by the DDF-PIPELINE at $6''$ resolution. The source subtraction was performed individually for each sub-band of each observation: to speed up this step, we split the subtraction among different computing nodes using the Pleiadi computing system (Taffoni et al., 2024). Each of the available 24 nodes² is equipped with 256 GB of RAM and 8 TB of local storage. This allowed us to subtract multiple sub-bands in parallel, gaining a factor four in wall-clock time for the subtraction of a single observation. The resulting subtracted datasets were then used for further calibration of the IS.

We selected 4C +64.21 (RA: $17^h19^m59^s$, Dec: $64^\circ04'37''$, Pilkington & Scott, 1965) as the most suitable delay calibrator from the LBCS, a powerful radio source, compact on arcsec-scale, with flux density of ~ 4.87 Jy at 144 MHz. In Chapter 4, we detailed the initial sky model that we built and used for self-calibration on this source. We used FACETSELFAL to perform self-calibration. The adopted strategy follows the one described in de Jong et al. (2024), with some adjustments made for the characteristics of our calibrator.

1. `scalarphasediff`: solution interval 8 min, frequency smoothness 10 MHz;
2. `scalarphase`: 32 s, frequency smoothness increasing at each step from 2 to 20 MHz;
3. `complexgain`: 20 min, frequency smoothness 7.5 MHz;
4. `scalaramplitude`: 120 min, over the whole band.

We ignored all baselines shorter than 40 k λ , corresponding to an angular scale of about $5''$ at 144 MHz, using the parameter `uvmin`, to prevent possible incompleteness in the sky model. Through FACETSELFAL, we also averaged the input data down to 32 s in time and 488 kHz in frequency and used a Briggs weighting with robustness of -1.5 for the imaging (Briggs, 1995). At the end of the self-calibration routine on the in-field calibrator, one Hierarchical Data Format 5 solution file (`h5parm`) for each calibration step and one containing all the solutions merged, with phases and amplitudes corrections, are produced. The best solutions for visibilities were obtained after 19 self-calibration cycles.

Direction-dependent calibration of the ILT

After the DIE correction for the IS there are still residual DDE across the FoV, mainly due to the ionosphere and errors in the beam model, that need to be corrected. The standard strategy to correct for DDEs in the LOFAR-VLBI wide-field imaging is to select a number of direction-dependent calibrators across the field, dividing it into as many smaller facets, calibrate against these sources, and apply the resulting solutions across the entire resident facet (the so-called *faceting* technique, van Weeren et al., 2016). To choose suitable DDE calibrators, we ran the Python Blob Detector and Source Finder (PyBDSF³, Mohan & Rafferty, 2015) on a preliminary wide-field, DIE corrected, image at $1.5''$ resolution, obtaining a catalog of the sources in the field. Among all the detected sources, we selected only those with a peak surface brightness above 20 mJy beam $^{-1}$ within the selected area. A further visual selection was made based on the source morphology and flux (more compact and brighter), to remove bad candidate DDE calibrators beforehand.

²36 CPUs Intel Xeon E5-2697 v4

³<https://pybdsf.readthedocs.io/en/latest/>

RA (J2000)	Dec (J2000)	$\langle\sigma_{\text{rms}}\rangle$ [$\mu\text{Jy beam}^{-1}$]
17 ^h 13 ^m 29 ^s	64°02′49″	35
17 ^h 08 ^m 02 ^s	64°04′24″	41
17 ^h 08 ^m 14 ^s	63°51′17″	41
17 ^h 10 ^m 35 ^s	64°29′53″	35
17 ^h 10 ^m 55 ^s	64°51′07″	42
17 ^h 11 ^m 48 ^s	63°56′04″	36
17 ^h 12 ^m 59 ^s	64°09′31″	37
17 ^h 14 ^m 23 ^s	63°57′07″	33
17 ^h 17 ^m 36 ^s	64°53′21″	44
17 ^h 19 ^m 17 ^s	63°34′13″	42

TABLE 5.2: List of selected direction-dependent calibrators. Column 1: right ascension (in J2000). Column 2: declination (in J2000). Column 3: average rms noise of the final image from self-calibration.

We detail hereafter the calibration strategy to deal with DDE: all these steps have been done for each observation individually. We phase-shifted the subtracted datasets toward the direction of the candidate DDE calibrator for each sub-band, averaging the datasets down to 195.31 kHz and 16 seconds. Then, solutions from DIE calibration of the delay calibrator were applied to all the sub-bands, which were finally concatenated to obtain a unique dataset for each calibrator. Every DDE calibrator candidate was self-calibrated with FACETSELFAL, firstly using the automated settings and then, where necessary, refining the calibration with a better suited strategy. With the `auto` mode, the script is optimized to set automatically several calibration parameters, such as the solution interval. In case of divergent or not improving solutions with increasing self-calibration cycles we manually tweaked the solution interval and the frequency smoothness. We used as solution types two rounds of `scalarphase`, with the first one that resets the solution to 0.0 (for the phases) and 1.0 (for the amplitudes) for the Dutch stations (de Jong et al., 2025a), with an increasing solution interval ranging from 1-5 minutes. Then, we also used a `scalarcomplexgain` solve with a longer solution interval (120 minutes) and larger frequency smoothness (10-20 MHz). After a careful evaluation of self-calibration solutions from inspection plots and from final images, we ended up with 10 direction-dependent calibrators that were used to correct for DDE (listed in Table 5.2 and encircled in red in Figure 5.3).

One of the selected direction-dependent calibrators (J171259+640931) is located, in projection, just above the cluster center. After applying the solutions from this calibrator to its resident facet, the radio galaxies that populate the cluster center still showed several artifacts, requiring additional calibration refinement. We used the Double radio galaxy as an additional calibrator (J171329+640249), adding a secondary layer of calibration to adjust the phases for the central region of the cluster. On the Double, we used two rounds of `scalarphase` with solution interval of 5 minutes. The first one is in charge of resetting the solutions for the Dutch stations, while the second uses a smoothness in frequency over the whole bandwidth. Moreover, given the extended morphology of the source, we enabled the `multiscale` deconvolution algorithm (Offringa & Smirnov, 2017), setting a maximum number of seven, automatically selected, scales for the cleaning. The output solutions resulted in improved solutions quality for the most crowded region of the field.

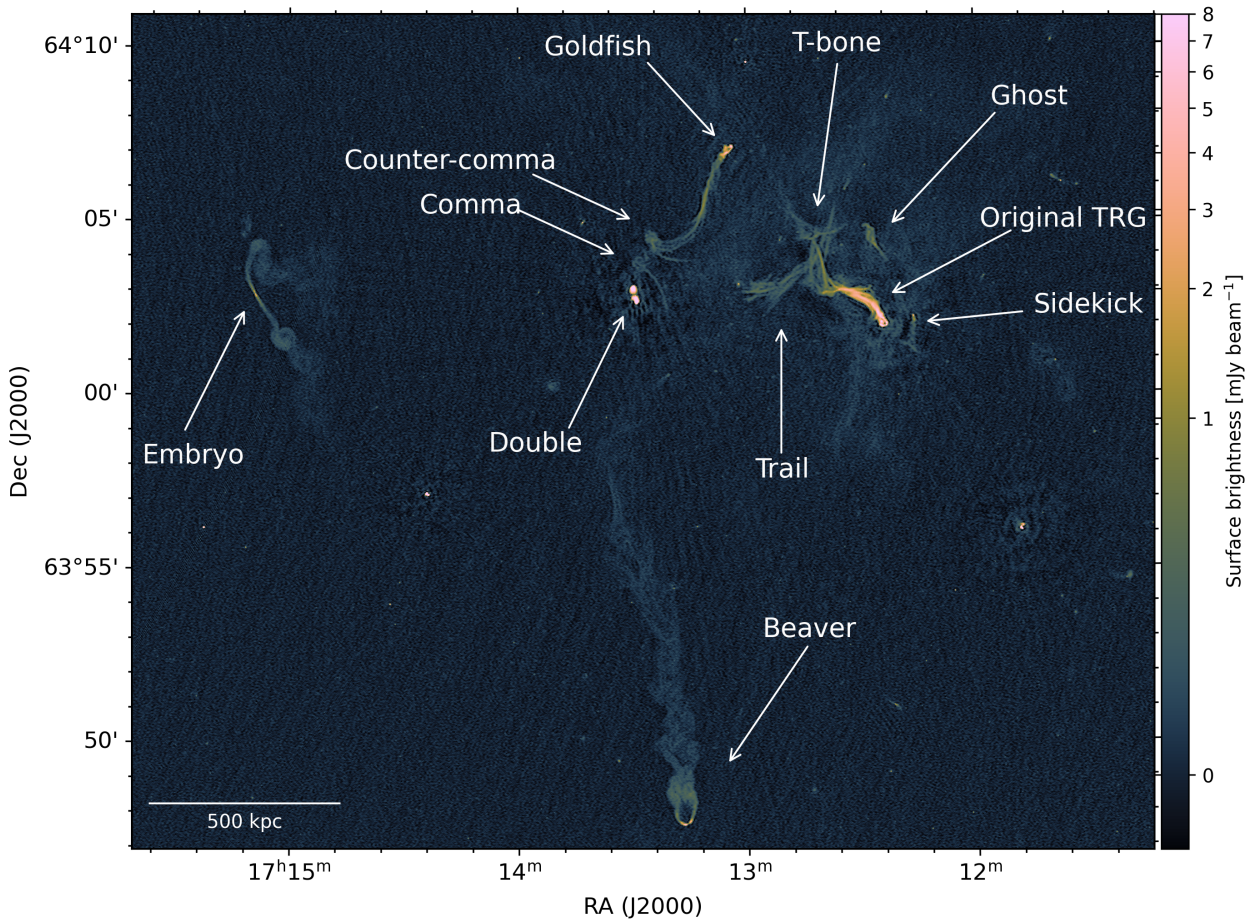


FIGURE 5.1: LOFAR-VLBI wide-field image of A2255 at 144 MHz comprehending the major cluster member radio galaxies and diffuse features, labeled in white following the nomenclature in Botteon et al. (2020b). The final image has resolution of $1.5''$ resolution, with rms noise of $38 \mu\text{Jy beam}^{-1}$. The restoring beam is shown in the bottom-left corner.

Wide-field imaging

The wide-field image was produced with an angular resolution of $1.5''$, covering a field of view of $1.5^\circ \times 1.5^\circ$, centered on RA $17^{\text{h}}14^{\text{m}}33^{\text{s}}.03$ and Dec $+64^\circ11'04''.10$. The different observations, which have been calibrated individually, are finally combined in this step. Before imaging, we averaged the input datasets by a factor of four in both time and frequency, which means a final time and frequency resolution of 4 s and 48.84 kHz, respectively. This ensures to have negligible smearing effects at the imaging resolution (de Jong et al., 2024), especially considering that most of the target sources of our analysis are close to the pointing center. To apply the corrections found for DDE calibration, we used the facet-based imaging in WSCLEAN, enabled by the parameter `facet-regions`, which requires a DS9 (Smithsonian Astrophysical Observatory, 2000) region file that contains all the facets used for wide-field imaging, produced through a Voronoi tessellation, wherein the calibration solutions are assumed to be constant (Schwab, 1984). The layout of the facets, together with the position of the resident direction-dependent calibrators, is shown in Figure 5.3. We also merged, for each observation, the h5parm solution files coming from all the selected DDE calibrators using the `H5_MERGER` script (de Jong et al., 2022): the h5parm merged files, for each observation, are used in WSCLEAN through the `apply-facet-solutions` option.

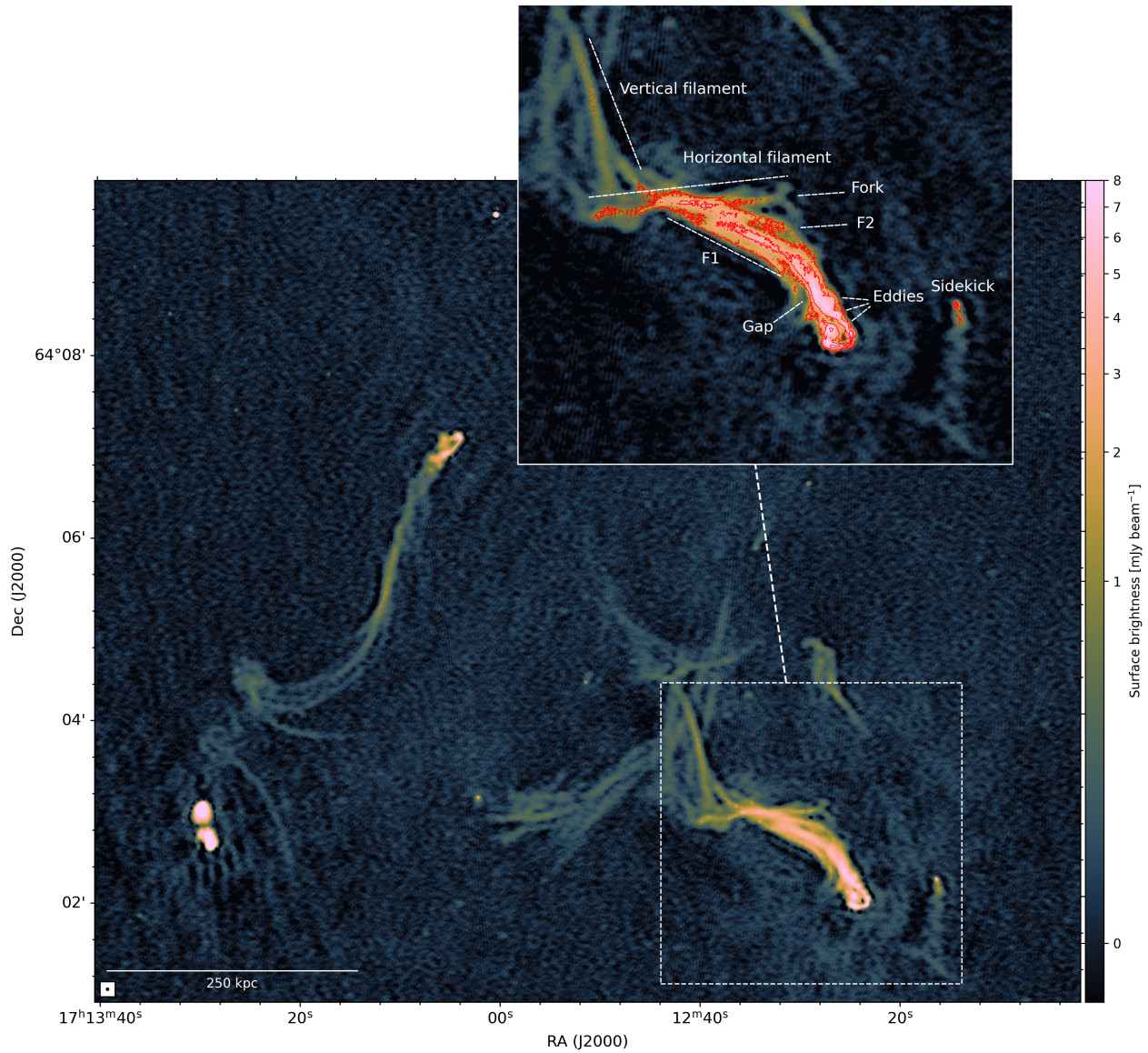


FIGURE 5.2: LOFAR-VLBI wide-field image of the central region (size $9.2' \times 7.5'$) of A2255 at 144 MHz (from Fig 5.1). The final image has a resolution of $1.5''$, with rms noise of $38 \mu\text{Jy beam}^{-1}$. The restoring beam is shown in the bottom-left corner. Top panel: zoom on the Original TRG with the main features labeled as in Chapter 4. The contour levels from the sub-arcsecond resolution image (Figure 4.4) are drawn in red at 3, 9, 27, 81, 243σ levels, with $\sigma = 18 \mu\text{Jy beam}^{-1}$.

The main difficulty in producing such images for a cluster field, especially for A2255, is the coexistence of diffuse emission up to several Mpc scales, which becomes more relevant with increasing sensitivity and enhances the local rms noise, and individual radio galaxies, especially with their thin ($\approx 4 - 10$ kpc) filamentary tails. If the rms noise is not correctly evaluated locally, the CLEANing process might not be deep enough for the sources embedded in the radio halo. Moreover, the tails and filaments are naturally disadvantaged during CLEAN because of their shape, which is elongated only along one direction. All of these points required specific settings and several imaging attempts to fine-tune the imaging strategy to be used in WSCLEAN.

For the final image (size $13,500 \times 13,500$ pixels, with $0.4''$ pixel scale), we used a spatially varying

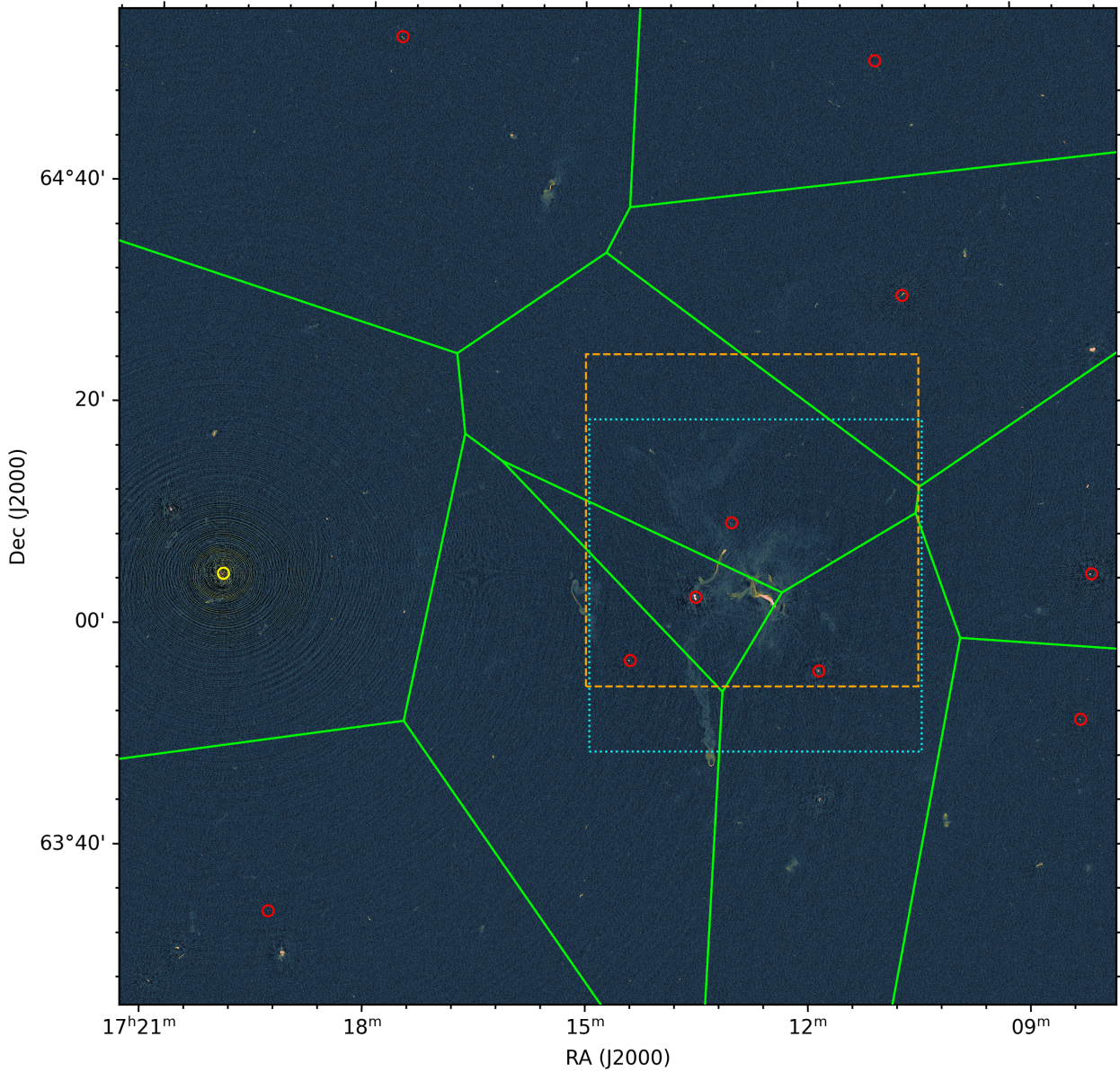


FIGURE 5.3: The facets layout (in green) for wide-field imaging with LOFAR-VLBI. In red we highlighted the position of the direction-dependent calibrators, while in yellow the delay-calibrator. We also indicated, with squares, the position and size of the full uGMRT (in cyan, dotted line) and VLA (in orange, dashed line) maps.

rms noise, evaluated within regions of 200 point spread functions (PSF) each, and enabled direction-dependent PSFs with a size of 3 cells in each direction; we employed a Briggs weighting scheme with robust -1.5 , automatic masking, multiscale deconvolution and parallel reordering and deconvolution. We imaged the whole FoV view at once, since the image fits the memory of a single computing node. After deconvolution, we corrected the image flux density scale using the in-field calibrator as a reference, given that it is a well known radio source on multiple frequencies: comparing the flux density at 144 MHz between the $6''$ and the $1.5''$ image, we found a correction factor of 1.067, which we applied to the whole image. The use of a sky model for the in-field calibrator already provided reasonably good astrometric accuracy (within $0.06''$ over the entire FoV with respect to the positions of the extragalactic objects provided by Gaia Data Release 3, Gaia Collaboration et al.,

2023). The final image, shown in Figure 5.1 (with a zoom on the central region in Figure 5.2), has a rms noise of $38 \mu\text{Jy beam}^{-1}$, with the main features labeled following the nomenclature in Botteon et al. (2020b). This represents the deepest and only LOFAR-VLBI wide-field image ever obtained targeting a galaxy cluster, and will be used for high-resolution spectral studies later in this Chapter.

5.2.2 uGMRT Band 5 data

We observed A2255 using the uGMRT in Band 5 (1060 – 1460 MHz) for around 33 hours on target (Table 5.1, proposal codes 46_063 and 48_082, P.I. De Rubeis). The bandwidth is divided into 4096 channels, each with a resolution of 97.656 kHz. For the first observation, both the uGMRT Wideband Backend (GWB) and the GMRT software Backend (GSB) were available; for the others, we used only the GWB. We processed all the data using the Source Peeling and Atmospheric Modeling pipeline (SPAM, Intema et al., 2009). For each observation, the wideband data were split into six sub-bands, spanning around 66 MHz each, which were independently processed. After flux density scale calibration and bandpass (primary calibrators: 3C48 for the first observation, 3C286 for the second observation), using the flux density scale model from Scaife and Heald (2012), the pipeline corrects for direction-independent gains using a starting global sky model obtained from GSB data. Given the lack of a sufficient number of sources to peel for the direction-dependent self-calibration, we settled with the direction-independent ionospheric corrections. To produce deep, wideband images, we combined the calibrated sub-bands and imaged the data with WSCLEAN. We used the multiscale deconvolution algorithm, and automatic masking for deconvolution with a spatially varying rms noise for masking. The final image, whose zoom around the Original TRG is shown in the top panel of Fig. 5.4, central frequency 1.26 GHz, was obtained using a Briggs robust of -0.5 to reach a noise level of $5 \mu\text{Jy beam}^{-1}$.

5.2.3 VLA L-band data

A2255 was observed with the VLA in L-band (1008 – 2032 MHz) in A-configuration for a total amount of 10 hours (Table 5.1, proposal code 24B-067, P.I. De Rubeis). The bandwidth is divided into 1024 channels, each with a resolution of 1000 kHz. We processed the data using the VLA CALIBRATION PIPELINE v2024.1.0.8, which uses the Common Astronomy Software Applications (CASA v6.6.5.31 CASA Team et al., 2022) to perform total intensity standard flagging and calibration procedures. We used 3C286 as the primary calibrator for bandpass, using the flux density scale model from Perley and Butler (2017), and J1634+627 as the secondary calibrator for gains. Subsequent to reviewing the calibration outcomes from the National Radio Astronomy Observatory’s (NRAO) automatic data processing, it became necessary to re-execute the pipeline for supplementary data flagging. The primary calibrator was also used for the calibration of the absolute polarization angle: we modeled the polarization angle as in Hugo and Perley (2024), which observed a drop in the intrinsic angle of 3C286 approaching the lower bound of the L-band. The secondary calibrator was used instead to calibrate the on-axis instrumental leakage. We made a polynomial fit to its known values of linear polarization fraction and polarization angle to build a frequency-dependent polarization model, following the NRAO polarimetry guide⁴. The final calibration tables were applied to the target. Radio frequency interference (RFI) was removed both manually and using statistical flagging CASA algorithms also from the cross-correlation products. For Stokes I imaging, together with data in A-configuration, we added archival data of the same target in B- and C-configuration (proposal code 14B-165, P.I. L. Rudnick), to add short spacings and increase the sensitivity, especially to the more extended emission of the filaments. The calibration strategy for these data will be detailed in an upcoming publication (Rajpurohit et al. *in preparation*). We concatenated the measurement

⁴<https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol>

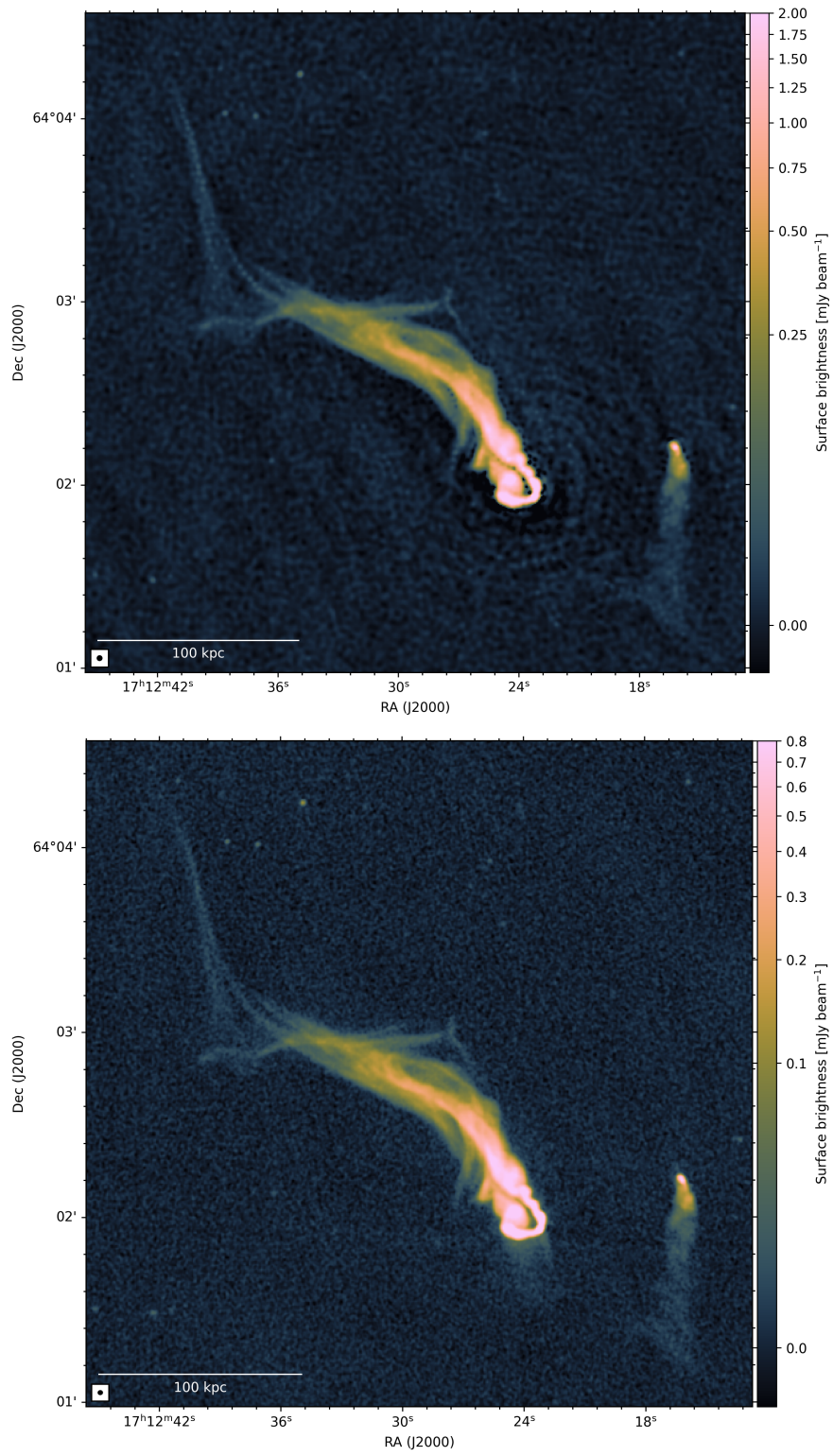


FIGURE 5.4: Original TRG radio maps at GHz frequencies. Top: uGMRT map of A2255. Total intensity image in Band 5 (central frequency 1260 MHz), resolution $1.5'' \times 1.5''$, rms noise $5 \mu\text{Jy beam}^{-1}$. Bottom: VLA map of A2255. Total intensity image in L-band (central frequency 1520 MHz), resolution $1.3'' \times 1.2''$, rms noise $3 \mu\text{Jy beam}^{-1}$.

sets and re-calculated the weights based on the new data. Then we imaged the concatenated visibilities using WSCLEAN 3.5. The final image was obtained using a Briggs weighting scheme, with `robust=-0.5`, and `multiscale` deconvolution algorithm. A zoom in on the Original TRG is shown in the bottom panel of Figure 5.4. It has an rms noise of $\sim 3 \mu\text{Jy beam}^{-1}$, a final synthesized beam of $1.3'' \times 1.2''$. We also performed several rounds of self-calibration to further improve the final image, but since these efforts did not yield significant improvements, the self-calibration results were not included in this work.

5.3 Methods

5.3.1 Spectral index maps

To study the formation and characteristics of the observed filaments, we produced spectral index maps of the cluster center combining maps at 144 MHz, 1260 MHz, and 1520 MHz, having a common resolution of $1.5''$ (corresponding to a physical scale of 2.3 kpc at the cluster redshift). Highly resolved spectral index maps are important for disentangling different emitting components and substructures, especially along the Original TRG. The spectral index α is defined as

$$\alpha = -\frac{\ln(S_1/S_2)}{\ln(\nu_1/\nu_2)}, \quad (5.1)$$

with S_1 and S_2 being the flux densities at frequencies ν_1 and ν_2 , respectively. The errors on the spectral index values are computed using the standard error propagation formula

$$\Delta\alpha = \left| \frac{1}{\ln(\frac{\nu_1}{\nu_2})} \right| \sqrt{\left(\frac{\Delta S_1}{S_1} \right)^2 + \left(\frac{\Delta S_2}{S_2} \right)^2}, \quad (5.2)$$

where ΔS_1 and ΔS_2 are the flux density errors for S_1 and S_2 , respectively, evaluated as

$$\Delta S = \sqrt{(f_{\text{cal}} \cdot S)^2 + (\sqrt{N_{\text{beams}}} \cdot \sigma_{\text{rms}})^2}. \quad (5.3)$$

Here, f_{cal} is the absolute flux density calibration uncertainty, S the flux density, σ_{rms} the rms noise, and N_{beam} is the number of beams covering the source. We assumed the absolute flux density uncertainty to be 10% for the LOFAR-VLBI (Shimwell et al., 2022; Timmerman et al., 2022), 5% for the uGMRT (as in Lal, 2020), and 4% for the VLA (as in Perley & Butler, 2013).

To ensure recovery of flux on the same spatial scales for all the observed frequencies, imaging was done with an inner uv -cut at 420λ , corresponding to the largest minimum baseline among the three interferometers (namely the uGMRT); we used a common resolution, and Briggs `robust` of -1.5 for the LOFAR-VLBI and -0.5 for the uGMRT and VLA map, to balance the short spacings coverage and recover the emission from the extended features at higher frequencies. We checked the astrometric accuracy of the uGMRT and VLA maps with respect to LOFAR-VLBI (for which we checked the astrometry of the delay calibrator), and corrected the flux density scale of the uGMRT map following the routine explained in Appendix A.1. This ensured the flux scale between the Scaife and Heald (2012) and the Perley and Butler (2017) catalogs for 3C286 to be consistent, within the chosen flux density uncertainties; for LOFAR-VLBI, the two flux scales for 3C48 were already consistent within the flux density uncertainties (Perley & Butler, 2017). After re-gridding to a common pixelation, we computed the spectral index for each pixel having surface brightness values above a $3\sigma_{\text{rms}}$ threshold using the Broadband Radio Astronomy Tools (BRATS, Harwood et al., 2013; Harwood et al., 2015). This tool uses the linear least squares regression method in logarithmic space to fit the spectral index to the observed flux densities. The final spectral index map for the

Original TRG is shown in Figure 5.5 (with the spectral index error map shown in Appendix A.2) and discussed in Section 5.4.4.

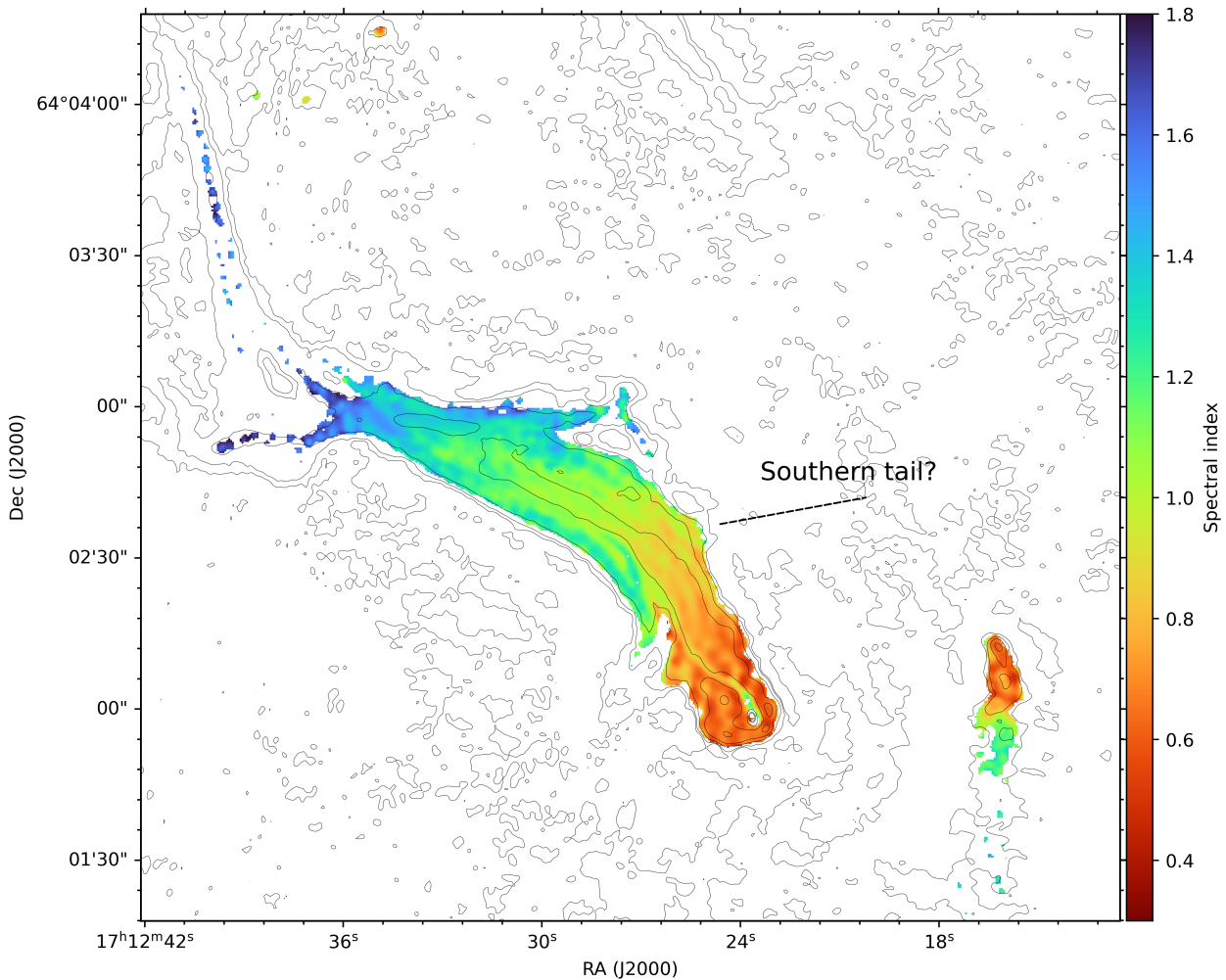


FIGURE 5.5: Spectral index map using LOFAR-VLBI (144 MHz), uGMRT (1260 MHz), and VLA (1520 MHz) data for the Original TRG. Grey contours represent 3, 6, 12, 24... σ_{rms} levels, with $\sigma_{\text{rms}} = 38 \mu\text{Jy beam}^{-1}$.

5.3.2 Radiative aging

Spectral index information is useful to recover the radiative age of the electrons in the tail and the filaments. Relativistic particles ejected from the core of radio galaxies are expected to progressively lose their energy mainly through synchrotron and IC radiation mechanisms (Section 2.2.1). The age due to synchrotron plus IC losses is then expressed, in Myr, by the following relation (Miley, 1980):

$$t = 1590 \cdot \frac{\sqrt{B'_{\text{eq}}}}{B_{\text{eq}}'^2 + B_{\text{CMB}}^2} \cdot \sqrt{\frac{1}{\nu_b(1+z)}}, \quad (5.4)$$

where ν_b is the break frequency in GHz, B'_{eq} is the revised equipartition magnetic field in, and B_{CMB} is the equivalent magnetic field of the cosmic microwave background in μG as $B_{\text{CMB}} = 3.25(1+z)^2$. Although our frequency coverage is not sufficient to determine the break frequency, we can use the formula derived in Bruno et al. (2019) to produce a radiative age map of the Original TRG using

the spectral index information, the injection index, and the revised equipartition magnetic field

$$t = \frac{1590}{\sqrt{(1+z)}} \cdot \frac{\sqrt{B'_{\text{eq}}}}{B'_{\text{eq}} + B_{\text{CMB}}^2} \cdot \sqrt{\frac{\ln(\nu_1) - \ln(\nu_2)}{\nu_1 - \nu_2}} \cdot (\alpha - \alpha_{\text{inj}}). \quad (5.5)$$

To obtain the revised equipartition magnetic field, we start from calculating the *standard* equipartition magnetic field, B_{eq} , assuming minimum energy density in the source as

$$B_{\text{eq}} = \left(\frac{24\pi}{7} u_{\text{min}} \right)^{1/2}, \quad (5.6)$$

with u_{min} being the minimum energy density in units of erg cm^{-3} and derived as

$$u_{\text{min}} = \xi(\alpha, \nu_1, \nu_2) (1+k)^{4/7} (\nu_0)^{4\alpha/7} (1+z)^{(12+4\alpha)/7} \times I_0^{4/7} d^{-4/7}. \quad (5.7)$$

Here, $\xi(\alpha, \nu_1, \nu_2)$ is a constant (see Table 1 in Govoni & Feretti, 2004), k is the proton-to-electron energy ratio, I_0 is the surface brightness in units of mJy arcsec^{-2} at frequency ν_0 in MHz, z is the redshift of the source, and d is the depth of the source in units of kpc. A filling factor of 1 was assumed. In this method, the synchrotron luminosity is calculated assuming a low and a high frequency cutoff: however, given that they depend on the energy of the emitting electrons, it is more appropriate to set a low and a high energy cutoff (Brunetti et al., 1997; Beck & Krause, 2005). This provides the so-called *revised* equipartition magnetic field

$$B'_{\text{eq}} \sim 1.1 \gamma_{\text{min}}^{\frac{1-2\alpha}{3+\alpha}} B_{\text{eq}}^{\frac{7}{2(3+\alpha)}}, \quad (5.8)$$

where γ_{min} is the minimum Lorentz factor for the electrons, assuming $\gamma_{\text{min}} \ll \gamma_{\text{max}}$. The value of B'_{eq} is based on several assumptions. k depends on the mechanism that generates the emitting electrons: in the literature it is usually assumed to be $k = 1$ or $k = 0$ (Govoni & Feretti, 2004) and this former value has been assumed for the filaments. We also assumed the filaments and the main tail to be cylinders, with depth d corresponding to their projected width, and for α we used the integrated values corresponding to each feature combining the LOFAR and VLA maps. The lower energy cutoff γ_{min} is difficult to estimate because it depends on the exact shape of the radio spectrum: we assumed $\gamma_{\text{min}} = 100$ (van Weeren et al., 2009). All these assumptions resulted in equipartition magnetic fields of 10 μG for the main tail, 13 μG for F1, 12 μG for the horizontal filament and 17 μG for the vertical one. The injection index was obtained using BRATS, which fits the spectral index of the target source and returns the value of α_{inj} that minimizes the distribution of χ^2 for the fitted model. We derived $\alpha_{\text{inj}} = 0.55 \pm 0.01$, in agreement with the values measured close to the core of the Original TRG.

Using the revised equipartition magnetic field and the injection index in Equation 5.5, we found radiative ages of 33 – 35 Myr for F1, ranging from 37 to 44 Myr from west to east for the horizontal filament, and ~ 36 Myr for the vertical one. For the Trail, considering the constraints on the spectral index, the radiative age is over 33 Myr. Of course, these values are based on the value of the assumed revised equipartition magnetic field, which, as already discussed above, relies on several assumptions. These actually depend also on the full history of the fields in which electrons were found, as well as unaccounted for possible adiabatic losses. Still, these time scales are well within the typical synchrotron radiative lifetimes of electrons; moreover, compared to the dynamical lifetime of the filaments (from Section 4.4, $\tau_{\text{dyn}} \sim 160 - 220$ Myr), we confirm that these filaments are younger than the time required to be dissipated by the turbulence.

5.3.3 Color-color diagrams

In tailed radio galaxies, one would expect to observe a progressive decline in surface brightness and steepening of the radio spectrum moving away from the core, due to synchrotron and IC losses of the relativistic particles (e.g., Feretti et al., 1998). However, thanks to the high resolution, we observed multiple narrow components that bind to the tail of the Original TRG showing enhanced surface brightness and local flattening of the spectral index (Figure 5.5). Moreover, the different filaments traced in the vicinity of the Original TRG show different spatial trends of spectral index, possibly not compatible with pure aging scenario (Section 5.4.4). This motivates a better investigation of different aging models, to constrain the nature and possibly the formation of these features. Radio color-color diagrams, first introduced by Katz-Stone et al. (1993), represent a useful tool to trace the spectral shape of different regions of a source. These are obtained by comparison of local spectral indices computed at two pairs of frequencies (specifically, the x-axis and y-axis report the low-frequency and high-frequency spectral index, respectively). An example is shown in the right panel of Figure 2.4 (van Weeren et al., 2012). The points located on the bisector correspond to regions of plasma with a power-law spectrum having injection spectral index α_{inj} ; the ones located below correspond, instead, to regions showing particles aging ($\alpha > \alpha_{\text{inj}}$). Such diagrams are generally used to discriminate between theoretical synchrotron aging spectral models. In fact, the position of the points depends on the aging model, which were introduced in Section 2.2.1. For our analysis, we used a low-frequency spectral index between LOFAR-VLBI at 144 MHz and uGMRT at 1260 MHz (α_{144}^{1260}) and a high-frequency spectral index between uGMRT at 1260 MHz and VLA at 1520 MHz (α_{1260}^{1520}). In this case, the spectral index and the associated error were calculated using Equations 5.1 and 5.2. We used BRATS to calculate the synchrotron spectrum produced by the different aging models, using the revised equipartition magnetic field and the injection index from Section 5.3.2. The resulting color-color diagrams for the main tail and the filaments are shown in Figure 5.9, and are discussed in Section 5.4.4.

5.3.4 Rotation measure synthesis technique

VLA data in A configuration were calibrated for polarization (Section 5.2.3) and used for the analysis of the Original TRG and its filaments. Given their faintness, and the disadvantaged position of the radio galaxy (within the depolarizing ICM, close to the cluster center), we tried to detect polarized emission using the RM synthesis technique (Brentjens & de Bruyn, 2005). This technique allows combining the polarized signal of each channel that constitutes the full band (1.0 – 2.0 GHz in this case) to avoid bandwidth depolarization, which is an instrumental effect that occurs when a significant rotation of the polarization angle of the radiation (so-called Faraday rotation effect, Section 2.2.2) is produced across the observing bandwidth and the polarization fraction is computed averaging over the band (Sokoloff et al., 1998). We refer to Brentjens and de Bruyn (2005) for a detailed description of this procedure. In brief, it uses an observing bandwidth split up into many individual narrow-frequency channels. Adding up the individual channels may cause bandwidth depolarization; however, using the value of Faraday depth that maximizes the signal resulting from the co-addition of the polarized flux from all channels, it is possible to recover the polarized flux.

To apply this technique, we first produced multiple deconvolved images in Stokes Q and U at different frequencies with WSCLEAN, having common resolution of $2''$ (corresponding to the resolution of the lower frequency channel): these cubes are required by the RM-TOOLS v1.4.8 (Purcell et al., 2020), which is the software used for the RM synthesis. To have enough signal per channel, required to detect also the more extended emission in tails and filaments, we produced 48 images across the entire band, with bandwidth of 16 MHz each. This also ensures that, within each channel, we are sensitive to a maximum observable Faraday depth of 655 rad m^{-2} , and so to not have significant bandwidth depolarization within each channel, since the Faraday depth in non-cool-core clusters

Name	Length [kpc]	$\langle$ Width $\rangle$ [kpc]	$S_{144 \text{ MHz}}$ [mJy]	α
Comma	154	7	45 ± 5	> 2.3
C-comma	147	7	110 ± 10	> 2.3
Ghost	107	9.5	100 ± 10	> 2.5
Trail	250	7.5	404 ± 40	> 2.0
T-bone	85	7.5	78 ± 8	> 2.0
Horizontal	110	9	319 ± 32	1.41 ± 0.05
Vertical	105	7	210 ± 21	1.74 ± 0.05
F1	83	5	168 ± 17	1.13 ± 0.05
F2	60	6	154 ± 15	1.12 ± 0.05

TABLE 5.3: Main properties of the filaments and diffuse patches of radio emission discussed in this Chapter. Column 1: name of the feature from Chapter 4 and from Botteon et al. (2020b), reported in Figure 5.2 and Figure 5.1. Column 2: projected length in kpc from Figure 5.1. Column 3: average width in kpc from Figure 5.1, evaluated as in Chapter 4 (Section 4.4). Column 4: flux density in mJy at 144 MHz from Figure 5.1 with flux density error as in Equation 5.3. Column 5: integrated spectral index between 144 MHz and 1520 MHz.

is generally below 500 rad m^{-2} (Böhringer et al., 2016). We used the RMSYNTH3D tool of the RM-TOOLS software to process the Stokes Q and U cubes and deconvolved the Faraday spectrum with RMCLEAN3D: the final map, which contains the maximum polarized intensity in each pixel, was then used for polarization analysis. We corrected for the Ricean bias, following George et al. (2012), evaluating the polarization noise at the outer boundaries (in the ranges $[\mp 1000, \mp 600]$) of the Faraday spectrum for each pixel. We corrected the RM for the Galactic foreground using a value of 37.8 rad m^{-2} (Hutschenreuter et al., 2022) and assuming it to be constant over the radio galaxy. In Figure 5.6 the polarized intensity, the polarization fraction, and the RM map are shown.

5.4 Results

In this Section, we detail the characteristics and results obtained for each of the main features of the cluster. First, we briefly describe the results for features that were only detected in the LOFAR-VLBI image, and then we focus on the main target of this investigation, the Original TRG. The lengths reported are projected, while the widths are obtained following the procedure already described in Section 4.4. The results for the main features are listed in Table 5.3. In Figure 5.8 we also report the surface brightness (left panel) and spectral index (right panel) trends along some of the main features of the Original TRG and the filaments (regions in Figure A.2).

5.4.1 Comma, Counter-comma, and tethers

The Comma and Counter-comma (C-comma in Table 5.3) are two quasi-specular patches located between the end of the Goldfish’s tail and the Double, discovered by Botteon et al. (2020b) and labeled in Figure 5.1. The former is closer to the Double and has a flux density at 144 MHz, measured within $3\sigma_{\text{rms}}$ level, of $45 \pm 5 \text{ mJy}$ and a length of $\sim 154 \text{ kpc}$; the latter, instead, has a flux density of $110 \pm 10 \text{ mJy}$ and a length of $\sim 147 \text{ kpc}$. Both features are undetected at higher frequencies with the current sensitivity of our uGMRT and VLA observations, which constrain their spectrum to be steeper than $\alpha \sim 2.3$. They also have a similar morphology, presenting a *head* in the upper part ($\sim 35 \text{ kpc}$ wide), followed by a thin curved component which extends below it (length of 120 kpc for the Comma, and $\sim 95 \text{ kpc}$ for the Counter-comma). The Counter-comma is attached

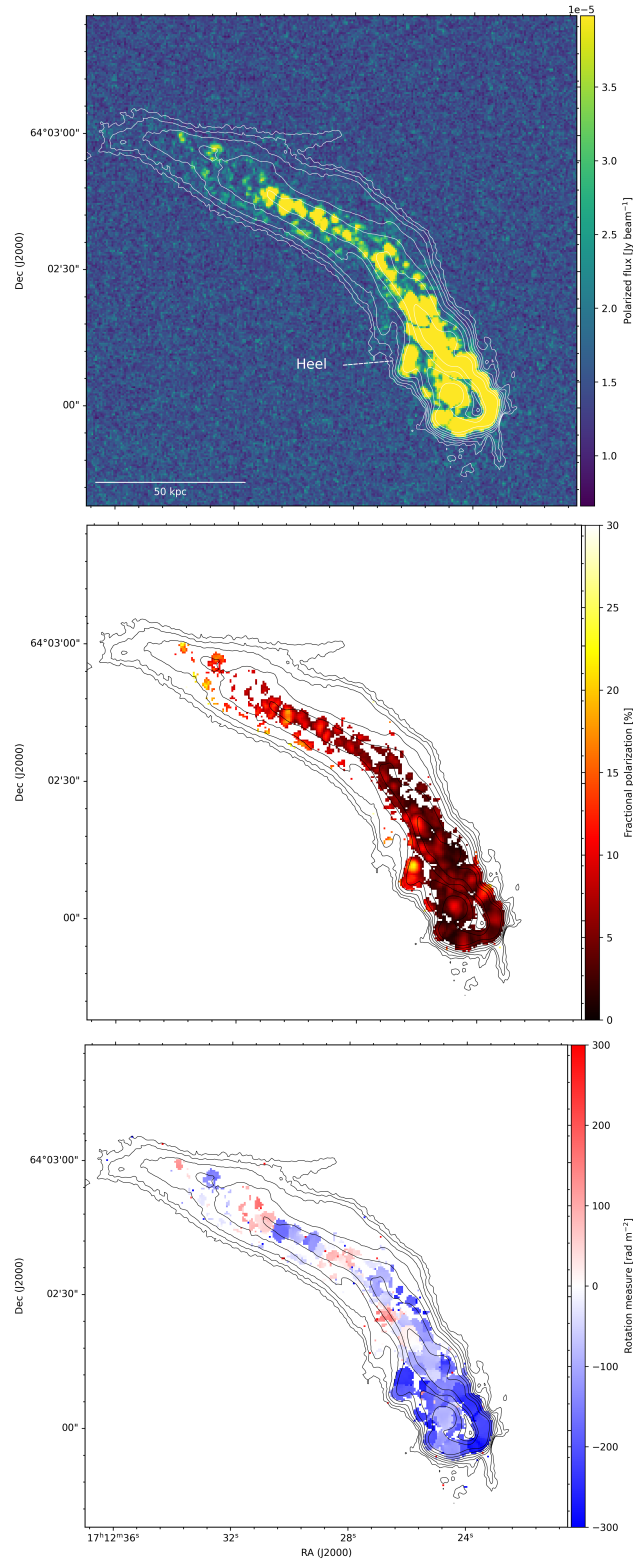


FIGURE 5.6: Polarization results for the Original TRG at 2'' resolution using the VLA. From top to bottom: polarized flux, fractional polarization, and RM map. Contours in black are from the VLA map in total intensity used for the polarization analysis at 3, 6, 12, 24, 48, 96, 192 σ noise level, with $\sigma = 10 \mu\text{Jy beam}^{-1}$.

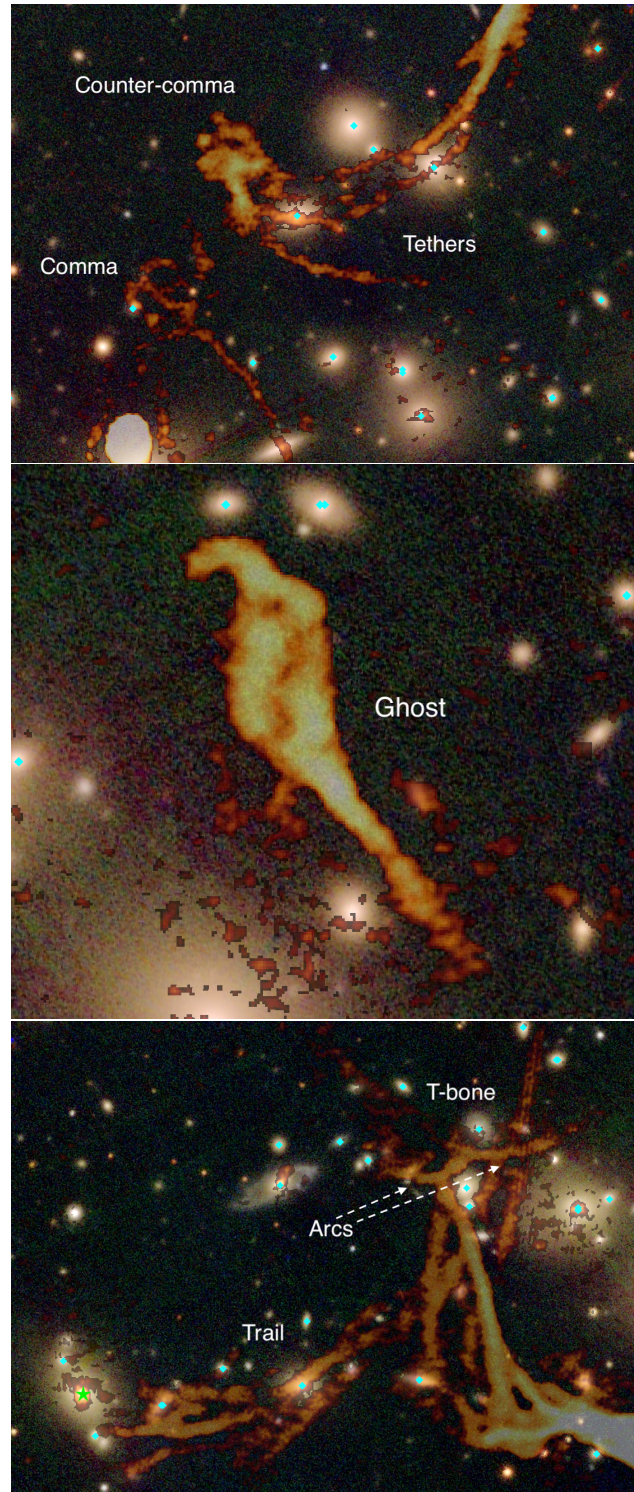


FIGURE 5.7: Radio features observed from the LOFAR-VLBI image in Figure 5.1. Radio emission is shown in orange/yellow, superimposed on an optical image from the Panoramic Survey Telescope & Rapid Response System (PanSTARRS, Chambers et al., 2016). Cyan rhombi represent cluster member galaxies from Yuan et al. (2003), Shim et al. (2011), and Tyler et al. (2014), which may have provided electrons to generate these features. Top: Comma, Counter-comma, and tethers. Center: the Ghost. Bottom: the Trail and T-bone.

directly to the bottom end of the Goldfish’s tail (Figure 5.7) still at high-resolution, suggesting a possible connection between the two; this, however, can also be due to projection effects. There are multiple thin components connecting the Counter-comma and the Goldfish resembling the tethers observed in the Mystail in Abell 3266 (Rudnick, 2021) and in the radio galaxy IC711 in Abell 1314 (van Weeren et al., 2021). The A2255 tethers are made of three components, with widths ranging between 4 – 8 kpc. Their origin is still unclear: there are three cluster member galaxies observed in the optical (Yuan et al., 2003; Tyler et al., 2014) corresponding to the position of the tethers (two superimposed, one just above, highlighted in cyan in Figure 5.7) which could have provided electrons to the system. The Comma upper end is spatially coherent with two potential host galaxies, one of these identified as a cluster member ($z = 0.0809$, Yuan et al., 2003), that could have provided electrons to supply the observed emission.

5.4.2 Ghost

The Ghost is another radio patch discovered by Botteon et al. (2020b). It is well-detected at 144 MHz (~ 0.10 Jy, 5σ level, flux density) and has a length of 107 kpc and a width up to 34 kpc. At high-resolution (with LOFAR-VLBI) it appears to consist of two distinct components of 9 – 10 kpc each. At the Ghost position there is no optical counterpart (middle panel of Figure 5.7), which makes any interpretation about the origin of this patch of emission non-trivial. One possibility is that it represents residual radio emission from past activity of a galaxy that moved away from its original position; it can also be emitting plasma which moved away from its host galaxy because of the ongoing cluster merger. As already seen for the Comma and Counter-comma, the non-detection of the Ghost at higher frequencies allowed us to constrain its spectrum to be $\alpha > 2.5$ (in agreement with Botteon et al., 2020b).

5.4.3 Trail and T-bone

Together with the filaments directly attached to the Original TRG, discovered in Chapter 4, there are other bundles of filaments located, in projection, beyond 200 kpc from the radio galaxy core. These have been labeled the Trail and were discovered by Botteon et al. (2020b). They extend for about 250 kpc in projection, with a radius of curvature of 180 kpc. These filaments are not observed at higher frequencies by the uGMRT and the VLA, resulting in a very steep spectrum ($\alpha = 2 - 2.5$, Botteon et al., 2020b). Thanks to LOFAR-VLBI wide-field calibration and imaging, we resolved many narrow extended components in the Trail at $1.5''$. These filaments are less bright than the others in the Original TRG: the Trail at 144 MHz is about 15-25 times less bright than the main tail, 6-15 times than the horizontal filament and 2-3 times than the vertical filament. The Trail may represent the remnant of past AGN radio activity from a nearby host-galaxy, as suggested also by the presence of a cluster member galaxy at its bottom-left end (RA: $17^{\text{h}}13^{\text{m}}02^{\text{s}}.04$, Dec: $64^{\circ}03'08''.3$, highlighted with a green star in the bottom panel of Figure 5.7). At high-resolution, we observe the Trail to be detached from this candidate host galaxy. Considering also the lack of surface brightness trends along this feature (as shown by the red line in Figure 5.8 and claimed also in Botteon et al., 2020b), usually observed along aging tails, it is plausible that the plasma in the Trail was injected by a previous activity of the host candidate and then went to some re-energization process, possibly related to the turbulent cluster center. High-resolution spectral index studies would be required to confirm this scenario, but with current facilities there is no way to trace such features at higher frequencies with matching resolution given their steep spectral index.

The T-bone is a quasi-horizontal narrow component of around 85 kpc length and 7 kpc width which terminates both the Trail and the vertical filament. As already observed in other cases, going to high-resolution we resolved for the first time two arc-like structures (Figure 5.7, bottom panel), with a radius of curvature of 20 and 55 kpc.

5.4.4 Original TRG

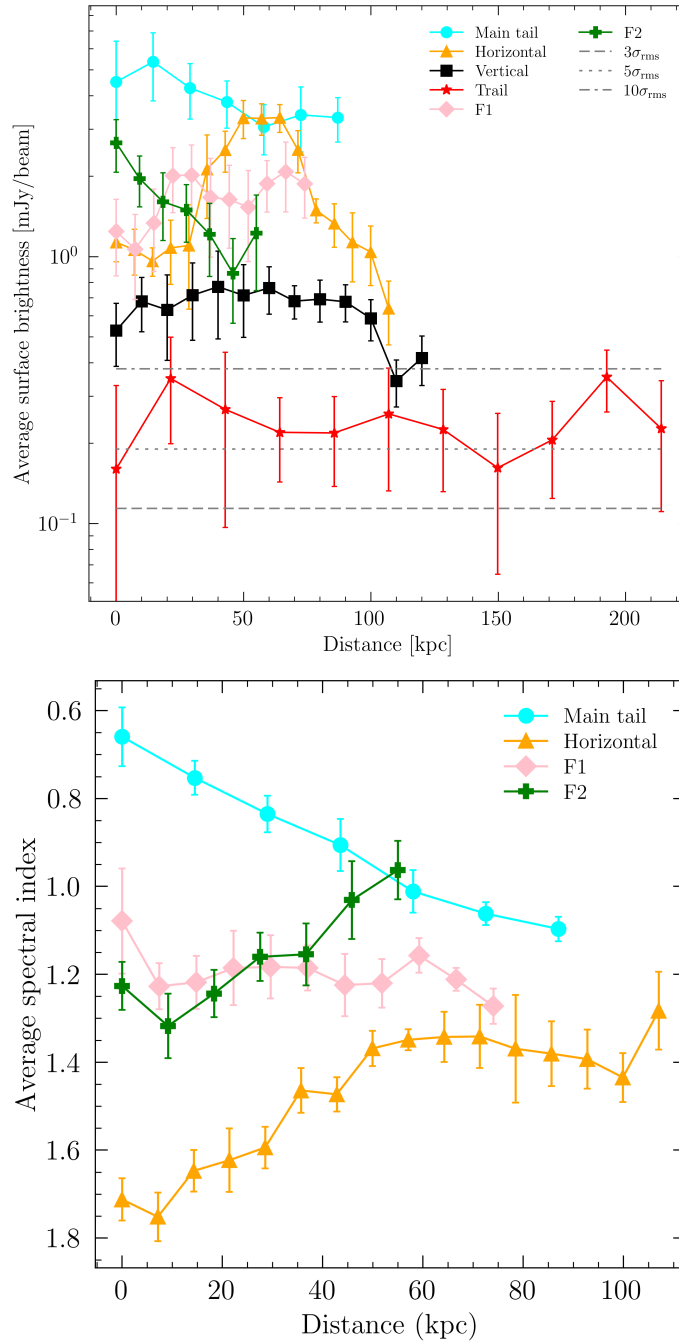


FIGURE 5.8: Surface brightness and spectral index trends for the Original TRG and the related filaments. The regions used to evaluate the average surface brightness and spectral index, with different color corresponding to different features, are shown in Figure A.2, as well as the arrows that indicate the direction of the trends. These are the main tail (cyan), the horizontal (orange) and vertical (black) filaments, F1 (pink), F2 (green), and the Trail (red). Left: Average surface brightness trends along the features' extension at 144 MHz. Right: Average spectral index trends along the features' extension, considering only pixels above a $3\sigma_{\text{rms}}$ threshold. The spectral index is not shown for the vertical filament and for the Trail given the lack of enough pixels above the chosen threshold.

The Original TRG is the brightest tailed radio galaxy in A2255, well detected also at higher frequencies and showing multiple filamentary substructures. For this reason, it was designated as the main focus of our investigation. It is a NAT extending for ~ 270 kpc overall, considering all its components. In Chapter 4, we discovered and detailed many filamentary features observed at sub-arcsecond resolution along its tail: in particular, we discovered the presence of two filamentary extensions alongside the main tail, namely F1 and F2, a horizontal filament at the upper end of the tail, and a vertical filament extending upward (Figure 5.2). These same features are also observed at higher frequencies with the uGMRT and VLA (Figure 5.4). Being at lower resolution (with respect to the work in Chapter 4), we detected the filaments along their entire extent, as well as other features which were barely detected at high-resolution, such as the fork at the western end of the horizontal filament or the gap observed between the southern jet and F1 (Figure 5.2). The morphological properties of the filaments in the Original TRG are also reported in Table 5.3.

Spectral index values from 144 MHz to 1520 MHz range from 0.5, close to the host galaxy, to $\sim 1.7 - 1.8$ on the vertical filament and the left side of the horizontal one (Figure 5.5). The upper jet of the TRG, which then develops into the main tail, shows spectral steepening along its extension, in line with plasma aging under the assumption of pure radiative losses due to synchrotron and IC emission after relativistic particles are ejected from the core of the radio galaxy (e.g., Cuciti et al., 2018; Bruno et al., 2024; Koribalski et al., 2024). This approximately continuous steepening along the main tail (Figure 5.8, right panel, in cyan) proceeds for about 142 kpc, before it links with the horizontal filament. There is local flattening of the spectrum corresponding to the eddies that develop from the northern jet, possibly due to the instabilities driven in the jet by the interaction with the ambient medium (e.g., O’Dea & Owen, 1987; Sakelliou & Merrifield, 1999). F1 and F2 show a substantially different spectral behavior along their extension (Figure 5.8, right panel, F1 in pink and F2 in green). The spectral index remains almost constant for F1, meaning that the relativistic plasma that constitutes these features has a different energetic history with respect to the one in the main tail. Moreover, spectral index values in F1 suggest that, as already proposed in Chapter 4, it is not associated with the *missing* southern jet: after the gap, there is, in fact, a spectral index discontinuity between what comes from the southern jet ($\alpha = 0.8$) and values at the bottom of F1 ($\alpha = 1.3$), which does not follow the same aging spatial trend shown by the main tail. Moreover, spectral index values along the F1 do not correspond to those of the main tail at the corresponding distance from the core. There is also a component (right above the main tail, highlighted in Figure 5.5) which shows spectral index values compatible with the main tail but morphologically not coincident with it. It may either reflect the large spectral complexity which characterizes the tail, or represent some component which is hidden behind the main tail such as a filament or, potentially, the missing tail from the southern jet, which may have been bent behind the main tail in projection. The horizontal filament shows spectral flattening moving from east (almost 1.8) to west (around 1.4). The spectral index difference between the two sides, together with the enhanced brightness corresponding to the central part of the filament (already highlighted in Chapter 4), suggests the superimposition of multiple components, one corresponding to the steeper left side and one coming from the upper side, connected to the vertical filament, with a flatter spectral index; otherwise, the flatter part of the filament could come from the relativistic plasma deposited by the radio galaxy that underwent localized re-acceleration. From the spectral index map, only a few pixels have a detection above the $3\sigma_{\text{rms}}$ for the vertical filament. We also produced integrated spectra for the main features of the Original TRG, combining the flux density measurements from 144 MHz to 1.52 GHz. The resulting spectra are reported in Table 5.3. The entire tail, comprehending also the southern jet and termination, has a spectral slope of 0.69 ± 0.05 . The filaments are steeper, with F1 of 1.13 ± 0.05 , F2 of 1.12 ± 0.05 , the horizontal of 1.41 ± 0.05 , and vertical of 1.74 ± 0.05 .

The different spectral components in the Original TRG are better highlighted in Figure 5.10, where different colors identify different spectral index ranges. We notice how both F2 and the horizontal filament are rather formed by multiple, overlapping components. The bottom side of F2 seems rather connected to the tail electron component, supporting the fact that it is probably part of the southern bent jet emerging behind the main tail. The horizontal filament is also formed by at least two components, with $\alpha = 1.6$ being a good discriminant between the two. The steeper component (Figure 5.10, in magenta) occupies mainly the eastern part of the filament, with a thin extension toward the west just above the main body of the filament. The eastern and brightest part of the horizontal filament (Figure 5.10, in cyan) is instead flatter. Part of it seems to move upwards, toward the vertical filament, and also toward F2: disentangling all these components is however non-trivial, even at this resolution. These two spectral components overlap around the point where the central part of the horizontal filament connects with the main tail. This spectral index bimodality for the horizontal filament confirms what is already observed from the trends in Figure 5.8 (right panel, in orange).

Color-color diagrams for the main features of the Original TRG are shown in Figure 5.9. The large complexity of the structure and the number of features of interest required us to isolate these on the color-color diagrams to better constrain their spectral properties. Each data point corresponds to the value of the spectral index within a region, with the color scale changing depending on the distance of each region from a reference one: this is assumed to be the region with lower declination, apart from the horizontal filament for which it is the one on the eastern end of the feature. Lines with different styles trace the ideal spectral index trend determined by different aging models (Section 5.3.3). The large number of details revealed at high-resolution makes the interpretation of these plots non-trivial. Following the downstream deployment of the northern jet into the main tail (blue data points), the spectral index follows the aging trend predicted by all the tested models. However, the point are rather close to the power-law line, suggesting that although the aging appears monotonic, it is not due to a single electron population, but some mixture. Following the implications from the spectral tomography (Figure 5.10), we divided the analysis of the filament originally labeled as F2 into two components. The magenta data points represent the bottom part, which, as stated before, can possibly be related to an additional component obscured by the main tail. Connecting it with the emission coming from the southern jet, we observe how the trend is somewhat similar to the one found for the main tail, apart from the very first data points closer to the core. However, the possible co-existence of different electron components within the same defined areas prevents a clear conclusion from being drawn. Green data points are instead from the top part of F2, and show a similar behavior apart from the top-eastern part of F2 which presents spectral index values very close to each other. The straighter filaments, namely F1 (in black) and the horizontal one (in orange), show instead a different and peculiar trend. Both show a small spread at low-frequency (1.0 – 1.3 for F1, 1.2 – 1.5 for the horizontal, within the errors), varying then significantly at high-frequency (0.0 – 2.3 for F1, 1.0 – 3.0 for the horizontal).

The interpretation of these values for the filaments is not obvious. They are generally not consistent with a single electron population, but rather with a great deal of inhomogeneity within the boxes in terms of magnetic fields, or electron populations, or both. The electron populations could differ based on different acceleration sites, or losses. Despite the fact that filaments appear as coherent distinct structures, each with their own spectral trends, the color-color diagrams show that they are each complex mixtures, possibly due to unresolved substructures such as bundles of smaller filaments. From the available observations, it is not possible to unambiguously distinguish all the mixed emitting components.

Polarization results are shown in Figure 5.6. This source was already observed to be polarized at

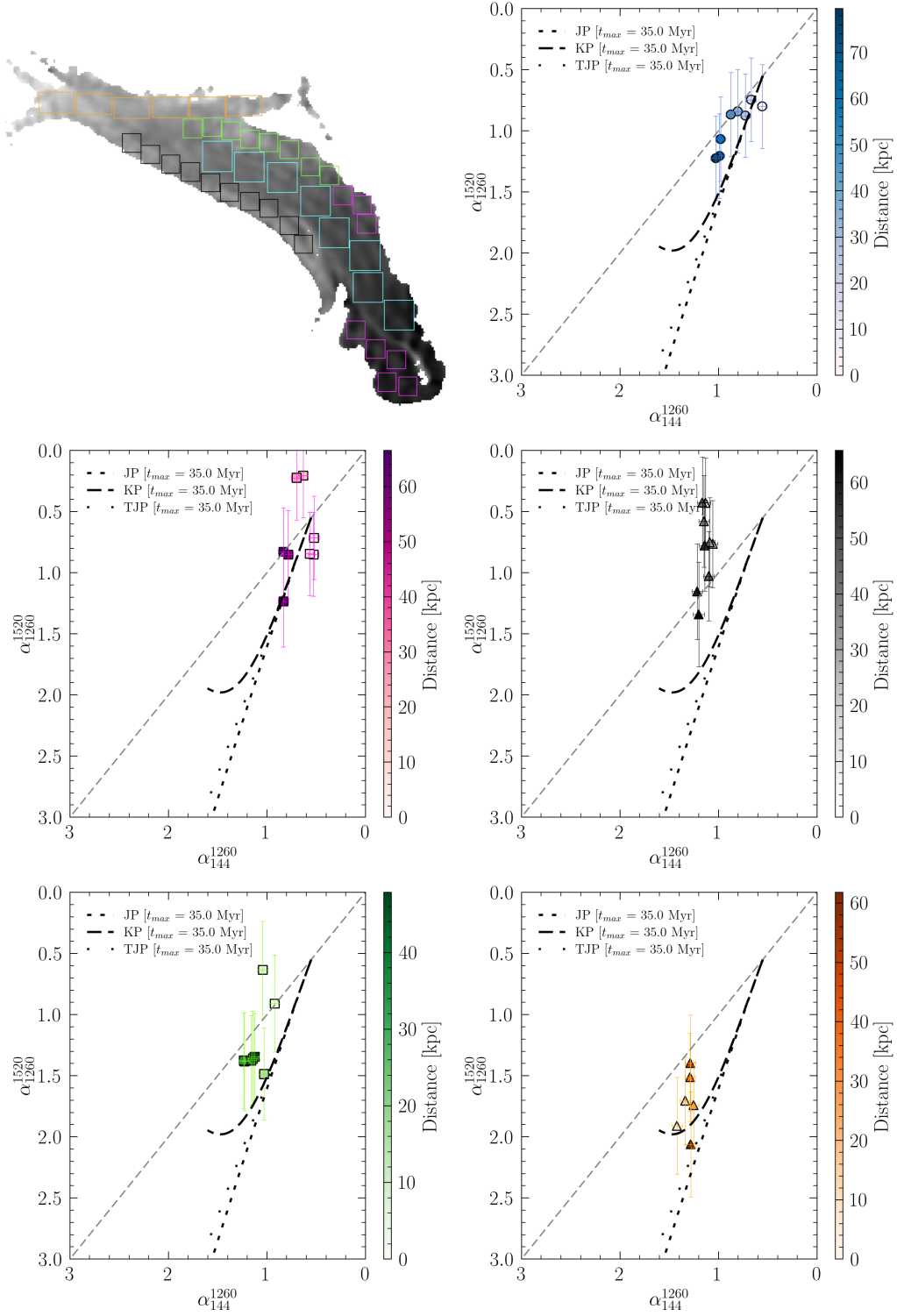


FIGURE 5.9: Color-color diagrams for different regions in the Original TRG. From top to bottom, from left to right: main tail (blue), southern tail (magenta), F1 (black), F2 (green), horizontal filament (orange). The distance is calculated between the centers of consecutive regions, starting from a reference region (Section 5.4.4), in the left-right direction for the horizontal filament, and in the bottom-top direction for all the others.

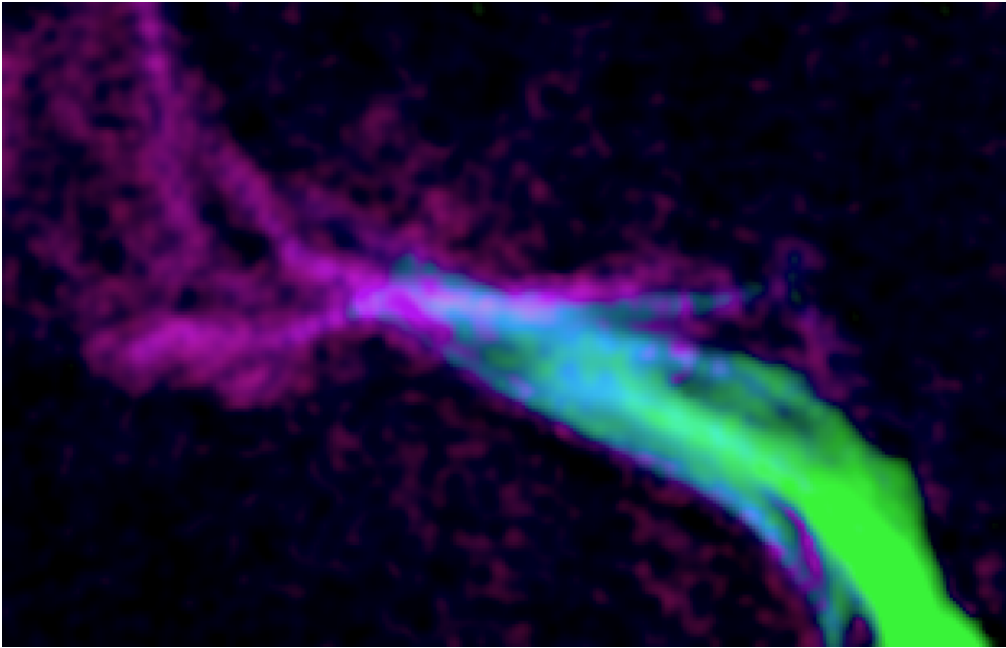


FIGURE 5.10: Spectral index tomography map between 144 MHz and 1520 MHz, where different colors highlight different spectral ranges. $\alpha < 1.2$ in green, $1.2 < \alpha < 1.6$ in cyan, $\alpha > 1.6$ in magenta.

5 GHz and 8 GHz, having a mean fractional polarization between 12.5–14% with fractional polarization increasing from the core (2–4%) along the tail (Govoni et al., 2006). At lower frequencies, the source was reported to have a fractional polarization of 2.1%, 2.0%, and 1.4% at 18, 21, and 25 cm, respectively (Pizzo et al., 2011). Thanks to the combination of high sensitivity and resolution, we recovered polarized emission from the head of the Original TRG, as well as along the brightest part of the tail up to the data point at which it connects to the horizontal filament. We report fractional polarization values at 1.5 GHz of $\sim 4 - 5\%$ at the core, which increase to 6–7.5% at the location of the northern jets. The inner regions of the radio source are expected to be more depolarized being more deeply embedded in the host galaxy (O’Sullivan et al., 2015). The southern jet, instead, shows even lower values (2–3%): this difference is also found in the RM map, with the northern jet displaying an average RM of -214 rad m^{-2} and the southern of -268 rad m^{-2} . The polarization fraction along the tail is not uniform but rather patchy, with local enhancements corresponding to the turbulent eddies (up to 13%) and close to the connection with the horizontal filament (up to 18–22%). On average, moving upward along the tail, values increase from 4% to 9%. Together with some pixels for the horizontal filament, we found polarized emission for F1 up to 22% in small patches in the middle and upper part of the filament. Interestingly, there is enhanced fractional polarization corresponding to the round southern jet termination ($\sim 10\%$), as well as to the narrow component emerging from the main tail labeled the Heel in Figure 5.6 (10–22%). The termination was already observed to be connected to the southern jet through thin features similar to tethers in Chapter 4. The Heel is then connected to the termination through a fainter component, observable both at low and high frequencies. Both components show compatible spectral properties, as well as polarization enhancement similar to that of the turbulent eddies: this may raise the possibility that they represent two components of the southern jet, which gets bent due to the instabilities that start developing in the tail, before it deploys behind the main tail. In Figure A.3 we show the distribution of RM values for the Original TRG. Large absolute values and variations in RM are expected for sources deeply embedded in the ICM, and close to the cluster center, due to the Faraday rotation that it generates on their polarized emission (Feretti et al., 1998; Govoni et al., 2001; Bonafede

et al., 2010). Along the tail RM values are predominantly negative, meaning that the magnetic field component along the line of sight, $B_{\parallel}$, is mainly directed away from the observer.

5.5 Discussion

In this Section, we discuss the main properties reported previously in this Chapter for the Original TRG and its associated non-thermal filaments, addressing their morphological and spectral characteristics and their formation.

5.5.1 Structure of the Original TRG and its filaments

Non-thermal radio filaments have been frequently observed in recent years in different objects in the cluster environment (see Section 2.3 for a complete description of cases). Thanks to the unprecedented high resolution and sensitivity at 144 MHz, we traced the morphological features of the steep and extended filaments beyond the tail, which are only observable at such low frequencies. Through our spectral studies, we have disentangled multiple spectral components along the Original TRG. The structure of the tail is, in fact, not homogeneous, with several narrow components emerging both from the total intensity and spectral index maps: this is possibly common to these sources when observed at high resolution, due to the strong instabilities developed downstream of the radio galaxy (Lal & Rao, 2004; Gendron-Marsolais et al., 2017). As already highlighted in Section 5.4.4, spectral and polarization information was also important to highlight the presence of a component, related to additional filaments or the missing southern tail. From the total intensity map in Figure 5.2 (as well as at sub-arcsecond resolution in Figure 4.4), the southern tail seems to terminate abruptly in a round feature, connected through narrow tethers. There is the possibility that it may be reappearing from behind the main tail, after being obscured by this; the bending point may then correspond to the round termination. It may also be a filament (F1-like) obscured by the main tail. Being these structures thoroughly embedded into the downstream structure, is not possible to clearly separate them from the flows from the original jets. For the Heel, instead, the large polarization fraction (up to 22%) and RM values suggest that it may not be related to the tail, but rather some additional filamentary component arising from behind the main tail. Polarization is a useful tool also to constrain the direction of the two jets. In fact, there is a polarization fraction and RM difference between the northern and southern jet, as stated in Section 5.4.4. Assuming a comparable thermal electron density in both jet locations, the southern jet's larger absolute rotation could be attributed to its orientation, receding from the observer, whereas the northern jet points more toward us. This may support the evidence discussed above (and already presented in Chapter 4) regarding the orientation between the two jets and the consequent configuration of the tails, with the northern tail settling above the southern one. Projection effects are a primary source of ambiguity as they hinder the disentanglement of numerous overlapping components: RM analysis is a powerful tool for addressing this, despite the inherent assumptions it involves. For the brightest part of the main tail, the progressively lower absolute value of RM moving toward the end suggests that the core region is located deeper in the ICM, with the tail deploying toward the outskirts. However, there are also many spots that show higher absolute RM values or have a positive RM sign (Figure 5.6), complicating the interpretation. Unfortunately, we miss similar information for the more outlying and faint filaments, where it would be even more important to decipher their 3D configuration to understand their relationship with the radio galaxy.

The configuration of the radio galaxy and filaments observed in A2255 resembles the one in Abell 3627 (Koribalski et al., 2024), with a NAT radio galaxy moving within the ICM and a system of steep, curved spectra filaments ($\alpha \sim 1.9 - 2.5$) extending perpendicularly at the end of the tail. In A2255, we can distinguish two sets of filaments following their location, morphology, and spectral properties.

F1, F2, horizontal, and vertical are all directly related to the Original TRG: they were also observed to be interconnected at higher resolution in Figure 4.4, and show overall spectral indices between $\alpha = 0.9 - 1.8$ and structural linearity. The horizontal filament resembles the one observed for Source B in Abell 2443 (Cohen & Clarke, 2011). It was explained to be pre-existing filament which was re-energized by the passing of source B. The Trail and possibly the T-bone instead have steeper spectra ($\alpha > 2$) and are much fainter than the first group. Part of the Trail overlaps with the end of the vertical filament, probably due to projection effects, and also the T-bone seems to terminate the vertical filament in its upper side. No hint of curvature has been observed for the filaments with the available frequency coverage, given also the very narrow difference between the uGMRT and VLA frequencies. The spectral index map suggests how structures that seem to be uniform from the brightness maps are instead made of multiple, overlapping, electron components. This was observed through tomography in Figure 5.10, which highlights the difference between the eastern and western sides of the horizontal filament, as well as for F2 which is made by two distinct underlying components. For the filaments inside the tail of the Original TRG we did not observe any significant spectral index trend: this is particularly true for F1 and for the western side of the horizontal filament (Figure 5.8). This can be explained by the large Alfvén speed (Equation 1.8) due to the magnetic field lines stretching (and consequent magnetic field enhancement). An example of this is the filament discovered in the radio galaxy J1333–3141 in Abell 3562, where the magnetic field is thought to be stretched behind a sloshing cold front that aligns with the radio filament (Giacintucci et al., 2022). Electrons would have to diffuse fast enough along the magnetic field lines to cover the entire filaments’ extension within their radiative ages (Churazov et al., 2026). Electrons diffusing along field lines in a time t can cover a distance of $d \sim 2\sqrt{D_{\parallel}t}$, where $D_{\parallel}$ is the diffusion coefficient along the field lines. Considering the radiative ages (reported in Section 5.3.2) and lengths (reported in Table 5.3), we found values for $D_{\parallel} \sim 1.5 \times 10^{31} \text{ cm}^2 \text{ s}^{-1}$. This value is extremely large (Brunetti & Jones, 2014), implying super-Alfvénic streaming along the filaments with a scattering timescales of the electrons $\tau_s \sim 1600 \text{ yr}$. Large Alfvénic speeds may reflect either enhanced magnetic field or ICM depletion in the filaments, which would mean that the plasma beta in these structures, as already proposed in Rudnick et al. (2022), approaches unity. In the case of Abell 194, a spatial correlation between the radio filaments and a dip in the thermal X-ray emitting plasma was observed. The underlying idea is that the enhanced magnetic pressure may reach a significant fraction of the ambient thermal pressure, and together with accompanying cosmic rays can expel the local thermal plasma. For the Original TRG, we used the Chandra ACIS-I data used by Botteon et al. (2020b) to investigate any possible correlation between the filaments and the thermal emission at high-resolution. However, the filaments are mostly located at the intersections of the detector’s chips, making any interpretation about the thermal component non-trivial. Given also that deeper Chandra observations of the cluster are scheduled (460 ks, P.I. Rajpurohit), we defer this analysis for the future.

5.5.2 Formation scenarios for the non-thermal filaments

To explain the nature and formation scenarios of the observed filaments, we propose and discuss several scenarios.

Instabilities in the downstream region

One possibility to explain the formation of the filaments is that they arise from the instabilities generated downstream of the Original TRG, with the radio galaxy being the main provider of electrons to the filaments. The radio galaxy is crossing the denser region of the ICM, which is already turbulent due to the cluster merging state, generating additional turbulence downstream. In Figure 4.4 (from Chapter 4), we observed jet bending due to ram pressure effects close to the core. Moving upward, we resolved several regions, labeled eddies, which represent the development of dynamical

instabilities that arise due to the bending and complex motions in the turbulent wake of the radio galaxy. Observation of the tail structure at sub-arcsecond resolution confirmed the large complexity of such structures already resulting from higher frequency observations (e.g., Lane et al., 2002; Owen et al., 2014; Gendron-Marsolais et al., 2020) and simulations (O’Neill et al., 2019a; Ohmura et al., 2023). These phenomena are possibly common to any tailed radio galaxy when observed at sufficiently high resolution. The radio galaxy can contribute in two different ways to the formation of the filaments. Crossing the ICM, it deposits fresh electrons in its wake that may be subject to both the turbulence generated by the merger and the crossing. Turbulence generates magnetic field lines stretching/bending, enhancing the magnetic field and so the corresponding synchrotron emission for the electrons, illuminating the filaments.

Another possibility is that the radio galaxy *injects* the filaments in its wake due to its interplay with the ICM. In Figure 4.4 (Chapter 4), we resolved filaments in the envelope of the tail, such as F1 and, partially, F2. The dynamical instabilities at the boundary of the tail can strip these filaments and mix them in the ICM motions behind. In this scenario, we would observe different stages of this mechanism at different resolutions. At sub-arcsecond resolution, we observed the raising of the instabilities at the beginning of the tail in the forms of eddies and bending of the tail. These create the filaments observed around the main tail, which are at the first stage of their evolution. Then, at $1.5''$ (Figures 5.2 and 5.4), we can see distant filaments that were once part of the radio galaxy and now exist independently. These are the horizontal and vertical filaments (closer, flatter and brighter), and the Trail (further, steeper, and fainter). At the very end of this process, the filaments will feed the ICM with plasma that is unable to emit significant radio emission but as soon as it is efficiently mixed and re-energized by other mechanisms it can provide seed electrons to the diffuse radio structures observed in this cluster at lower resolution (such as the giant radio halo or radio relics, Botteon et al., 2020b; Botteon et al., 2022).

The lack of spectral index trends in the filaments inside the radio galaxy, as highlighted in Figure 5.8 and Section 5.5.1, further supports the main role of the radio galaxy. The filaments part of the Trail, left behind the radio galaxy, are instead expected to show spectral steepening because the fresh plasma extracted from the Original TRG is mixed in a turbulent medium (turbulent ICM plus turbulence generated by the radio galaxy crossing), being subject to expansion and/or compression and resulting in steepening of the spectrum. Indeed, we observe different spectral values for the filaments in the Trail, which are steeper than $\alpha = 2$.

5.6 Conclusions

Non-thermal filaments represent new intriguing phenomena for studying the complex magnetic and particle processes that coexist in the ICM. In this work, following the detections already presented in Chapter 4, we analyzed the main spectral and polarization properties of the filaments in the central region of the galaxy cluster A2255. We obtained a deep, wide-field ($1.5^\circ \times 1.5^\circ$) map of the cluster at $1.5''$ using LOFAR-VLBI which, combined with new and archival uGMRT and VLA data at higher frequencies, allowed for a high resolution spectral index analysis of the filaments, crucial to disentangle the multitude of sub-structures and try to constrain their formation scenario. VLA data were also calibrated for polarization, expected with large fractional polarization in presence of ordered magnetic fields. We summarize hereafter the main findings of this work.

1. In LOFAR-VLBI map, we detected a bundle of extended (~ 250 kpc) and steep spectrum ($\alpha > 2$) filaments, known as the Trail and the T-bone, placed (in projection) at the end of the Original TRG. The high resolution allowed us to disentangle multiple components in these structures, with widths ranging between 4 – 11 kpc.

2. We found integrated spectral index values for the filaments of 0.69 (main tail), 1.13 (F1), 1.12 (F2), 1.41 (horizontal), and 1.74 (vertical).
3. From VLA data, we recovered fractional polarization up to 22% in a few patches of F1, increasing up to 18 – 22% moving upward along the main tail.
4. Spectral index analysis revealed that F2 is rather formed by two overlapping components: one going downward, and the other coming up from the horizontal filament. Also, the horizontal filament resulted to be not homogeneous, with the flatter western side which appears to be connected to a component coming down from the vertical filament.
5. Overall, there is signature of the presence of an additional component obscured by the main tail from the spectral index and polarization information, which emerges from the main tail. We speculate that it may be the southern tail which re-emerges after being bent behind what we see as the main tail. However, the large complexity of the structures, which deeply overlap, hinders a clear detection of this potential tail.

From their spectral and morphological properties, we believe that the filaments directly related to the Original TRG are low- β_{pl} plasma structures, illuminated by enhanced magnetic fields due to line stretching. For the Trail, we miss clear spectral information, but the very steep spectral index $\alpha > 2$ suggests that its plasma originates from the Original TRG. We propose that the radio galaxy has a crucial role in the formation of the filaments. Such structures can arise from the plasma deposited by the jets' activity which is then subject to turbulence injected by the motion of the host galaxy added to the one related to the cluster merger. Another possibility is that the filaments are stripped away directly from the radio galaxies because of instabilities in the downstream region. We resolved the starting point of such instabilities in Chapter 4 (Figure 4.4), the eddies: these then turn into filaments, and the filaments are successively dissipated by the turbulence, providing seed electrons to the ICM which can then be re-energized to generate large-scale diffuse radio emission (Botteon et al., 2020b; Botteon et al., 2022).

Deep, upcoming X-ray observations are critical to confirm the low- β_{pl} plasma scenario, with potential X-ray dips serving as key indicators at the filament locations. Additionally, we have around 300 hours of overall cluster data available for calibration and imaging. Recently developed strategies, such as sidereal visibility averaging (de Jong et al., 2025b), efficiently reduce the computational expense of imaging and aid in processing these data.

Chapter 6

Radio imaging code kernels

¹When referring to High Performance Computing (HPC), there is no unique definition. HPC can be defined as a technology that uses servers, clusters, and supercomputers that work in parallel - plus associated software, tools, components, storage, and services - to process massive, multidimensional data sets and solve complex problems at extremely high speeds. This Chapter discusses the work in enabling the interferometric imaging in radio astronomy to HPC resources. After an instrumental overview on the main forms of parallelism, with particular focus on accelerators, we present Radio Imaging Code Kernels (RICK), the code developed in this Thesis, which represents the first tentative application of advanced distributed parallelism to interferometric imaging algorithms. We discuss the pro and cons of our approach, as well as new solutions that we have recently developed to overcome the main bottleneck of distributing the problem. RICK represents a promising approach to deal with the huge data volume required by the upcoming generation of radio interferometers.

6.1 Introduction to HPC

An HPC system is fundamentally a co-design of specialized *hardware* and *software* components, dedicated to massive parallel processing. The backbone of a HPC *cluster* consists of many servers filled with thousands of computing nodes; each node contains one or more Central Processing Units (CPUs), memory banks, internal fast interconnects, accelerators (Section 6.1.4), network boards and cables, and an interface between the CPU and the accelerator/network cables (e.g., Peripheral Component Interconnect Express, PCIe, Fountain et al., 2005). The performance of these interconnects, interfaces, and networks is fundamentally defined by their *bandwidth*, generally measured in the amount of data transferred per unit of time.

The CPU is the primary component of a computing node, and acts as its control center. In its simplest form, it can be described by three main components.

- *Arithmetic Logic Unit*. Performs all the mathematical operations and logical functions.
- *Control Unit*. Fetches, interprets, and executes program instructions, coordinating the activity of all other components.
- *Cache memory*. A fast but small memory that stores the most important or frequently used instructions and data. It is organized into a hierarchy of different levels, typically L1, L2, and L3 (from fastest to slowest, Figure 6.1), to balance speed, cost, and capacity. The *Random Access Memory* (RAM) acts as the next level of storage in the memory hierarchy, serving as a larger, slower staging area for data that the CPU's much faster cache might need.

¹This Chapter is based on De Rubeis et al. (2025a), Lacopo et al. (2025), and De Rubeis et al. (2025b)

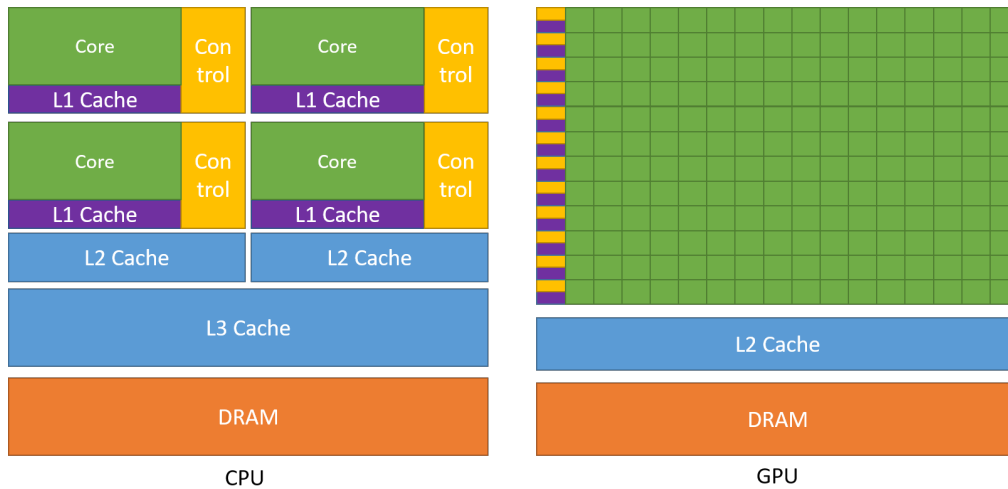


FIGURE 6.1: Graphic comparison between a CPU (left) and a GPU (right), to highlight the difference in transistors devoted to the data processing (credits: <https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html>).

The first CPUs to be produced were characterized by a single-core architecture. Since the development of the first commercially available microprocessor (the Intel 4004, in 1971), this architecture provided sufficient computational power to handle increasingly complex operations over the years. This sustained growth was largely due to *Moore's law* (Moore et al., 1965), which is an empirical law stating that the number of transistors in an integrated circuit doubles every two years. This growth in transistor count was accompanied by the *Dennard's law* (Dennard et al., 1974; Dennard et al., 1999), which stated that as transistors shrink, their power density remains nearly constant because both voltage and current scale down proportionally with physical dimensions, allowing the clock speeds to increase without any significant surge in power consumption. However, around the early 2000s, this scaling broke down. As transistors became too small, quantum effects became dominant and power consumption started to increase with each new generation of smaller transistors, leading to a phenomenon known as the *power wall* (Pollack, 1999). As shown in Figure 6.2, even though the number of transistors continued to follow Moore's Law, the increased power and heat generation prevented further substantial increases in CPU frequency and single-thread performance (e.g., Esmailzadeh et al., 2011). This is the main reason that prevented typical CPU clock speeds to increase beyond 3 GHz since the last decade. Recognizing that the limit was in single-core speed and not transistor count, the new strategy was then to utilize the increasing number of transistors predicted by Moore's Law to increase the number of CPU cores (from dual-core CPUs up to current ~ 100 cores CPUs). This allowed computing power to keep increasing by executing operations in parallel across multiple cores, even if the speed of each individual core was capped.

Another solution to the power-wall is represented by the *graphics processing units* (GPUs, Section 6.1.4), thanks to their native throughput-optimized, massively parallel design combined with an architectural solution which improves the computation rate relative to the amount of electrical power it consumes (the so-called *performance per watt*²).

6.1.1 Parallel computing

Many single-core CPUs first, and multi-core CPUs (schematic view in the left panel of Figure 6.1) later, characterized the era of parallel computing. A parallel architecture allows the simultaneous

²<https://www.supermicro.com/en/glossary/performance-per-watt>

execution of multiple instructions or instruction sequences. One way of describing this is due to Flynn (1966). Flynn’s taxonomy characterizes architectures by whether the data flow and control flow are shared or independent. For our purposes, we discuss the following types which stand as the dominant and most influential paradigms for modern parallel computing.

- *Single Instruction Multiple Data* (SIMD). Multiple processors, each operating on its own data item, but they are all executing the same instruction on that item simultaneously.
- *Multiple Instructions Multiple Data* (MIMD). Multiple CPUs operate on multiple data items, each executing independent instructions asynchronously.

6.1.2 Shared memory

Beyond the instruction-data matrix, the second fundamental dimension of parallel computing lies in how processors access and share data. This memory architecture dictates the communication model for parallel programs and introduces a new set of trade-offs. In a *shared memory* system, all processors have direct access to a single, unified address space. This architecture simplifies programming because communication between processors is implicit; a processor writes to a specific memory location, and any other processor can read from that same location. Modern shared memory systems are often implemented as *non-uniform memory access* (NUMA) architectures, where memory is physically distributed across different processor sockets but logically presented as a single address space. The primary advantage of this model is the ease of programming, which can reduce parallel software development; however, its main drawback is a lack of scalability. As the number of processors increases, contention for memory access and the complexity of maintaining cache coherency degrade performance.

The primary programming model for this architecture is OPENMP³, a high-level directive-based model designed for scientific programming. It operates on a *fork-join* execution model, where a single master thread forks a team of parallel threads to execute a parallel region of code, and they join back to the master thread upon completion.

6.1.3 Distributed memory

In contrast, the *distributed memory* model provides each processor with its own private, local memory. A processor has no direct access to another’s memory. For data to be shared, it must be explicitly packaged into a message and sent from one processor to another via an interconnection network. This message-passing model requires the programmer to manage data distribution and communication explicitly, which adds significant complexity. The key advantage of distributed memory is its superior scalability, provided that communication is carefully managed. Since each processor operates on its own local memory without contending for a shared bus, this architecture can scale to systems with thousands or even millions of processors, forming the backbone of modern supercomputers. The disadvantage, as noted, is the increased software complexity required to manage the explicit message passing, which can be a challenging task.

The *Message Passing Interface* (MPI) is the standard solution for programming distributed memory, where each MPI *process* (or *rank* or *task*) owns a specific memory region. Several implementations of this standard exist, e.g., OPENMPI⁴, MPICH⁵, INTELMPI⁶. In message-passing programs, two processes can communicate by calling functions: one process calls a *send* function (MPI_Send) and the

³<https://www.openmp.org/>

⁴<https://www.open-mpi.org/>

⁵<https://www.mpich.org/>

⁶<https://www.intel.com/content/www/us/en/developer/tools/oneapi/mpi-library.html>

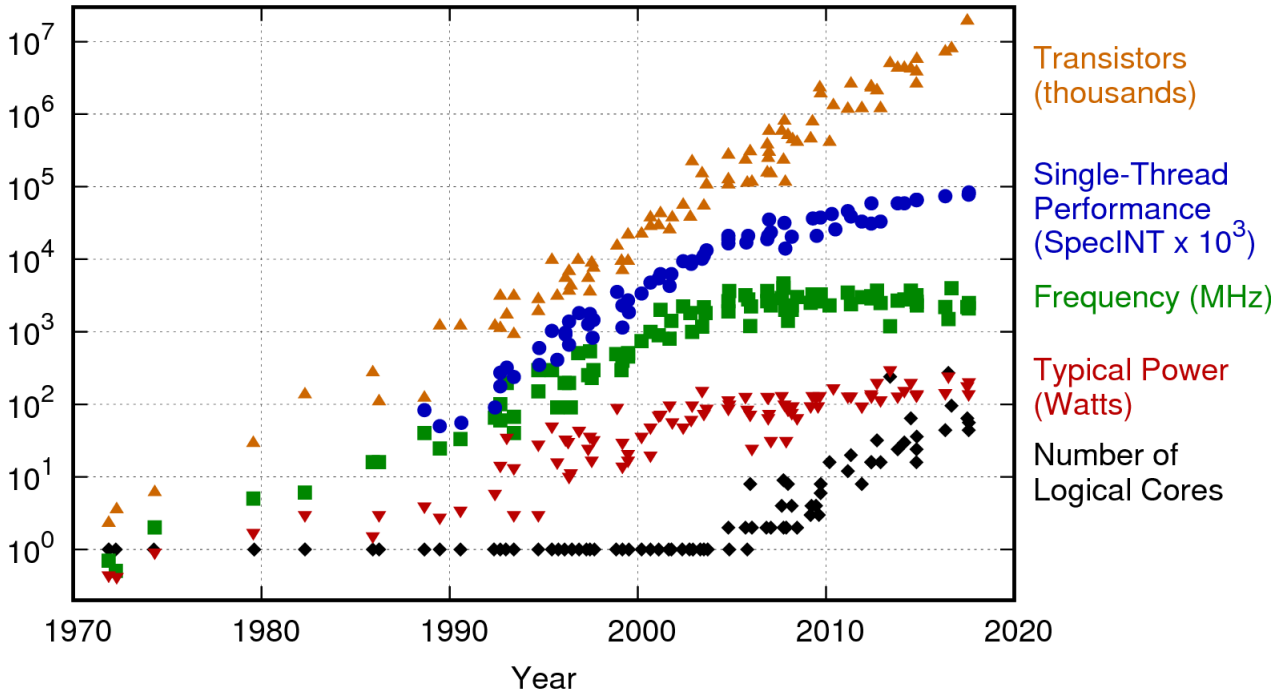


FIGURE 6.2: Visual representation of the Moore's law, with performance measured in arbitrary units ⁷.

other calls a *receive* function (`MPI_Recv`). These are also known as *point-to-point* communications. In MPI it is usually defined also a *communicator*, a collection of processes that can send messages to each other (`MPI_COMM_WORLD`). The communication functions that involve all the processes in a communicator are called *collective communications*. One important example of collective call is the *reduce* (`MPI_Reduce`), which performs a global reduce operation (such as sum, max, logical AND, etc.) across all the members of a group; this will be addressed later in this Thesis (Section 6.3.3).

6.1.4 GPU computing

A GPU provides much higher instruction throughput and memory bandwidth than a CPU within a similar price and power envelope. This difference in capabilities between the GPU and the CPU exists because they are designed with different goals in mind. While a CPU is designed to excel at executing a sequence of operations as fast as possible and can execute a few tens of threads in parallel, a GPU is designed to excel at executing thousands of them in parallel (amortizing the slower single-thread performance to achieve greater throughput). The GPU is therefore designed such that more transistors are devoted to data processing rather than data caching and flow control (Figure 6.1). Devoting more transistors to data processing is beneficial for highly parallel computations; the GPU can hide memory access latencies with computation, instead of relying on large data caches and complex flow control to avoid long-memory access latencies, both of which are expensive in terms of transistors. Recalling Section 6.1, GPUs represent one of the best candidates for a leading technology the post-Moore era, thanks to their advance in performance and energy efficiency. This is achieved not only through transistor scaling, but rather through architectural (e.g. specialized cores, parallelism) and software (e.g., memory efficient algorithms) innovations.

GPUs were already diffused by the late 1970's, when graphic cards were developed to carry out information from the central processor to the display. Their market increased in the 1990's, when users began purchasing 2D/3D display accelerators for their personal computers. At the same time,

Silicon Graphics opened the programming interface to its hardware by releasing the OpenGL⁸ library, intended as a standardized, platform-independent method for writing graphic applications. DirectX⁹ followed shortly after. Among the many hardware limitations (e.g., Sanders & Kandrot, 2010), these programming languages were far too restrictive and characterized by a cumbersome application program interface (API). General purpose GPU computing (GPGPU) became then popular only when NVIDIA introduced its new own architecture known as Compute Unified Device Architecture (CUDA¹⁰, Garland et al., 2008). CUDA comes with a software environment that allows developers to use C/C++ as a high-level programming language. In the CUDA language, we identify the CPU as *host*, and the GPU as *device*; we will refer to these later in this Chapter. The CUDA programming model also assumes that both the host and the device maintain their own separate memory spaces in dynamic RAM, referred to as *host memory* and *device memory*, respectively. A standard CUDA program is usually divided into two main parts. The APIs are functions called by the CPU whose purpose is to manage the host and the device interactions. Several functions are available to allocate memory on the GPU, to copy memory from host to device and vice-versa, to synchronize both the host and the device, etc. The *kernels*, instead, are functions that, when called, are executed N times in parallel by N different CUDA threads, as opposed to only once like regular C/C++ functions. A multi-threaded program is partitioned into blocks of threads that execute independently from each other. Blocks are organized into a one-dimensional, two-dimensional, or three-dimensional grid of *thread blocks*. The number of thread blocks in a grid is usually dictated by the size of the data being processed, which typically exceeds the number of processors in the system. The number of threads per block is instead limited by the hardware of the GPU; e.g. the NVIDIA Hopper 100 (H100) has 1024 threads per block¹¹. Thread blocks are required to execute independently. Threads within a block can cooperate by sharing data through some shared memory and by synchronizing their execution to coordinate memory accesses.

CUDA is specifically made for NVIDIA GPUs, but it is not the only model available. For instance, AMD GPUs use another programming model called Heterogeneous-computing Interface for Portability (HIP¹², Sun et al., 2022), included in the AMD software stack, ROCm¹³. HIP is strongly based on CUDA, with extremely similar APIs. There are also other pragma-based paradigms, such as OPENACC¹⁴ and OPENMP, which ensure larger portability of the code across different architectures and easier code adaptation, at the cost of reduced performances. As these languages are not specifically addressed in this Thesis, we will not delve into them further.

6.1.5 Performance measurement

The performance in parallel codes is measured in terms of the *scalability*, which describes the change in the code runtime when computing resources or problem sizes increase. One relevant quantity associated with scalability is the *speed-up*, defined as

$$S = \frac{T_1}{T_{N_p}}, \quad (6.1)$$

where T_{N_p} is the code runtime measured using N_p computing units (e.g., MPI tasks or GPUs), while T_1 measured using a single processing unit (serial case). Scalability can be assessed in terms of *strong* and *weak scaling*. For strong scalability, the problem size is fixed but the number of parallel

⁸<https://www.opengl.org/>

⁹<https://devblogs.microsoft.com/directx/>

¹⁰<https://developer.nvidia.com/cuda-toolkit>

¹¹<https://resources.nvidia.com/en-us-hopper-architecture/nvidia-h100-tensor-c>

¹²<https://rocm.docs.amd.com/projects/HIP/en/latest/>

¹³<https://www.amd.com/en/products/software/rocm.html>

¹⁴<https://www.openacc.org/>

workers increases; the ideal scaling would then be $S = N_p$, meaning that the code execution time should scale linearly with the number of computing units. In weak scalability, both the number of processing units and the problem size are progressively increased, resulting in a constant memory and work load per processing unit; the ideal scaling here should be $S = 1$.

6.2 HPC for radio astronomy

The adoption of HPC solutions for radio astronomy has gained significant momentum in recent years. Some of the challenges facing radio astronomy today have always existed, but the wish for increased performance requires higher accuracy in processing. With the advent of larger radio facilities, such as the upcoming SKA and its precursors/pathfinders, the sheer volume of data produced requires a shift to high-performance processing in dedicated facilities; to give some numbers, the SKA is expected to produce overall around 700 PB year⁻¹ of data¹⁵. Large developments have been made, mostly focusing around improving the image quality and the sensitivity to detect a greater number of objects or more of their associated emission. There are a number of computational challenges in processing data from radio telescopes and interferometers, from correlation (e.g., Broekema et al., 2018; Romein, 2021) to imaging. Most of the performance improvements expected from the new facilities rely on addressing these challenges. This Section provides a brief overview of relevant topics concerning challenges and potential solutions in modern and future radio astronomy, focusing mostly on imaging. For a complete treatment, please refer to **vardoulaki2024**.

Advances in sensitivity and image quality mainly arise from two options (and, in many cases, both): increasing the number of antennas and the bandwidth. The increasing baselines imply an improved uv coverage, providing both a greater collecting area and a more complete aperture for synthesis observations. However, it also presents increased data volume both pre- and post-correlation, which can be dramatic even with the addition of a small number of antennas. Increasing the bandwidth requires instead taking into account, during both calibration and imaging, changes in the frequency response of the instrument, the atmosphere, and the source itself. Moreover, it increases also the total number of channels (and so the total data volume), resulting in the need for higher data throughput and storage.

6.2.1 Novel techniques for interferometric imaging

To obtain science-ready end-products, the data from a radio interferometer need to be calibrated and imaged. Calibration, described in Section 3.2, is computationally expensive, especially when considering large FoV which may require DDE calibration (e.g., for LOFAR or SKA-Low). Imaging is instead required to convert the calibrated visibilities into a 2D brightness distribution of the sky. The imaging was extensively described in Section 3.3, focusing particularly on the non-coplanar baselines problem for large FoV (e.g., LOFAR-VLBI wide-field, Section 3.4.2 and Chapter 5) and the consequent solutions to efficiently take into account the curvature of the sky. The gridding is a task which is easily made scalable: the visibilities can be split in time or frequency, and can be gridded in parallel or even distributed. The resulting grids can be added together before or after the FT, to obtain the final result. After FT, deconvolution is required to remove the effects of the dirty beam on the image. Deconvolution algorithms such as CLEAN work in image space, and model the true (deconvolved) sky iteratively. An image-space deconvolution can not model all the (direction dependent) effects that may affect an observation. To remedy this, the full deconvolution process is split into minor iterations that operate in image space, and major iterations that, once a first order model is obtained, forward predict this model. This corrects for the simplifications that are made

¹⁵<https://www.skao.int/en/explore/big-data>

during the image-based deconvolution. Subsequently, the residual visibilities are again gridded. As a consequence, the gridding/de-gridding process needs to iterate multiple times over the data.

In recent years, several attempts have been made to exploit HPC solutions for imaging in radio astronomy. WSCLEAN supports, by default, multi-threading parallelism using the BOOST.THREAD library¹⁶, and can also be compiled with MPI support (through OPENMPI) across multiple nodes. However, MPI capabilities are (currently) supported only for the gridding. WSCLEAN also implements the *image-domain gridded* (IDG¹⁷, van der Tol et al., 2018; Veenboer & Rømer, 2020), which supports multi-threading and GPU for gridding, w -term correction and a -term correction. DDFACET also supports distributed parallelism based on the frequency domain through MPI4PY¹⁸ (Monnier et al., 2022), as well as multi-threading using OPENMP and the PYTHON MULTIPROCESSING package. Imaging in CASA¹⁹ employs two types of embarrassing parallelism (Bhatnagar & The CASA HPC Team, 2015): multi-threading (for FFT and some gridding and deconvolution options) and multi-processing (using MPICASA to parallelize the major cycle for continuum imaging). The w -projection algorithm (Section 3.3.2) has been parallelized and ported to the GPU by Lao et al. (2019), who however limited the data distribution to the visibility data. A CUDA GPU-based implementation was proposed also by Muscat (2014). The w -stacking and w -projection approaches have been combined and parallelized on distributed memory systems by Pratley et al. (2020). There are also completely different approaches to the imaging problem, such as the *Bluebird Imaging algorithm* (BIPP++, Kashani, 2017; Tolley et al., 2025), which addresses the inversion steps of imaging reconstructing a least-squares consistent image of the sky based on the theory of sampling and interpolation operators. It currently supports CUDA and HIP for GPU offloading, and will support distributed parallelism in the future.

For the deconvolution step, many novel parallel algorithms have been developed, alternative to the widely used CLEAN. Valuable examples are the *MOdel REconstruction by Synthesis-ANalysis Estimators* (MORESANE, Dabbech et al., 2015) and the sparsity-based image models embedded in optimization algorithms, such as the *Sparsity Averaging Reweighted Analysis* family of deconvolution algorithms (SARA, e.g., Carrillo et al., 2012; Onose et al., 2017; Repetti et al., 2017; Dabbech et al., 2018; Abdulaziz et al., 2019; Dabbech et al., 2021; Thouvenin et al., 2023b; Thouvenin et al., 2023a) or the *AI for Regularisation in Imaging* (AIRI, e.g., Dabbech et al., 2022; Terris et al., 2023; Wilber et al., 2023). All these algorithms support CUDA, but no distributed parallelism.

Considering the unprecedented, large amount of data that will be collected by the SKA, combined with the large FoV (especially for SKA-Low), current state of the art software will have to be adapted, if not completely re-designed, to efficiently run at scale. The exploitation of large computing capabilities is fundamental, combined with the use of heterogeneous systems that combine general-purpose processors with accelerators (e.g., Mittal & Vetter, 2015, and references therein), high-speed networks, and composite storage devices. The opportunity of using cutting edge systems is not anymore only a way to reduce the time-to-solution, but the sole approach to process datasets of the expected size and complexity. The related challenges, which are main topics of the work in this Thesis, can be summarized as follows.

- *Memory challenge.* Huge datasets cannot be loaded in the memory of a single CPU and cannot be handled by a single processor, but by distributed memory systems. Distributed computing, based on the adoption of the MPI standard, represents a feasible and effective solution. Data

¹⁶<https://www.boost.org/doc/libs/latest/doc/html/thread.html>

¹⁷<https://idg.readthedocs.io/en/latest/>

¹⁸<https://mpi4py.readthedocs.io/en/stable/index.html>

¹⁹https://casadocs.readthedocs.io/en/stable/notebooks/synthesis_imaging.html#Imager-Parallelization

are split among multiple processors (even among multiple computing nodes), speeding-up the computation.

- *Acceleration challenge.* Multi (e.g., multi-core CPUs) and many (GPUs) cores architectures have to be exploited, through programming models already presented in Section 6.1.4.

To overcome all these challenges, we developed a code, called Radio Imaging Code Kernels (RICK, Gheller et al., 2023; Gheller et al., 2024; De Rubeis et al., 2025a; Lacopo et al., 2025; De Rubeis et al., 2025b), which addresses the inversion step for interferometric imaging implementing parallel and accelerated solutions. In the following part of the Chapter, we describe the main properties of RICK, with particular emphasis on the GPU offloading of the code, discussing the pro and cons of a fully distributed approach for such problem in the SKA framework.

6.3 RICK

RICK²⁰ is a publicly available code for interferometric imaging that aims at speeding-up the problem using a parallel approach (hybrid MPI-OPENMP) and, particularly, able to distribute the problem between multiple GPUs. Currently, the code is capable of doing only the *inversion* step, meaning that starting from calibrated visibilities it can produce a dirty image, using the *w*-stacking algorithm to deal with non-coplanar baselines; in the future, we aim to include also the *prediction* (way back from the image to the visibilities), as well as the deconvolution steps. It is written in C, with extensions in C++ only to support GPUs through CUDA), and has not been fine-tuned to any specific computational architecture, in order to avoid introducing specialized solutions that would limit its portability. However, optimal performance requires the availability of suitable hardware and software solutions. Parallelism is exploited supporting multi-core processors (via OPENMP), and distributed HPC architectures (via MPI). Moreover, RICK supports a wide variety of accelerators, thanks to GPU offloading made using CUDA (for NVIDIA), HIP (for AMD), and also OPENMP; the latter case will not be discussed throughout the Thesis. Depending on the desired configuration or on the available platform, it is possible to activate different parallel and accelerated options in the compilation phase for each step of the code individually, with a small number of adjustments in the Makefile (e.g., the path to the required installed libraries). This also includes specific macros to easily enable full-GPU offloading for both NVIDIA and AMD. For the input parameters (e.g., the image size, the input dataset, the names of the end-products, etc.), RICK requires a parameter file that can be specified at the execution time; this feature will be soon implemented also for the RICK LIBRARY (Section 6.3.10).

As stated before, RICK deploys the *w*-stacking algorithm to deal with the *w*-term correction (described in Section 3.3.2), in which the computational mesh has a third dimension in the *w* direction and visibilities are mapped to the closest *w*-plane (Equation 3.22). Once gridding is completed, each *w*-plane is Fourier transformed separately, and a correction is applied as $e^{i2\pi w(\sqrt{1-l^2-m^2}-1)}$. This algorithm is implemented in RICK in the so-called *w-stacking gridder*, whose workflow and main steps are shown in Figure 6.3. We detail hereafter the five main algorithmic components, focusing on all the HPC implementations that were developed for each of them in the context of this Thesis. Throughout the Chapter, we refer to *computing* or *processing unit* as the computing entity addressing some parts of the work. In the case of parallel work based on MPI, a computing unit is a single core (mapping to an MPI *task*). In the case of multi-threaded OPENMP implementation, it is a multi-core CPU. In the case of accelerated computing, it is a GPU.

²⁰<https://github.com/ICSC-Spoke3/RICK>

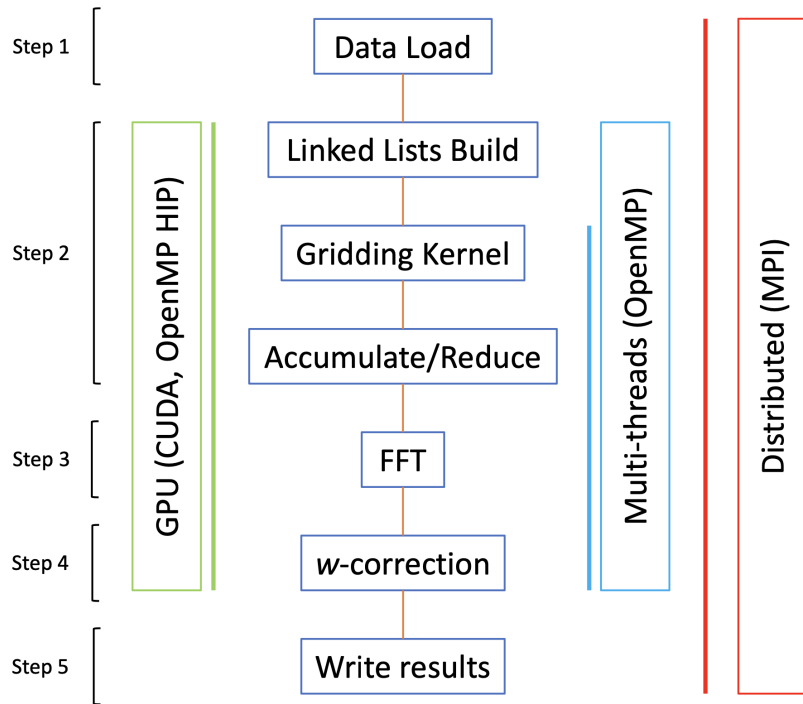


FIGURE 6.3: Schematic code architecture and workflow of RICK (De Rubeis et al., 2025a). Different kind of HPC enabling are highlighted with different colors: distributed memory parallelism in red (through MPI), shared memory parallelism in blue (through OPENMP), and GPU offloading in green (through CUDA, HIP, or OPENMP).

6.3.1 Data distribution

Two main data structures characterize the algorithm. The first is an unstructured data set storing the (u, v, w) coordinates of the antennas array baselines at each measurement time. Each baseline has a number of associated visibilities, which is determined by the frequency bandwidth, the frequency resolution, the number of correlations, and the total observing time. Visibility *weights* are assigned by the correlator to each measurement: this number allows the user to adjust the balance between angular resolution, sidelobes of the beam and sensitivity (Briggs, 1995). The second is a Cartesian computational mesh of size $N_u \times N_v \times N_w$, where N_u , N_v , and N_w are the number of cells in the three coordinate directions. The convolved visibilities and their FT counterpart are calculated on this mesh. The two data structures determine the memory request of the algorithm.

The first step of the code consists of reading the observational data from binary files stored on the disc. Before being used for RICK, the input MS(s) needs to be converted to a binary file using a Python script named `create_binMS.py` (and present in the RICK Github repository²¹). This choice has two main motivations. Firstly, we wanted to avoid dealing with CASACORE²² and its relative dependencies for the compilation and execution of the code, which would have required its availability on every HPC infrastructure where the code was (and is being) tested. Secondly, since we plan to integrate RICK into state of the art codes for interferometric imaging, we expect these codes to already have full support of CASACORE and its dependencies. The file(s) is read in parallel, assigning the same fraction of the data to each different parallel task. Data distribution is needed to

²¹https://github.com/ICSC-Spoke3/RICK/blob/main/scripts/create_binMS.py

²²<https://casacore.github.io/casacore/index.html>

achieve an effective memory utilization. Point-like visibilities are collected in time series during an observation. The resulting visibility distribution (uv coverage, Section 3.3.3) has a number density which depends on the antenna configuration and on the observation time. For instance, for arrays with a core-dense layout, areas around $(u, v) = (0, 0)$ are denser than peripheral areas. Also radial number density is not uniform, changing with orientation (Taylor et al., 1999). In our approach, visibilities are distributed among processing units in *time slices*. Being t_{obs} the total observing time, and N_{pu} the number of processing units, the data are divided into N_{pu} time slices, each comprising data in a time interval $t_{\text{pu}} = t_{\text{obs}}/N_{\text{pu}}$. This data distribution has several advantages.

- Balance, because each processing unit has the same number of visibilities.
- Immediate parallelism, because data can be distributed already when it is read from the disc, without subsequent communication.
- Data lying on the same area of the Cartesian grid where the visibilities are convolved are distributed among different processing units, reducing the computational pressure and potential race conditions.

Main drawbacks are represented by the non-locality of the data that are spread all over the spatial domain, hence the computational mesh, and possible unbalances for short observations. These issues can be limited, e.g. by sorting the data according to appropriate criteria; however, this may introduce additional computational and communication overheads, counterbalancing any possible benefit (e.g., Hariri et al., 2016). We will discuss further this choice and possible ways to efficiently sort the visibilities.

The data defined on the Cartesian computational grid have been partitioned among the processing units adopting a slab-like decomposition (Figure 6.4), assigning to each unit a rectangular region of $N_{\text{mesh}} = N_u \times N_w \times (N_v/N_{\text{pu}})$, with the mesh size in the v direction is split in N_{pu} parts (equal to the number of computing units). Such domain decomposition allows storing on each memory only a fraction of the whole mesh, avoiding replicas. Hence, each different computing unit is in charge of storing and managing a specific part of the mesh (so-called *resident slab*). Furthermore, slab decomposition represents a natural layout for the usage of the parallel *Fastest Fourier Transform in the West* (FFTW²³, Frigo & Johnson, 2005), which will be described in Section 6.3.4. Major drawbacks are the maximum number of processing units that can be used, limited to the cells in the v direction, and the requirement of a communication scheme in order to recompose the images. The latter will be extensively discussed in Section 6.3.3.

6.3.2 Gridding

Gridding operation is presented in Section 3.3.1. It is required to interpolate the data onto a regular grid, so that a FFT algorithm can be used. In RICK, gridding of the visibility data is done in successive rectangular sectors along the v -axis. First, an array is created for each sector, concatenating the data with u, v coordinates inside the corresponding sector. Then, visibilities V are convolved with a gridding kernel $C(u, v, w)$ (Section 3.3.1). C is usually chosen to have a FT that drops off very rapidly beyond the edge of the image: examples are a truncated sinc (O’Sullivan, 1985), a Gaussian, or a Kaiser-Bessel (Jackson et al., 1991) function. Once boundary data among different slabs are properly managed, this part of the computation is completely local and can be executed on multiple cores or accelerators (see Gheller et al., 2023, for details).

²³<https://fftw.org/>

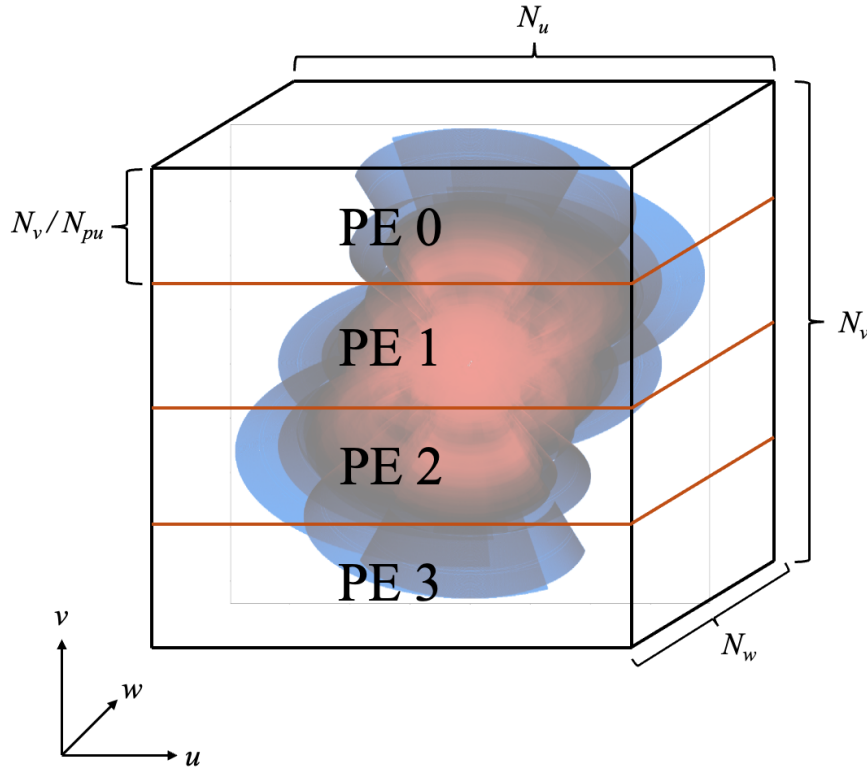


FIGURE 6.4: Cartesian computational mesh data distribution. Each computing unit (indicated as PE#) owns a rectangular resident slab of size $N_u \times N_w \times (N_v/N_{pu})$ cells. In this example, data are split among $N_{pu} = 4$ computing units (adapted from Gheller et al., 2023).

6.3.3 Reduce

The Cartesian mesh is split into slabs (Section 6.3.1) that are processed according to the following procedure. Each processing unit concurrently calculates the local contribution of its own visibilities lying on a given slab; this local contribution is stored by each processing unit in an auxiliary buffer of the same size of the resident slab. As soon as visibilities of the given slab are processed, the local contribution stored onto the auxiliary slab is summed to the relevant resident slab on the processing unit to which it belongs. Once gridding is complete, collective communications are used to reduce the contribution of each processing unit on the resident slab. In the original code from Gheller et al. (2023), the parallel summation is implemented using a blocking `MPI_Reduce` function from all the MPI tasks to that owning the resident slab, implying that all the communication must be completed before the next iteration starts. Synchronization is imposed only at the end of the loop over slabs, calling a collective `MPI_Win_fence` function. Despite being still the standard for CPU parallelism in RICK, Gheller et al. (2023) concluded that this operation can introduce significant overhead, even on single node, when the number of MPI tasks per node is large or the problem size increases. However, with the distributed parallel approach adopted in RICK (Section 6.3.1), communication is not avoidable. To reduce this bottleneck, we developed two different solutions.

Hybrid CPU-based Reduce

This hybrid reduce technique combines MPI and OPENMP parallelism and exploits the NUMA topology. This allows to optimize the access to local data and to minimize the number of MPI tasks and related message passing communication overheads.

This hybrid implementation works as follows: as first, two MPI communicators are built: 1) an intra-node communicator, where only the MPI ranks pertaining to each computing node are included and are ranked from 0 to $P - 1$, with P being the number of MPI ranks on every node, 2) an inter-node communicator that groups all ranks 0 in the intra-node communicators. In communicator 1, each MPI task knows its siblings and exchanges data using shared-memory windows with a ring algorithm. Each MPI task spawns two threads. Thread 1 is in charge of calling the shared-memory reduce function with a ring fashion involving all the other tasks in the intra-node communicator with its siblings, while thread 0 manages the MPI communications among the nodes. It is important to say that although each task needs at least two threads, only task 0 (i.e. the master) is actually involved in the MPI communications. So in the current implementation, all the other tasks spawn “silent” threads. In a future implementation, we plan to fully occupy the CPU cores with OPENMP and let all the threads participate to the summation. When the shared-memory reduce is done, task 0 gathers the result: this is the total summation in case of a single node run, and it is a partial summation in multi-node cases. The partial sums on each node are finally added using an `MPI_Ireduce` call among the tasks in communicator 2, resulting in the overall sum. In Section 6.3.5, when we discuss the results about hybrid MPI+OPENMP tests, we assume that the hybrid reduce is used; a future work will be dedicated to a full description of this reduce.

GPU-based Reduce

GPU-GPU communication allows exploiting the NVLINK NVIDIA high-speed interconnect within a node (or INFINITYFABRIC for AMD), and to avoid the CPU-GPU data transfer necessary for standard MPI communication. NVLINK is a wire-based communications protocol that can be used for data and control code transfers in processor systems between CPUs and GPUs and solely between GPUs. The Leonardo Booster is equipped with NVLINK 3.0, which provides a transfer rate of 50 Gbit s^{-1} and a bandwidth per GPU of 600 GB s^{-1} .

We refer to NVIDIA Collective Communication Library (NCCL²⁴) which implements the reduce operation as a ring intra-node, and an inter-node ring, when GPUs assigned to the main tasks communicate with *Remote Direct Memory Access* (RDMA) with GPUs in different nodes without passing through the CPUs (Li2020). A similar solution can be adopted for AMD GPUs thanks to ROCM Collective Communication Library (RCCL²⁵), simply by replacing CUDA calls with HIP calls.

6.3.4 Fourier transform

After gridding (and data communication), a FFT algorithm can be used to efficiently convert the gridded visibilities to the image space (Section 3.3.1). For the w -stacking gridded, each w -plane is computed separately. This is performed using the FFTW library. On CPUs, Gheller et al. (2023) used the parallel FFTW to execute the FFT through MPI (FFTW-MPI²⁶): for each w -plane, the FFT is simultaneously computed by the processing units on their resident slab. To speed-up this operation, we developed a hybrid CPU-based FFT and a fully distributed multi-GPU FFT.

Parallel FFT on multiple GPUs

Running the FFT directly on the GPUs represents a pivotal step for the RICK code since it reduces the computational cost of this operation and removes the data movement associated with it (see Gheller et al., 2023).

²⁴<https://developer.nvidia.com/nccl>

²⁵<https://rocm.docs.amd.com/projects/rccl/en/latest/>

²⁶https://fftw.org/doc/Distributed_002dmemory-FFTW-with-MPI.html

We have adopted the NVIDIA CUDA FFT library (cuFFT²⁷), which provides an interface for computing FFTs on an NVIDIA GPU. In particular, given our distributed memory parallelism approach, we exploited the distributed version of the cuFFT, namely the *cuFFT Multi-process library* (cuFFTMp²⁸). This is a multi-node, multi-process extension to cuFFT that supports multiple GPUs across multiple nodes, a key feature given that large size problems hardly fit into a single GPU memory. At the time of writing, cuFFTMp is the only library capable of solving the FFT problem among distributed GPUs. Specifically, we have used version 11.0.14 of the cuFFTMp, included in version 23.11 of the NVIDIA HPC SDK toolkit. The cuFFTMp library uses NVSHMEM²⁹, a communication library based on the OPENSHPMEM standard that creates a global address space that includes the memory of all GPUs in the cluster. The main steps of the cuFFTMp implementation of the 2D FFT on NVIDIA GPUs are listed hereafter.

- A plan for 2D complex-to-complex FFT is created, which contains all information necessary to compute the transform, including the pointers to the input and output arrays.
- For each w -plan, distributed data are copied to the respective *descriptor*, that represents an ad-hoc structure for data that have to be transformed.
- The previously-initialized plan is executed doing a 2D inverse FT.
- Data are redistributed to the original order with a `DEVICE_TO_DEVICE` copy, because after the FFT they are distributed in a permuted order.
- Finally, transformed data are brought back from descriptors and written into a new device pointer, always distributed among multiple GPUs, which is then used for the following steps of the code.

This operation is executed for each w -plan, as required by the w -stacking algorithm. Within the loop over w , we need to allocate and free device memory for the first descriptor used by the cuFFTMp, that is the one used for the execution of the FFT plan. A second descriptor is instead used only to redistribute data in the original order, so it can be allocated and freed just once outside the w -layers loop. The number of layers to be transformed has a significant impact on the overall performance of this step. Also the initialization of the library, in particular with the creation of the plan at the beginning of the FFT step, impacts the computing time. This will be further discussed in Section 6.3.5.

Having data resident on the GPU memory, we managed to use a CUDA kernel to write the to-be-transformed input array into a `cufftDoubleComplex` data type, dividing the real and imaginary parts, and copying it directly within the descriptor, speeding up its creation and optimizing the requirement of adopting this kind of data structure. We also used a CUDA kernel to write FFT transformed data back to the right pointer on the GPU which is then used for the following the w -correction step. This fully eliminates the communication between host and device, hence preventing the need for data transfer between the CPUs for every process and w -plan.

Hybrid CPU-based FFT

When GPUs are used, each of them is assigned to a single MPI task, running on a single CPU core. These cores are the only ones that can contribute to a pure MPI FFTW calculation: therefore, a significant fraction of the node's computational capacity is wasted. In order to overcome this limitation, we have exploited the MPI+OPENMP parallelism using the Hybrid FFTW³⁰, which

²⁷<https://docs.nvidia.com/cuda/cufft/contents.html>

²⁸<https://docs.nvidia.com/hpc-sdk/cufftmp/index.html>

²⁹<https://developer.nvidia.com/nvshmem>

³⁰https://www.fftw.org/fftw3_doc/Combining-MPI-and-Threads.html

allows the combination of MPI tasks and OPENMP threads to fully utilize the CPU as follows.

- First, data are distributed among all the MPI tasks as in the FFTW-MPI implementation.
- Then, each MPI task spawns a certain number of OPENMP threads for a further workload distribution.

This allows exploiting all available hardware: in the previous example, the hybrid FFTW runs on 4 MPI tasks, each task spawning 8 threads, effectively maximizing the CPU performance. In addition, when all cores of each CPU are used, the hybrid implementation is expected to scale better compared to the pure MPI one, since the number of MPI tasks performing communication is reduced, leading to a lower communication overload.

6.3.5 Performance tests

To evaluate the performance of RICK, we run several tests exploiting the Leonardo HPC architecture, available at the CINECA supercomputing center. CINECA is the Italian national HPC facility and the Leonardo Booster system is made of 3456, 32-cores, Intel Xeon Platinum 8358 CPU nodes equipped with 4 NVIDIA Tesla Ampere 100 GPUs. Each CPU node has 512 GB of DDR4 memory, the memory of the GPU is a 64 GB HBM2. The CPU and the GPU are interfaced by a PCIe Gen4 interconnect, while the 4 GPUs per node adopt NVLINK 3.0. The system interconnect is a Nvidia Mellanox network, with Dragon Fly+, capable of a maximum bandwidth of 200 Gbit s⁻¹ between each pair of nodes. The system deploys a Lustre parallel file system as working storage area. The source code has been compiled using the GCC and the NVCC compilers and OPENMPI v4.1.4. The only dependency of the code is on the FFTW3 library. The building procedure requires only a few seconds. The GPU tests have been performed using CUDA version 12.1 and NVIDIA HPC SDK version 23.11: this suite includes NCCL version 2.18.5, NVSHMEM version 2.10.1, and cuFFTM version 11.0.14.

Three different input data configurations have been used for the tests, namely the *Small*, *Intermediate* and *Large*, addressing different test sizes. The first can run on a single CPU/GPU up to a small number of computing units. This allows for testing the performance of each unit and comparing the scaling within a node and between nodes. The second encompasses a number of intermediate computational configurations, that can be frequently expected for radio astronomical data. The third focuses on extreme cases, for which large images have to be generated and hundreds of computing units are required to ensure that enough memory is available to manage the computational mesh. The input data comes from two different radio MS from LOFAR 8 hours, dual inner mode, observations in HBA. One of the MS is only constituted by the Dutch stations (LOFAR Dutch), the other using the full ILT (LOFAR ILT). The main characteristics of the two observations, together with the size of the computational mesh adopted in the three test cases, are presented in Table 6.1 and 6.2. The dataset for the *Small* tests is a single sub-band of 2 MHz of the LOFAR Dutch observation at 150 MHz. The *Intermediate* and *Large* tests used instead the same LOFAR ILT MS, with the only difference residing in the size of the computational mesh.

For each test, we report the following wall-clock time measurements related to specific code components:

- the gridding time, which is the time required for the gridding operation on the visibilities;
- the reduce time, related to the reduce operation;
- the FFT time, which is the time required for inverse Fourier transform of the gridded visibilities;
- the *w*-correction time, the last step of the code before writing the final outputs;

	LOFAR Dutch	LOFAR ILT
RA	15:58:18.96	17:12:50.04
Dec	+27.29.19.20	+64.03.10.60
Observation time	8 hrs	8 hrs
Integration time	4 sec	4 sec
N. of stations	62	72
Bandwidth	1953.1 kHz	1953.1 kHz
Reference frequency	150.5 MHz	144.6 MHz
N. of channels	20	160
Channel width	97.656 kHz	12.207 kHz
Project code	LC14_018	LT16_005
Principal Investigator	F. Vazza	A. Botteon

TABLE 6.1: Main characteristics of the LOFAR HBA datasets used for the *Small* (LOFAR Dutch) and *Intermediate/Large* (LOFAR-ILT) configuration test.

	Small	Intermediate	Large
N. visibilities (approx)	0.54×10^9	47.05×10^9	47.05×10^9
Input data size (GB)	4.4	533	533
$N_u = N_v \times N_w$	$4096^2 \times 16$	$16384^2 \times 32$	$65536^2 \times 32$
Mesh size (GB)	10.81	258.81	4098.81

TABLE 6.2: Configuration and computational mesh used in the *Small*, *Intermediate* and *Large* tests. The mesh size takes into account the total amount of memory required for the real and imaginary part depending on the size of the grid.

- the total parallel time, which is the total execution time of the code neglecting the initial setup time, which involves mainly I/O data load operations and the writing of the final image.

In order to assess the performance of the different code components, we have measured the wall-clock times they took to complete the different tests, and we have discussed the best performance for each configuration. We have then analyzed the code scalability (Section 6.1.5), defined as the ability to handle more work as the size of the computing system or of the application grows. Scalability has been assessed in terms of both strong and weak scaling.

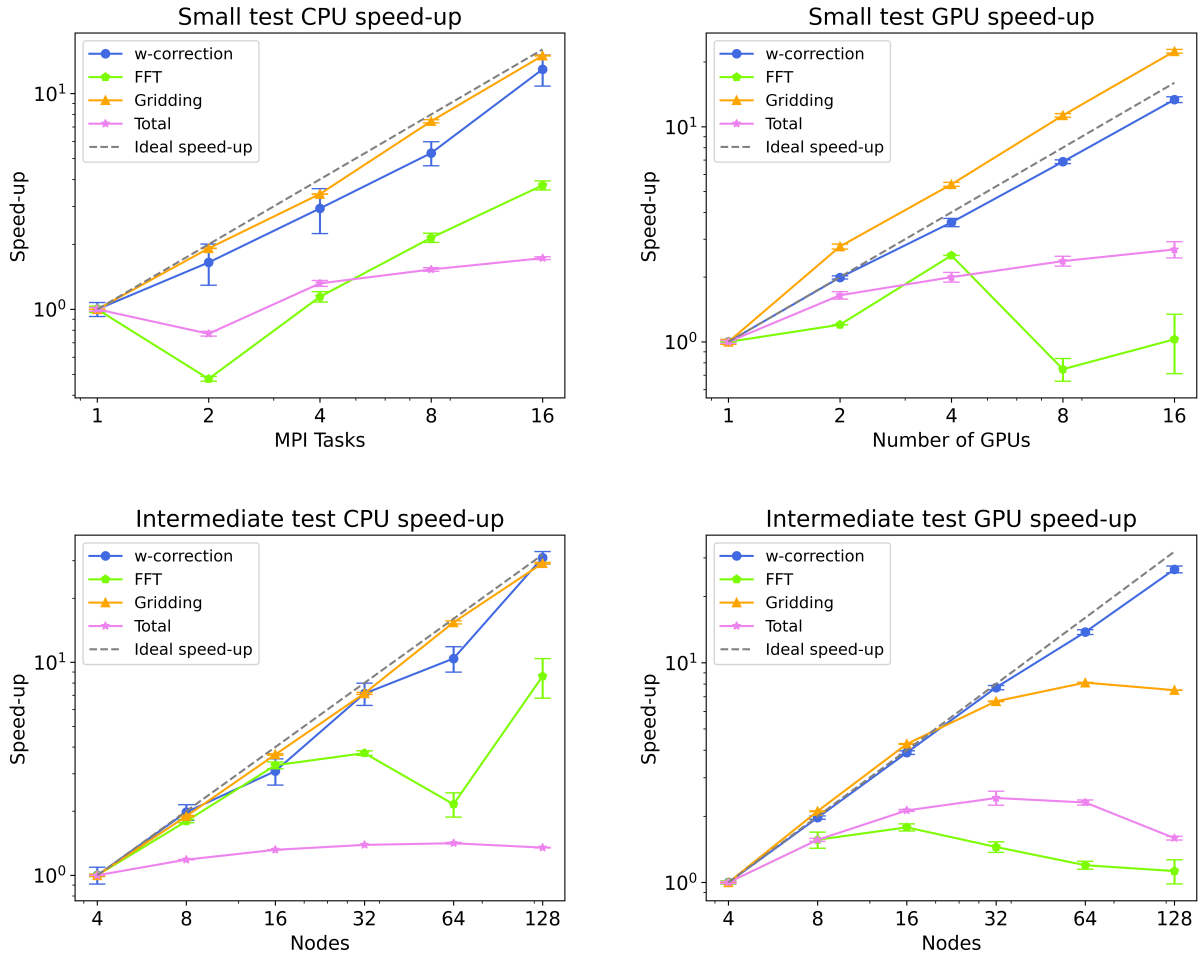


FIGURE 6.5: Speed-up results for each step of the code for both full CPU and full GPU code, using *Small* (top) and *Intermediate* (bottom) dataset. The dashed gray line represents the ideal scaling trend. For the *Intermediate* test, the number of resources per node is of 4 MPI tasks and 8 OPENMP threads for the full CPU and 4 GPUs and 8 OPENMP threads for the full GPU test.

	Nodes	MPI (threads)	GPUs	Gridding (s)	Reduce (s)	FFT (s)	w -correction (s)	Total (s)
<i>Small</i> CPU	4	16 (8)	0	0.304±0.001	4.351±0.002	0.676±0.028	0.179±0.028	5.636±0.039
<i>Small</i> GPU	4	16 (8)	16	0.104±0.001	0.207±0.001	0.615±0.04	0.010±0.001	1.187±0.048
<i>Intermediate</i> CPU	64	256 (8)	0	1.719±0.026	138.352±0.064	9.646±1.253	0.419±0.050	150.944±1.256
<i>Intermediate</i> GPU	32	128 (8)	0	1.244±0.026	10.132±0.436	1.803±0.058	0.021±0.001	15.965±0.440

TABLE 6.3: Best performance times for *Small* and *Intermediate* tests both full CPU and full GPU.

Results for each configuration are provided to achieve the following objectives: *i)* inform the user about the expected runtime of the code in various setups; *ii)* compare the CPU and GPU time to solution. For each configuration, we showcase the best possible result achieved by varying the number of processing units. The timings encompass all the various stages involved in processing the data, including the time spent for communication and for a minor algorithmic component that has not yet been parallelized. Data reading and writing are, instead, not addressed here. Additional information on the single CPU/GPU performance can be found in Gheller et al. (2023).

Best performance is presented in Table 6.3 for the *Small* and *Intermediate* tests, while for the *Large* test it corresponds to the set-up with 64 and 32 nodes for the CPU and GPU cases respectively, reported in Table 6.4.

For the *Small* configuration, the best result is obtained using 4 nodes for both the CPU and the GPU tests. Both tests run with 4 MPI tasks per node, the former spawning 8 OPENMP threads per task, and latter assigning one GPU per MPI task. The total time to solution is around 5.6 seconds for the CPU setup. The GPU setup runs around 4.5 times faster, in about 1.2 seconds. The breakdown in the different algorithmic components shows that gridding and w -correction are around 3 and 18 times faster on the GPU respectively. The FFT times are instead comparable. The big difference emerges for the MPI reduce time which is more than 20 times faster for the GPU setup. We will discuss in details the impact of the reduce in the following sections.

The *Intermediate* configuration shows the best performance on 64 and on 32 nodes for the CPU and GPU setups, respectively. Overall, the GPU setup takes around 16 seconds to complete, almost 10 times faster than the CPU one. In both setups the majority of the time is spent in the reduce operation, while the FFT becomes much faster on the GPU, thanks to the parallel cuFFTW implementation, much more efficient than the hybrid FFTW.

For the *Large* tests, the GPU setup runs on 32 nodes around 150 times faster than the CPU setup, achieved on 64 nodes. Such result is mainly due to the huge difference in the reduce time. Once more, a dedicated discussion on this aspect is provided below. The breakdown shows that gridding times on GPU and CPU setups are similar, with CPU time faster around 1.4 times than GPU one. We will discuss the reason for this behavior in the next section. The breakdown shows that FFT times on GPU setup are much faster than in *Intermediate* tests, around 25 times compared to CPU setup.

Strong scaling tests

Strong scaling results are shown in Figure 6.5, where the speed-up is measured as a function of the number of computing units for the *Small* and *Intermediate* configurations. In Table 6.4 we report the execution times for the *Large* test. The tests have been conducted on a progressively larger number of computing units, varying in a range that depends on the test size. The minimum number of computing units is set so that the problem can fit within the available memory. The maximum number of computing units is chosen to guarantee that the computing time is higher than the communication time, with the exception of the *Large* test, which will be discussed separately

The *Small* tests have been performed using up to 4 nodes with 4 MPI tasks/node for the MPI runs (up to 16 MPI tasks in total) or 4 GPUs/node for the GPU runs (with 1 MPI task associated to each GPU), with 8 OPENMP threads. *Intermediate* tests range between 4 and 128 nodes, with a fixed number of 8 OPENMP threads and 4 MPI tasks (or GPUs) per node. The *Large* tests required at least 32 nodes because of the large memory request. Computing resources increased progressively up to 128 nodes, which means a total of 4096 MPI tasks for pure CPU runs or 512 GPUs for the CUDA runs.

Gridding time. For the GPU version of the gridding algorithm, the timings account also for the offload time of visibilities and relative weights from CPU to GPU through asynchronous memory copies. The gridding kernel is called iteratively, once per each mesh sector (see Gheller et al., 2023, for details), so we report here the sum of the times spent for each individual sector (namely the total gridding time).

For the *Small* tests, Figure 6.5 top panels, we first perform a baseline test using 1 MPI task and 8 OPENMP threads. All the other CPU runs double each time the number of MPI tasks, keeping 8 OPENMP threads per task. We notice the almost perfectly linear scaling of the gridding over a single node, ranging from 1 to 4 MPI tasks. Since each node has 4 GPUs, we have not explored other hybrid single node configurations any further. The tests with 8 and 16 MPI tasks have been performed using 2 and 4 computing nodes, respectively, with 4 MPI tasks per node and 8 threads. The GPU tests for the *Small* dataset show a good scaling starting from 1 GPU up to 16 GPUs distributed again into 4 Leonardo booster nodes. GPUs result to be $\simeq 2 - 3$ times faster than CPUs (see Table 6.3).

For the *Intermediate* strong scaling tests (Figure 6.5, lower panels), we measure the speed-up of the hybrid MPI+OPENMP implementation for CPUs (bottom left panel), observing that gridding scales almost ideally even up to 128 nodes. In this case a thread synchronization is needed because different threads of each MPI task have to perform gridding in concurrent regions of the mesh. Anyway, in Intel CPUs, this multi-threading synchronization, which can lead to an overhead, does not impact on the code performance and the algorithm scales linearly. For the GPU case (bottom right panel), we observe that the gridding shows an ideal scaling only up to 16 nodes, meaning that from 32 to 128 nodes the scaling is not linear anymore. This behavior appears also for the *Large* tests and it will be discussed further at the end of this Section.

For the *Large* case (see Table 6.4), the CPU tests are pure MPI, running on 32, 64, 128 nodes with 1024, 2048, 4096 MPI tasks, respectively (meaning 32 MPI tasks per node). Gridding time scales linearly when we double the computing resources, due to the fact that no communication overhead is included. For the GPU tests, the gridding time does not scale increasing the number of accelerators from 128 to 512, remaining approximately constant. This trend is similar to what was found in the *Intermediate* tests when more than 16 nodes were used. This behavior is due to the overhead related to CUDA GPU memory management and, more specifically, to repeated *cudaMalloc* and *cudaFree* calls that are implied by the iteration procedure through mesh sectors. At each iteration, the GPU memory storing visibilities is allocated and de-allocated, causing the observed overhead. The number of CUDA calls increases with the number of sectors, which is equal to the number of MPI processes. With 2 GPUs these calls contribute to $\sim 20\%$ of the gridding time, while this number increases to $\sim 34\%$ in the 4 GPUs case. When a large number of resources are used, it dominates the entire gridding time.

	Nodes	MPI tasks (threads per task)	GPUs	Gridding (s)	Reduce (s)	FFT (s)	w -correction (s)	Total (s)
CPU tests	32	1024 (1)	0	4.5	9631.4	160.6	7.2	10246.0
	64	2048 (1)	0	1.9	9598.2	107.1	3.5	10153.5
	128	4096 (1)	0	1.1	9715.8	98.4	1.7	10266.5
GPU tests	32	128 (8)	128	2.6	54.8	4.2	0.3	67.4
	64	256 (8)	256	2.4	59.4	2.8	0.2	69.4
	128	512 (8)	512	2.7	72.6	2.7	0.1	83.4

TABLE 6.4: Strong scaling results for each step of the code for *Large* test, which has a mesh size of $65, 536 \times 65, 536 \times 32$ using LOFAR IIT dataset. Both full CPU and full GPU execution times in seconds are shown, with increasing computational resources for each. For these measurements we did not report the errors because multiple execution of this test would have consumed a large fraction of our available computing time.

FFT time. While on the CPU the Fourier Transform is calculated using the FFTW3, on the GPU the cuFFTM library is adopted. In the *Small* test (Figure 6.5, top right panel), the speed-up shows a peculiar behavior. Within a single node, the performance worsens from 1 to 2 GPUs. This is because the FFT accounts for two distinct contributions: plan creation and actual computation. Due to the small mesh size, the plan creation contribution is comparable to computation causing the measured performance loss. From 2 to 4 GPUs the FFT scales linearly, exploiting the intra-node NVLINK high-speed interconnect. On multiple nodes the FFT performance drops due to the progressively smaller problem size per GPU and the heavier communication overhead associated with the all-to-all required by the FFT. Similarly, in the *Intermediate* case (Figure 6.5, bottom right panel) the FFT scales efficiently up to 8 nodes, decreasing when a larger number of GPUs is increasingly used. In addition, the cuFFTM has a startup time for initializing NVSHMEM and the 2D plan for the Fourier transform. This startup time ranges from 0.5 s to 1.5 s for the *Intermediate* test, increasing with the number of MPI tasks.

For the *Small* tests on the CPU (Figure 6.5, top left panel), the FFT is computed through the hybrid FFTW MPI+OPENMP approach, keeping 8 OPENMP threads for each combination of MPI tasks. This explains the lack of scaling from 1 to 2 MPI tasks, where communication arising from calling multiple tasks determines an increase in the FFT time. The scaling is instead linear from 2 to 16 MPI tasks. In the CPU *Intermediate* test (bottom left panel in Figure 6.5), the scaling is close to ideal up to 16 nodes. In Figure 7 from Gheller et al. (2023), it turns out that in the pure MPI case the FFTW scaling reproduces the expected linear scaling up to $\sim 10^2$ MPI tasks. Here the hybrid MPI+OPENMP FFTW is used instead. This choice is due to the fact that we have less GPUs than CPU cores in each node, and to use efficiently the entire node OPENMP parallelization is unavoidable. Hybrid FFTW is faster than the MPI one when less cores than available are utilized, but at least in these tests that we have performed, the code scalability gets worse with 128 MPI tasks distributed among 32 nodes. Understanding this scaling of the FFTW with OPENMP requires a deep code's profiling and was beyond the scope of this work.

For the *Large* case (Table 6.4), in pure CPU tests the FFT's performance improves by $\sim 60\%$ when passing from 32 to 64 nodes, while the performance gain is poor when passing from 64 to 128 nodes. With such a large number of MPI tasks, all to all communication dominates the runtime and the performance gain in the computation is almost completely suppressed. In the GPU tests, the FFT's performance improves by $\sim 50\%$ when passing from 32 to 64 nodes, while the performance gain drops when using 128 nodes. Again, this is due to the all-to-all communications and, at the same time, the progressively lower computation related to an increasingly larger amount of MPI processes.

***w*-correction time** Strong scaling tests of the *w*-correction reveal that the code scales almost linearly both for the *Small*, hybrid MPI+OPENMP, CPU tests and for the *Intermediate*, pure MPI, CPU tests. The same holds for GPUs, for which this step is implemented within a CUDA kernel. For this algorithm, GPUs are more than order of magnitude faster than CPUs. In the *Large* tests, *w*-correction time keeps scaling linearly in both CPU and GPU tests. In particular, this kernel turns out to run efficiently on GPUs, there existing a factor of ~ 20 on average in runtime between CPU and GPU tests. *w*-correction is performed directly on the grid which has already been mapped on GPUs, such that no unnecessary memory management is needed.

Full code Overall, RICK shows a sub-linear scalability in both the *Small* and *Intermediate* configurations, both for the CPU and the GPU tests. As already pointed out above, such behavior can be mainly ascribed to the impact on the code of the reduce related overhead and is also evident from the figures presented in Table 6.4. Additional factors, like the progressively smaller amount of data to process as the number of computing units grows, affect in particular the GPU runs.

6.3.6 Weak scaling tests

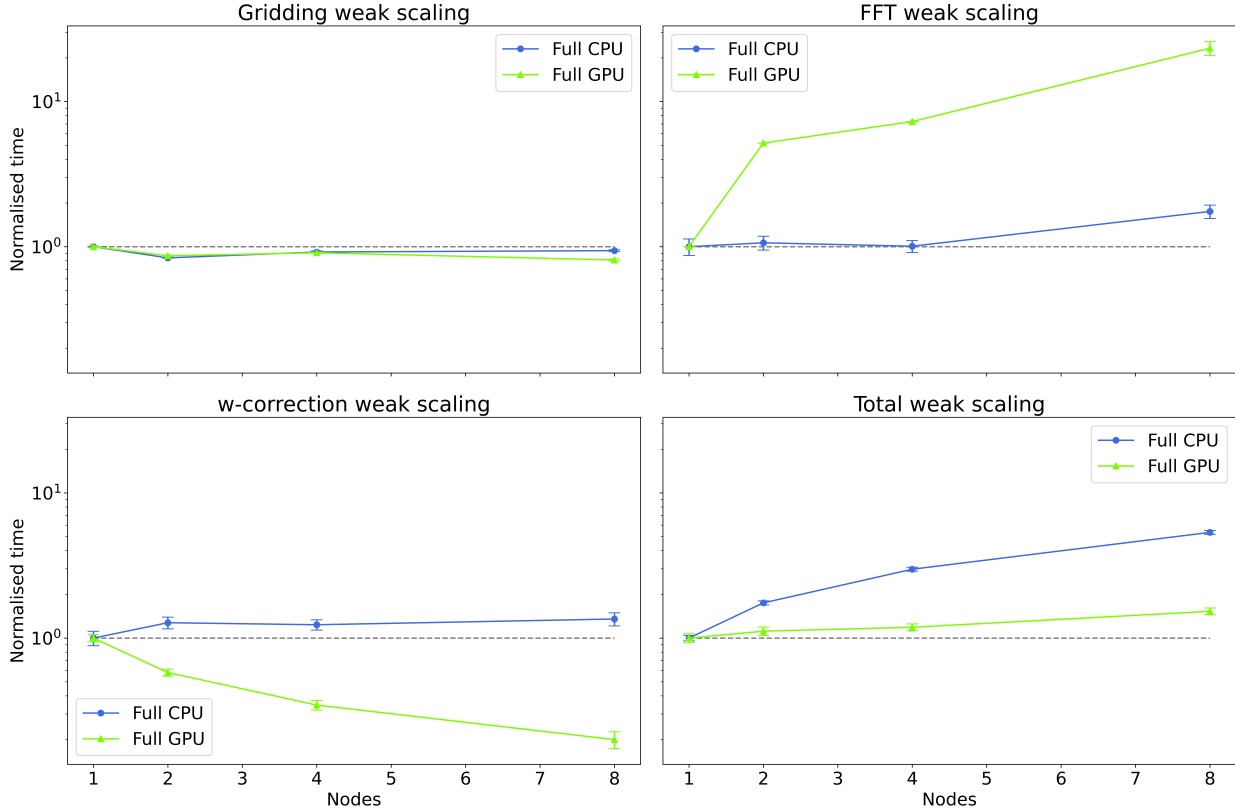


FIGURE 6.6: Results for the weak scaling tests for each step of the code. The *normalized time* on the y axis is defined as the ratio between the wall clock time measured using N_p computing nodes for a $N_1 \times N_p$ size problem and the wall clock time measured using a single computing node for a N_1 size problem (which is our baseline configuration). Values below 1 indicate an enhancement in performance, whereas values above 1 represent a reduction in scalability. The horizontal dashed gray line represents the ideal weak scaling of the code (Section 6.1.5). From the top left corner, clockwise, results are shown for the gridding, FFT, w -correction, and total. The full CPU execution is shown in blue, while in green the full GPU enabling of the code. For each run 8 OPENMP threads were spawned.

Weak scaling tests have been performed using the LOFAR Dutch dataset over 1, 2, 4 and 8 computing nodes, instancing 4 MPI tasks per node and doubling at each step both the input size data and the number of w planes. For each configuration, 8 OPENMP threads per MPI task have been spawned. In Figure 6.6, we present the runtime normalized to that of a single node (adopted as reference) of the different parts of the code and of the full code. The ideal weak scaling would result in a value of 1 regardless of the number of nodes.

Gridding, top-left panel, shows an almost ideal weak scalability for both the CPU and the GPU tests, with performance slightly improving increasing the number of nodes from 1 to 2 and showing small fluctuations for 4 and 8 nodes. The FFT weak scaling is presented in the top right panel. The hybrid MPI+OPENMP FFTW3 scales almost ideally from 1 to 4 nodes. On 8 nodes, the performance loss can be attributed to the impact of the all-to-all communication. For the GPU, cuFFTM based tests, a significant performance drop is observed when the number of nodes increases from 1 to 2. This is mainly due to the switch from the intra-node high-speed NVLINK interconnect to the lower bandwidth Infiniband network connecting different nodes. From 2 to 8 nodes, the performance

is also worsening. This can be explained as a result of the way the weak scaling test is designed, maintaining constant the grid dimension and doubling at each step the number of w -planes. This increases the number of FFTs performed by the algorithm. However, the amount of computation per FFT that is performed by each GPU decreases with increasing the number of GPUs, leading to a computing efficiency loss, reflected by the weak scaling curve.

In the bottom-left panel, the weak scaling of the w -correction term is presented. The weak scaling for the CPU is nearly optimal, whereas in the case of the GPU, performance tends to increase significantly as the number of nodes grows. This behavior can be interpreted as a consequence of the decreasing volume of data transferred from the GPU to the CPU as the number of GPUs increases. Specifically, when the number of GPUs is doubled, the portion of the image that needs to be copied back to the host halves. This has a positive impact on the time needed to transfer data between the device and the host.

When considering the overall scalability of the code, GPUs exhibit just a small reduction in efficiency as the number of nodes increases. In the case of the CPU instead, the deviation from the optimal scaling is evident. Once more, the efficiency loss is mainly due to the effect of the reduce, as we will discuss in Section 6.3.8.

6.3.7 Energy consumption measurements

In Lacopo et al. (2025), we aimed to find the best trade-off in the code's energy efficiency and performance when more computing resources/different configurations are used. Although it is easy to measure either when a code is faster or less energy consuming, it is not trivial to find a physical quantity that relates the energy consumption with the runtime in a meaningful way. This led to the introduction of the green productivity (GP). It has the following definition:

$$GP = \frac{T_0/T_N}{\alpha E_N/E_0}. \quad (6.2)$$

T_0 and E_0 are the runtime and energy consumption of a reference configuration, respectively, while T_N and E_N are the runtime and the energy consumption of a run using N computing units. Clearly, when the same code implementation is being tested and the only thing changing is the number of computing resources, the quantity at the numerator is simply the speed-up in a strong/weak scaling test. α is a weight factor which changes depending on what we consider more important among performance and energy consumption. In their work, they treated them with the same importance and chose $\alpha = 1$.

Test results, conducted using the Setonix AMD architecture (Pawsey Supercomputing Centre, Australia), are listed in Table 6.5. We tested RICK both with full CPU, pure MPI and hybrid (MPI+OPENMP), and full AMD GPU configuration, both on single and multiple nodes: it is interesting to underline that, given the lack of a distributed library for the FFT problem on AMD GPUs, the full GPU test relies on the hybrid FFTW to be executed.

For single node tests, the hybrid implementation is 4 times faster and 3.3 times more green than the pure MPI run, while GPU implementation is 8.2 times faster and 3 times more green than pure MPI. The main difference is in the reduce operation, which is 20 and 40 times faster for the hybrid and GPU implementation compared to MPI, respectively. The performance difference in FFTW in GPU runs is due to the fact that it's still on the CPU and no OPENMP threadization is active for this test. Pure MPI tests are the fastest in gridding time, even when comparing them to GPU tests. This behavior is due to the overhead related to HIP GPU memory management, and, more

specifically, to repeated *hipMalloc* and *hipFree* calls that are implied by the iteration procedure through mesh sectors, as discussed in Sector 6.3.4.

Full GPU tests have been done using 4, 8 and 16 GPU nodes, equipped with 32, 64 and 128 accelerators, respectively. CPU+GPU tests revealed being 6 – 7 times more green than the pure CPU ones with high/default frequencies (CPU frequency, up to 2.60 MHz) and 4–5 times more green with medium/low frequencies (1.5 – 2.0 GHz). In terms of strong scaling performances, CPU+GPU tests are faster by a factor 9 – 11 for high/default frequencies and a factor 10 – 12 for medium/low frequencies with respect to pure CPU (Figure 6.7). For multi-node tests, GPUs turn out to be definitely the best choice because they are better in both energy saving and performance. This represents an important result for the accelerated approach to the imaging problem, particularly in the SKA framework: when operative, its dedicated facilities will process continuous signals streams from the telescope at an unprecedented scale and rate, making energy efficiency and cost containment a key concern, especially on long-term activity.

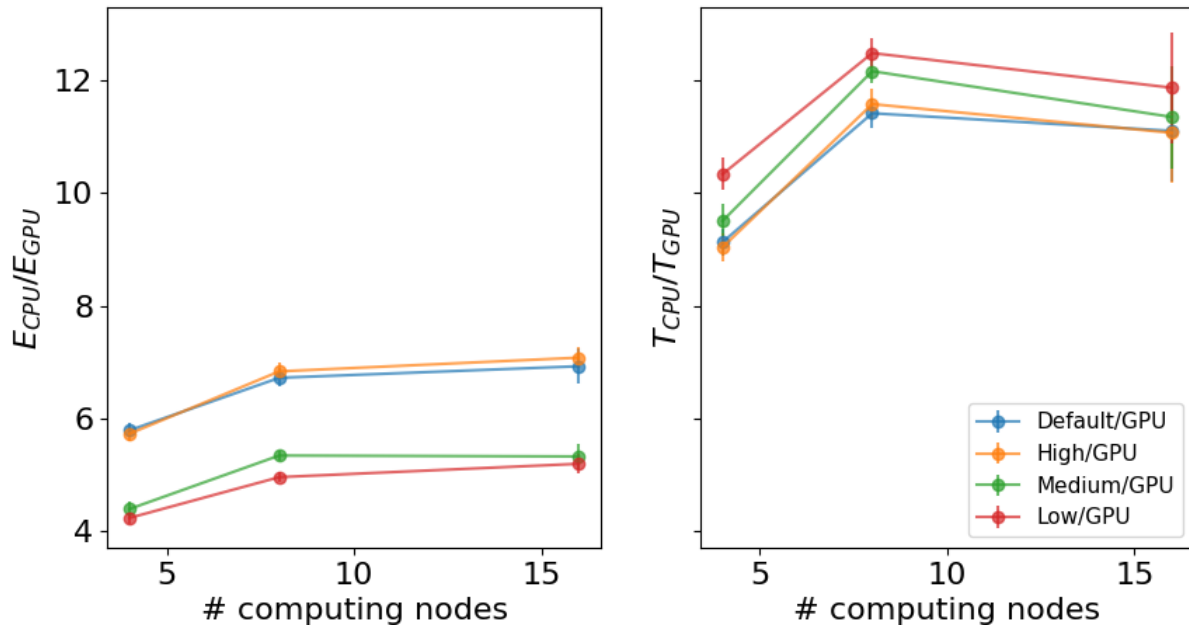


FIGURE 6.7: Left: ratio between the energy in the pure CPU case and the energy in the CPU+GPU case, at different CPU frequencies, as a function of computing nodes. Right: ratio between the CPU runtime and CPU+GPU runtime, at different CPU frequencies, as a function of computing nodes. In the GPU tests both CPU and GPU frequencies are set by the OS to their default values (Lacopo et al., 2025).

	MPI	Best MPI/OPENMP	GPU
Energy (KJ)	60.8375 ± 2.6709	18.3325 ± 0.2175	20.2325 ± 0.3790
Total time (sec)	95.9533 ± 0.1560	24.4133 ± 1.7793	11.7309 ± 0.0446
Gridding time (sec)	0.6624 ± 0.0013	1.5677 ± 0.0183	1.0925 ± 0.0001
Reduce time (sec)	84.3082 ± 0.1399	4.3494 ± 0.0054	2.0065 ± 0.0118
FFTW time (sec)	1.1941 ± 0.0982	1.8458 ± 0.0561	4.8540 ± 0.0205
w-corr. time (sec)	0.4039 ± 0.0007	0.5201 ± 0.0073	0.1112 ± 0.0003

TABLE 6.5: Total energy and runtimes for the relevant code portions in the MPI, MPI+OPENMP and GPU cases respectively. Averages and standard deviations over four runs each are reported.

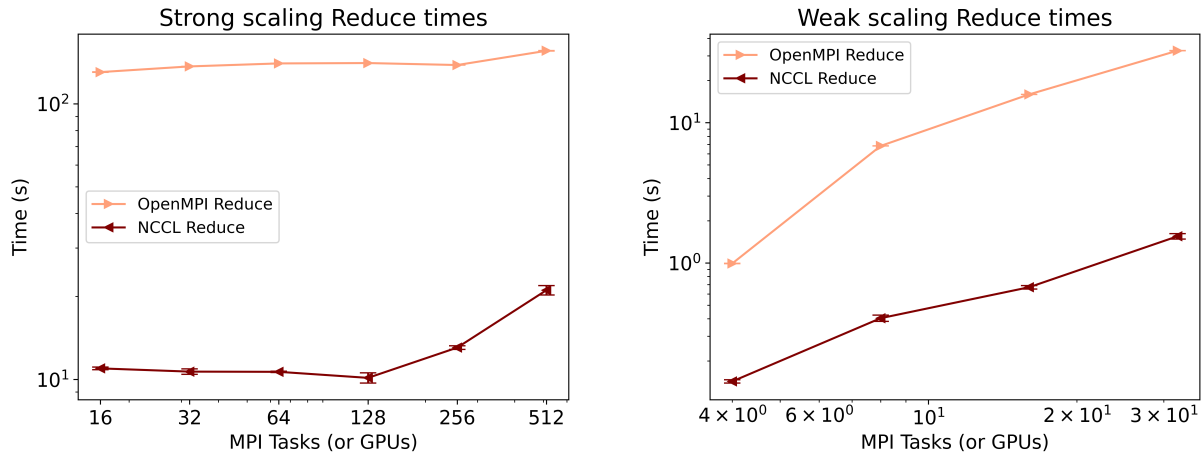


FIGURE 6.8: Time results for the reduce operation versus the number of MPI tasks or GPUs for the *Intermediate* strong scaling test (top panel), and the weak scaling test (bottom panel). Comparison between the OPENMPI *Ireduce* (in pink) and NCCL GPU reduce (in brown).

6.3.8 Discussion

The primary goal of the RICK code is to efficiently process huge datasets and generate large images in a reasonable time scale, of the order of seconds or minutes. In the tests provided, we used datasets with visibilities of up to 533 GB in size. Nevertheless, datasets of any size can be easily managed by splitting them into frequencies or time chunks. Chunks can be loaded sequentially, as described in Gheller et al. (2024). This also enables to reserve an appropriate fraction of memory for the computational mesh.

By employing an appropriate number of processing units, we have successfully generated images with a size of $65,536^2$ pixels. Utilizing GPUs significantly enhances the performance of all code components, resulting in a considerable decrease in the time to solution. In particular, the exploitation of the cuFFTMPI library reduces the impact of the FFT step. The corresponding computing time gain can range from one to two orders of magnitude compared to the FFTW CPU-only approach, depending on the scale of the problem. The current implementation of the library is highly efficient within a single node, taking advantage of the NVLINK interconnect. However, its scalability is limited when multiple nodes are used due to the slower network and the use of the NVSHMEM protocol. In the case of the FFT, this protocol does not seem to offer optimal scaling on a large number of GPUs, unlike other solutions such as NCCL, which is used for the gridding part. In all the CPU tests, the hybrid MPI+OPENMP version of the FFTW ensures good scalability. However, a slight performance loss is found in a few configurations. This cannot be easily explained, but it is interesting noting that this issue has not been observed using the MPI-only version of the library.

Our tests have demonstrated that, when the problem size and computational setup are increased, the code's performance and scalability are significantly impacted by MPI communication. In addition to the parallel FFT, communication is performed by the reduce operations required to collect and add up the mesh data from all computing units during the gridding step. This last contribution tends to dominate increasing the number of computing units. The remainder of this Section discusses the details of this aspect.

Visibilities are read evenly in parallel from an input data file in a time-log order, i.e. if we are

dealing with an 8 hours observation and $N_p = 8$, each MPI task reads data for one hour of observation. Conversely, the Cartesian computational mesh, where visibilities are gridded, is divided into rectangular slabs in the uv plane. Each slab is allocated to a distinct MPI task. Therefore, it is necessary to convert time-ordered into space-ordered data. To achieve this, the code iterates through the slabs. During each iteration i , each MPI task simultaneously computes its contribution to the i -th slab. Then, each MPI task stores its local contribution in an auxiliary buffer. Once local contributions are computed, they are summed together on a *target* buffer located on the i -th MPI task. Data collection and aggregation are achieved using an MPI reduction operation, which combines both communication (collecting data from several sources) and computation (calculating the sum of all contributions). As discussed in Gheller et al. (2023), for large images the code spends 80 – 90% of the total runtime in the reduce operation, when the reduce operation was implemented with the standard *Ireduce* from OPENMPI library.

The overhead introduced in the code by the reduction operation depends on several factors, namely: *i*) the amount of data communicated among the MPI tasks; *ii*) the number of MPI reduce calls *iii*) the amount of computation required to perform the sum; *iv*) the network topology. These factors are interconnected. During our iterative procedure, the number of iterations over slabs is equal to N_p . Each MPI task performs a reduce at every iteration, hence the theoretical reduce time T_R can be estimated as the sum of the communication (T_{co}) and the calculation (T_{ca}) times. For the CPU implementation, using the OPENMPI library, T_R can be calculated as:

$$\begin{aligned} T_R &= (T_{co} + T_{ca}) \times N_p \\ &= \left(\beta \frac{D}{N_p} + \lambda \log N_p \right) \times N_p + \left(\frac{D}{N_p} t_{\text{sum}} \right) \times N_p \\ &= (\beta + t_{\text{sum}})D + \lambda N_p \log N_p , \end{aligned} \quad (6.3)$$

where D is the total size of the data, β quantifies the bandwidth and the network topology, λ is the network latency, and t_{sum} is the time required for a single summation operation. The logarithmic term is due to the logarithmic tree algorithm used by the OPENMPI reduce.

The reduce time is then composed by two terms: the first depends on the data size and on β , while the second on the number of MPI processes. The latency term λ is generally very low ($\leq 0.6 \mu\text{s}$). In the strong scaling case, in which D is maintained constant increasing the number of MPI tasks, the first term is dominant on the second because of the low latency: for this reason, we observe a constant reduce time (Figure 6.8, top panel). Only once we use a considerably large N_p , e.g. over 128 MPI tasks (as reported in the top panel of Figure 6.8), we start to observe an increase in the reduce time: however, such increase is not due to the processes themselves, but rather to the network topology, because of the non-ideal interconnection between the nodes and to the impact of the latency term. For the weak scaling, instead, we have D that increases as well as N_p . The first term is still dominating, and for this reason we observe a reduce time which increases linearly with the data size (Figure 6.8, bottom panel).

The GPU implementation exploits the NCCL library, that implements a ring algorithm for the reduce: this means that T_R can be written as

$$T_R = (\beta + t_{\text{sum}})D + \lambda N_p^2 . \quad (6.4)$$

Due to the quadratic dependency from N_p , latency becomes non-negligible using a smaller amount of processes. For example, OPENMPI would necessitate 100,000 MPI tasks to produce a latency of 1 second, whereas the NCCL would require only 1,000 MPI tasks. On the other hand, GPUs are capable of completing the sum operation much faster than the CPUs, because of their large

computational throughput, about two order of magnitude larger than that of the CPU. This results in a considerably smaller t_{sum} , that contributes in reducing the NCCL reduce time. In addition the NCCL reduce performs better than the MPI one due to *i)* the high-speed NVLINK interconnection for intra-node GPU-GPU communication, *ii)* the number of network interface cards that equals the number of accelerators per node, leading to a bandwidth 4 times bigger than pure CPU cases. Overall we see that the the reduce operation is about 20 times faster on the GPU for the *Small* test (see Table 6.3) and up to $\times 175$ faster for the *Large* tests (see Table 6.4).

Table 6.4 also shows that the MPI *Ireduce* time remains constant scaling from 32 to 64 to 128 computing nodes. This has a progressively greater impact on the code compared to the more computationally intensive components of the algorithm. The GPU reduce time tends even to increase with the number of nodes. However, it is two orders of magnitude lower than that of the CPU. In both scenarios, increasing the number of nodes does not result in any improvement in speed, and in the case of the GPU, it actually leads to a decrease in performance.

In general, in all test regimes, the code runtime is strongly impacted by the reduce operation. In order to exploit with maximum efficiency the available computing systems, it is crucial to select a hardware configuration that has the fewest computing units necessary to meet the memory needs. This also results in saving energy, since the problem is solved in approximately the same amount of time while using less computational resources.

6.3.9 Overcoming the communication bottleneck

To overcome the communication bottleneck in RICK, largely discussed in Section 6.3.8, we have just developed a new version of the code³¹, which we describe below. It is currently in its testing phase, so we report here only a brief description of the main variations with respect to the version described above.

With respect to the structure presented in the previous Sections, the code has undergone to a comprehensive refactoring. First, MPI I/O has been implemented to read data from the filesystem and write the final outputs, replacing the *fopen*, *fread*, *fseek*, and *fwrite* functions. This supports both parallel and non-parallel filesystems (improving the portability of the code) and guarantees a better scalability than the previous version.

The most important improvement with respect to the classic RICK data structure is the new domain decomposition. This was made mainly to avoid the communication of the entire grid, which was needed to assign to each MPI rank its sector in the uv plane. By assigning visibilities to each MPI rank at once, ordered with a bucket sort algorithm along their v coordinate, it is possible to keep data local to each rank and carry out the following steps of the code without communicating any data. The whole grid is constructed based on the u and v coordinates of the visibilities. If a specific rank is assigned a slab between v_i and v_{i+1} , it means that data with a v coordinate in that interval must be assigned to the rank. Of course, data are originally unorderedly distributed, so *MPI_Sendrecv* operations are necessary to share out visibilities among the processes. However, the typical baselines distribution in radio interferometers produces a uv coverage that is denser at the center and sparser toward the edge, leading to a strong unbalancing in visibility re-distribution if an evenly distributed grid is used (as done to now, Section 6.3.1 and Figure 6.4). Consequently, tasks assigned to the outer slabs do not contribute to the gridding to the same extent as tasks assigned to the central slabs. To balance the gridding step, we deployed a non-trivial domain decomposition with finer partitions in the center and coarser partitions in the periphery of the uv plane. An example with 4 MPI tasks is shown in Figure 6.9. Due to the lower density of points in external

³¹<https://github.com/ICSC-Spoke3/RICK/tree/HeFFTe>

regions of uv plane, processes 0 and 3 would have a larger slab, whereas processes 1 and 2 would be assigned a smaller slab due to the higher density of points in central regions. The thickness of each region is assigned through a one-dimensional Gaussian distribution: we kept the one-dimensional slab distribution along v , pointing out that non trivial two-dimensional distributions are being taken into account and possibly implemented in RICK in the future. We summarize hereafter the main steps involved in this new domain decomposition. For the v axis, center and standard deviation (σ_v) of a non-normalized Gaussian distribution are computed. σ_v is then scaled by a *sigma factor*, an arbitrary parameter that controls the widths of the new domain decomposition slabs. The higher this value is, the more uniform the slab decomposition becomes. For each point i_v from 0 to $N_v - 1$, a *weight* is computed through

$$w_v(i_v) = e^{-\frac{(i_v - \mu_v)^2}{2\sigma_v^2}}. \quad (6.5)$$

Then, it iterates through the points i_v , accumulating the weights, and sets the boundary points where the cumulative weight for a partition is reached. The total weight is divided into partitions of equal weight. This method ensures that each process receives a sub-domain with an equal weight-load, even though the number of points in each sub-domain varies. Since visibilities must be spread out during gridding on a two-dimensional mesh, necessary for the FFT, one must consider that boundary points might be associated to more than one MPI task. This shrewdness led to the inclusion of *ghost regions* ε , which are given by half the convolution kernel dimension, normalized to grid size. This means that if one process is to be assigned data with $v_i < v < v_{i+1}$, the actual data assigned will be $v_i - \varepsilon < v < v_{i+1} + \varepsilon$. This code refactoring led to a much more balanced gridding operation.

This new, non-uniform grid must be supported by a FFT that enables using such decomposition. For this reason, we exploited the *Highly Efficient FFT for Exascale* (HEFFTE³², Ayala et al., 2020) library, that supports (among the others) the non-trivial 1, 2, and 3D decompositions. This library uses different back-ends to support already existing FFT implementations (e.g., FFTW, cuFFT, ROCFFT) which can be defined at compile time, ensuring portability across several HPC platforms.

As stated at the beginning of the Section, this new version of RICK is currently under benchmarking on Leonardo. We are testing the code using both LOFAR-VLBI (wide-field, from Chapter 5) and MeerKAT (from Botteon et al., 2025) data, to have a larger sample of SKA precursors and pathfinders datasets, both on CPUs and GPUs. With this new domain decomposition, maintaining the data locality, we expect the communication time to be significantly reduced with respect to the original version of the code. This is particularly true considering that typical interferometric imaging done using the Schwab CLEANing algorithm moves multiple times between the visibility and image space. While the original version of the code would imply a Reduce call for each major cycle, this could be avoided in the new version, saving further execution time. The benchmark results, together with a more extended description of the new code, will be presented in an upcoming paper (Lacopo et al., to be submitted).

6.3.10 The RICK library

Together with the new domain decomposition, and the subsequent work to limit the communication overhead, we also modified the framework of the code in order to make out a library³³ from it. We have isolated the three main steps of the code, namely the gridding, the FFT, and the w -correction, in three different functions (and relative scripts), that can be compiled and executed individually from any kind of C/C++ or PYTHON script. This is extremely beneficial for two main reasons.

³²<https://icl-utk-edu.github.io/heffte/index.html>

³³<https://github.com/ICSC-Spoke3/RICK/tree/library>

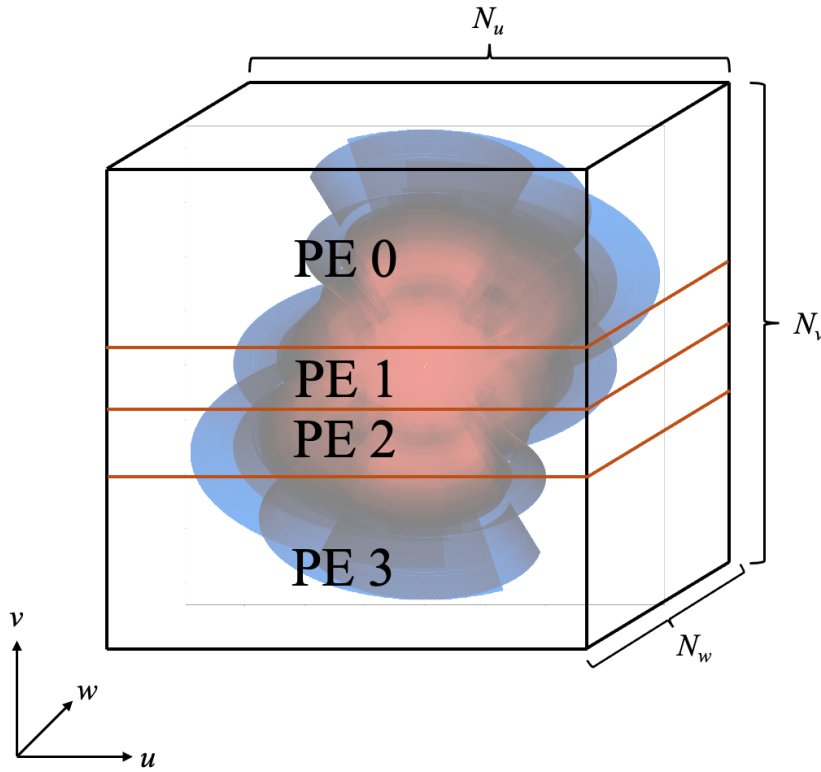


FIGURE 6.9: Cartesian computational mesh data distribution among $N_{\text{pu}} = 4$ computing units, using a non-trivial approach (based on Figure 6.4).

1. It will facilitate the possibility to implement RICK into other state of the art codes for interferometric imaging (e.g., WSCLEAN, DDFACET). The individual steps can be compiled and included in any code with minimal variations, namely calling the individual functions from the main code.
2. It improves the code portability and re-usability, even outside the pure radio astronomical environment. The individual steps can, in fact, be executed on arrays also independently on the imaging target. This implies that, for example, any code can use our optimized, multi-GPU, version of the FFT, providing potentially interesting expansion for our work.

6.3.11 Conclusions and future developments

In this Chapter, we presented RICK, a code which exploits distributed parallelism and GPU offloading to perform the inversion steps of the interferometric imaging. Starting from the code in Gheller et al. (2023), we described the work concerning the development of hybrid (MPI+OPENMP) and multi-GPU solutions to deal with communication and the FFT problems, enabling the code to fully run distributed on multiple GPUs, among multiple nodes. This is a first tentative in radio astronomy to perform imaging fully on GPUs, distributing the problem in order to be able to handle SKA-scale problems. We tested performance and scalability of the code on Leonardo HPC cluster at CINECA (Italy), with tests on strong and weak scaling of every step that constitute our code using real LOFAR data (also comprising International stations). Comparing our full-GPU code with the full-CPU, we observe a gain in total runtime of a factor $\times 9$ for the *Small* and *Intermediate* dataset configuration within a single node, and up to $\sim \times 130$ for the *Large* configuration over a large number of nodes. We overcame most of the code's computational costs, probing that this

approach is extremely promising for the upcoming data challenge brought by the SKA. The huge computational capabilities of the GPUs basically nullify the computational effort of the problem. The runtime is now mainly affected by communication. To fully exploit the improved capabilities of this implementation, one possibility is to select a computational setup that matches the problem size and minimizes communication as much as possible (Section 6.3.8). Recently, we developed a new version of the code that implements a completely different domain decomposition, capable of keeping the data local and so limiting the communication operations. This version, which is currently in the benchmarking phase, will potentially overcome the communication bottleneck, improving even further the code performances.

Our main aim for the future would be to implement RICK into any of the best state of the art software for interferometric imaging, to be more easily accessible and usable by the community. To facilitate this, we have converted RICK into a library. Moreover, RICK can do, to date, only the inversion step. We plan to extend its capabilities implementing also the *prediction* (meaning going from the image to the visibility space), and the deconvolution, which are instrumental for a complete imaging code.

Chapter 7

Summary and future perspectives

The SKA, together with its precursors and pathfinders, will enable extraordinary scientific and technical challenges, which need to be addressed by the community. A combination of new algorithms and computational approaches is needed to push the boundaries of our knowledge; exploitation of innovative HPC solutions, involving heterogeneous computing, is instrumental to process the unprecedented data volume involved, limiting time and energy consumption. This does not represent a mere exercise, but rather the best way to deal with similar data size and complexity. In the current framework, LOFAR-VLBI represents a great testing ground for the SKA challenges. It provides sub-arcsecond resolution capabilities at 150 MHz, a unique capability which will be unmatched even in the SKA era. This also brings many challenges, mainly related to the calibration procedures and the large amount of data involved (up to 20 TB after the calibration, for a typical 8 hours observation). Opening up the low-frequency radio sky to these resolutions is desirable for a wide range of cases. For cluster science, LOFAR-VLBI allows studying, among the others, the complex interplay between radio galaxies and ICM, especially in presence of turbulence. A spectacular demonstration of these interactions is represented by the non-thermal filaments, thin elongated structures, often connected to cluster radio galaxies, whose origin is still unknown. Their steep radio spectrum, combined with the narrow width, makes LOFAR-VLBI a great tool for resolving their complex spectral properties and, possibly, understand their formation scenario.

In this Thesis, we tackled the data challenge from LOFAR-VLBI both scientifically, studying the radio galaxies and filaments in the galaxy cluster Abell 2255 at unprecedentedly high-resolution, and computationally, developing a distributed, multi-GPU approach to the interferometric imaging problem. The most relevant results are outlined below.

A LOFAR-VLBI view of the galaxy cluster Abell 2255

We have targeted the merging galaxy cluster Abell 2255 to study its radio galaxies at sub-arcsecond resolution (Chapter 4). We combined 56 hours of observations with LOFAR-VLBI, that were calibrated from the raw data down to the final images, at 144 MHz. We selected the five brightest cluster member radio galaxies with for postage-stamp mode imaging, obtaining radio maps at $0.3 - 0.5''$ resolution with sensitivity ranging between $18 - 40 \mu\text{Jy beam}^{-1}$. These represent, to date, the deepest observations ever made using LOFAR-VLBI specifically targeting a galaxy cluster. The involved data volume is around 150 TB, considering only the calibrated visibilities. For the Double, we detected a narrow arc-like structure connecting the southern hotspot with the relative lobe, possible hint of collimated backflow, as well as the presence of a ring surrounding the northern hotspot, which may be due to shocks or inner lobes. The most interesting result regards instead the Original TRG. We discovered a plethora of filaments, observable only at such high resolution. In particular, F1 and F2 surround the tail, the horizontal filament is placed transversely to the tail, and the vertical filament extends upward from the horizontal one. These filaments have lengths ranging from 80 to 110 kpc,

with varying widths along their extension (3 – 10 kpc). We also resolved several instabilities developing at the beginning of the tail, possibly due to the combination of ram pressure effects and the instabilities developed in the downstream region. This is the first time these filaments are observed at such high-resolution, mainly possible thanks to the high-sensitivity provided by LOFAR-VLBI (especially combining such a large number of observing hours).

To detect the more faint and extended filaments, previously observed as the Trail and T-bone (Botteon et al., 2020b), we also produced a lower resolution (1.5'') LOFAR-VLBI map (Chapter 5). Given their extension, it was necessary to calibrate the data in the so-called wide-field mode, obtaining a large ($1.5^\circ \times 1.5^\circ$) image of the cluster field required to entirely detect filaments. We calibrated the same 56 hours of observations, which were then combined at the imaging step. This represents, to date, the deepest (and only) LOFAR-VLBI wide-field image specifically targeting a galaxy cluster. The high-sensitivity allowed to trace the filaments of the Original TRG for their entire length. Moreover, we resolved many filamentary components constituting the Trail and T-bone, having lengths of around 250 kpc and widths between 4 – 11 kpc.

To constrain the origin of these filaments, we combined the LOFAR-VLBI data with proprietary and archival uGMRT (1260 MHz) and VLA (1520 MHz) data at corresponding resolution, which allowed spectral index analysis at unprecedentedly high-resolution. The spectral index distribution along the tail is steepening moving away from the core, ranging from 0.5 to ~ 1.3 . However, we resolved several narrow components from both the total intensity and spectral index map, possibly due to the strong instabilities developing in the downstream of the radio galaxy. F1 has no clear spectral trend ($\alpha \sim 1.3$), meaning that its relativistic plasma has a different energetic history with respect to the one in the tail. The same behavior is observed for the eastern side of the horizontal filament, different from the other side, suggesting a possible overlapping of multiple spectral components. The high-resolution allowed disentangling two separate spectral components also for F2, with a component coming from the south which is possibly related to the southern tail, which can possibly be bent behind the tail. For the vertical filament, we calculated the integrated spectral index to be $\alpha \sim 1.75$. The filaments in the Trail and T-bone were not detected at uGMRT and VLA frequencies, constraining their spectra to be steeper than 2. Despite the high-resolution, the interpretation of color-color diagrams is still non-trivial because of the great deal of inhomogeneity in terms of magnetic fields, electron components, or acceleration sites. Spectral index information allowed to estimate the equipartition magnetic field of the filaments, ranging between 12 – 17 μG . Radiative ages are instead around 33 – 45 Myr, well below the dynamical lifetime of the filaments, meaning that they are younger than the time required to be dissipated by the turbulence.

VLA data also allowed polarization analysis. Because of the faintness of filaments at GHz frequencies, we found a fractional polarization up to 22% for a small number of pixels in F1.

The morphological, spectral, and polarization properties of the filaments suggest that these may represent low-beta plasma structures, meaning sites in which magnetic field amplification (e.g., due to magnetic field line stretching) or ICM depletion help the relativistic electrons to rapidly stream along the filaments, with negligible radiative losses and, consequently, spectral index trends. This is observed, for example, for F1 and the horizontal filament. The large diffusion coefficient along the filaments ($D_{\parallel} \sim 1.5 \times 10^{31} \text{ cm}^2 \text{ s}^{-1}$) supports this scenario, implying super-Alfvénic diffusion. This regime could be created by the turbulence in the downstream region, produced by either the merger and the radio galaxy crossing, which stretches/bends magnetic field lines enhancing the magnetic field and so the corresponding synchrotron emission of the electrons deposited by the radio galaxies. Another possibility is that the filaments arise from the dynamical instabilities (e.g., Kelvin-Helmholtz), that we resolved in our observations as discussed in Chapter 4, which can strip these filaments and mix them in the ICM motions.

Radio Imaging Code Kernels: a distributed and accelerated solution for the interferometric imaging

We have developed a code called RICK that aims at performing the interferometric inversion step of imaging employing parallel and accelerated solutions (Chapter 6). This code, written in C/C++, exploits CPU parallelism through both MPI and OPENMP, and uses CUDA, HIP, and OPENMP for the GPU offloading, to be portable among different HPC infrastructures. With respect to current state-of-the-art codes for interferometric imaging, RICK uses a distributed approach throughout the whole execution, meaning that data are split among multiple processing units, even among multiple nodes, in order to deal with potentially any problem size. Moreover, this can be done also using GPUs. RICK is capable of running completely on GPUs, copying the distributed data on the GPUs at the beginning of the code and keeping them in the GPUs' memory for all the steps, minimizing the data transfers between CPU and GPU and making it the first code currently available to efficiently exploit the GPU offloading. Distributing the workload across multiple GPUs is even more critical than on CPUs, primarily because the large volume of data being processed often exceeds the memory capacity of a single device.

To achieve this result, we developed several solutions to deal with the steps of the code that were not yet ported on GPUs. namely the *Reduce* operation and the FFT. For the first, we used the NVIDIA NCCL library, which exploits (where possible) the fast NVLINK interconnection for the communication among the GPUs, minimizing the GPU-CPU calls. A similar solution can be adopted for AMD GPUs thanks to the RCCL library. For the second, we managed to distribute the FFT problem among multiple GPUs using the NVIDIA cuFFT library (or rocFFT for AMD), that has been adapted in our code to support data that were already on GPUs memory. We also developed hybrid MPI+OPENMP solutions to speed-up the computation on the CPU for both the *Reduce* and the FFT. This resulted in a better scalability compared to the sole MPIFFT thanks to a reduced communication overload.

We tested RICK on real LOFAR data, also including the IS, having sizes up to ~ 533 GB, using the CINECA HPC cluster. Comparing our full-GPU code with the full-CPU code, we found a gain in total runtime of a factor $\times 9$ for an image of 16384^2 (260 GB of mesh size), and up to $\sim \times 130$ for an image of 65536^2 (4.1 TB of mesh size) over a large number of nodes. For the largest test, this meant moving from 2 hours and 40 minutes on CPUs to around 1 minute on GPUs. By fully offloading the workload to GPUs and efficiently exploiting data distribution, we successfully demonstrated the huge potential of this solution for current and future large radio facilities. Still, we found that, even if largely reduced thanks to the GPU computational capabilities, communication remains the main bottleneck of the code.

Final remarks and future prospects

The study of non-thermal filaments is gaining momentum because the high sensitivity of modern radio interferometers now reveals their presence more frequently in radio maps. Throughout this Thesis, we showed how the resolution capabilities of LOFAR-VLBI provide a unique view of these phenomena, detecting and disentangling narrow filaments related to the Original TRG. The resolution here is instrumental to their full understanding, given the large number of magnetic and electronic components that are often involved. Multi-frequency radio coverage at high-resolution is crucial to constrain their spectral properties and so their origin: this must be combined with high-sensitivity observations, given that the steep spectra of the filaments imply faint surface brightness at higher frequencies. Although arrays like the VLA, uGMRT, and MeerKAT can reconstruct the filament spectrum, they are limited by their inability to achieve the sub-arcsecond resolution required at sufficiently low frequencies to fully characterize the filaments. Both SKA-Low and SKA-Mid will

provide unpaired sensitivity, which will surely help in discovering more of these structures, but will not (at least to date) match the resolution capabilities of LOFAR-VLBI. This places LOFAR-VLBI in a special position to determine the nature of the non-thermal filaments, as well as to use them to constrain the magnetic field and CRe acceleration properties in the ICM. Radio only is not enough to completely understand the formation scenarios of filaments. In the case of low-beta plasma, discussed in Chapter 5, we expect the possibility of thermal ICM depletion from the filament sites. Combining radio with X-ray observations is then essential to prove or discard this scenario: this will be done in the future for Abell 2255, thanks to deep incoming Chandra observations. Another useful tool to the cause is the polarization information. We expect large fractional polarization in presence of amplified magnetic fields due to line stretching, which orders the magnetic field lines along the filament. VLA data were not enough to trace entirely the filaments, but still we got hints of high polarization fractions for one of them. LOFAR-VLBI polarization could possibly provide information for the fainter filaments, but the long wavelengths (which imply larger depolarization due to the ICM) and the early stage development of solid calibration strategies makes this a difficult target to pursue, at least in the near future.

Given the huge data volumes involved in this work, and the even larger amounts expected from the upcoming SKA, we must think about developing new, efficient solutions for future data management. A practical example is given by the LOFAR-VLBI wide-field image in Chapter 5, which took almost 1.5 months of wall-clock time, or by the ILoTSS survey, where the wide-field imaging will be deployed for every LoTSS pointing. With RICK, we provided valid evidences of the large potential of enabling parallel and accelerated solutions for interferometric imaging. We believe that the distributed parallelism represents the only viable approach for SKA-size problems: it is now the right time to think about adapting our codes to these solutions, to be ready for the challenges of the future. RICK is not yet ready for the full scientific usage, and new solutions are being tested to overcome the communication bottleneck of its approach. We plan for the future to include also the prediction and deconvolution steps in the code, with the final aim of making RICK easily available within any of the current state-of-the-art software for radio imaging. This will not only be beneficial for the SKA, but also for modern interferometers.

Appendix A

Appendix for Chapter 5

A.1 Flux density scale

For the spectral index analysis, we checked for any possible flux density scale offset in the uGMRT observations using the VLA as a reference. This choice is motivated by the larger amount of works in the literature in which the VLA L-band was used, witnessing the accuracy and stability of the VLA calibration procedure with respect to the less tested uGMRT Band 5. We produced maps with the same imaging parameters and inner uv -cut for both arrays, and obtained catalogs of radio sources using PyBDSF. We cross-matched the two catalogs, using $1''$ as maximum separation. We then calculated the spectral index between 1260 and 1520 MHz and selected only the sources having a spectral index in the range $-0.5 < \alpha < 1.5$, to take into account also sources with inverted spectrum. We also set a limit in the uGMRT signal-to-noise ratio to be over 5 and further reduced our sample considering only compact sources identified by a single-Gaussian component. This selection was made to isolate all the compact sources observed with both uGMRT and VLA, which display a spectral index distribution with median $\text{med}(\alpha) = 0.578$. Considering, as stated before, the VLA flux density scale as a reference, we re-scaled the uGMRT flux density scale with an upward scaling factor (8%) which returns a median of the spectral indices of 0.75, usually found in large samples of radio sources (e.g., Mahony et al., [2016](#)).

A.2 Spectral index error map

Spectral index error maps referred to Figure 5.5.

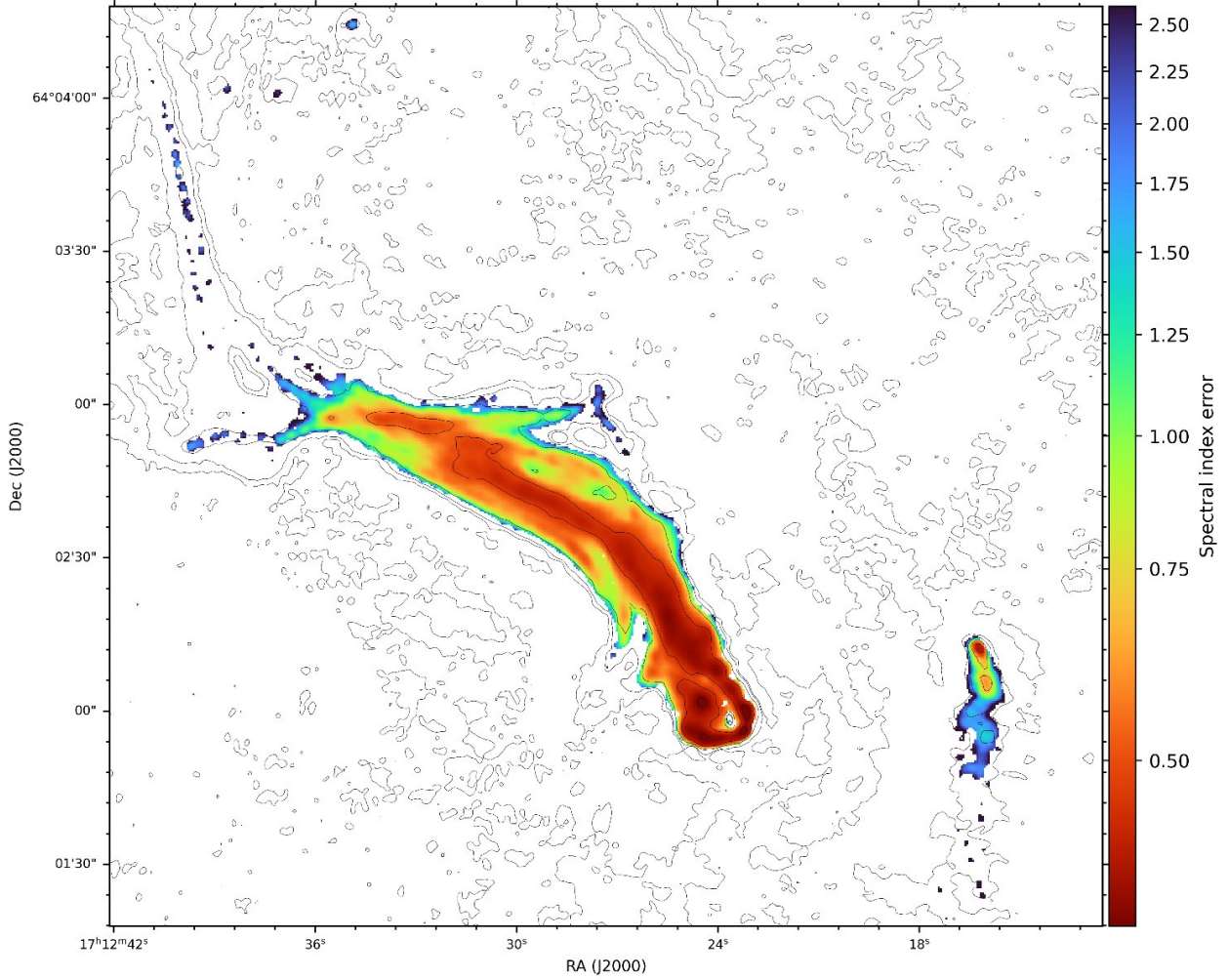


FIGURE A.1: Spectral index error map, referred to Figure 5.5, obtained using LOFAR-VLBI (144 MHz), uGMRT (1260 MHz), and VLA (1520 MHz) data for the Original TRG. Grey contours represent 3, 6, 12, 24... σ_{rms} levels, with $\sigma_{\text{rms}} = 38 \mu\text{Jy beam}^{-1}$ being the noise from the LOFAR-VLBI, wide-field image at $1.5''$ resolution in Figure 5.1.

A.3 Regions for surface brightness and spectral index trends

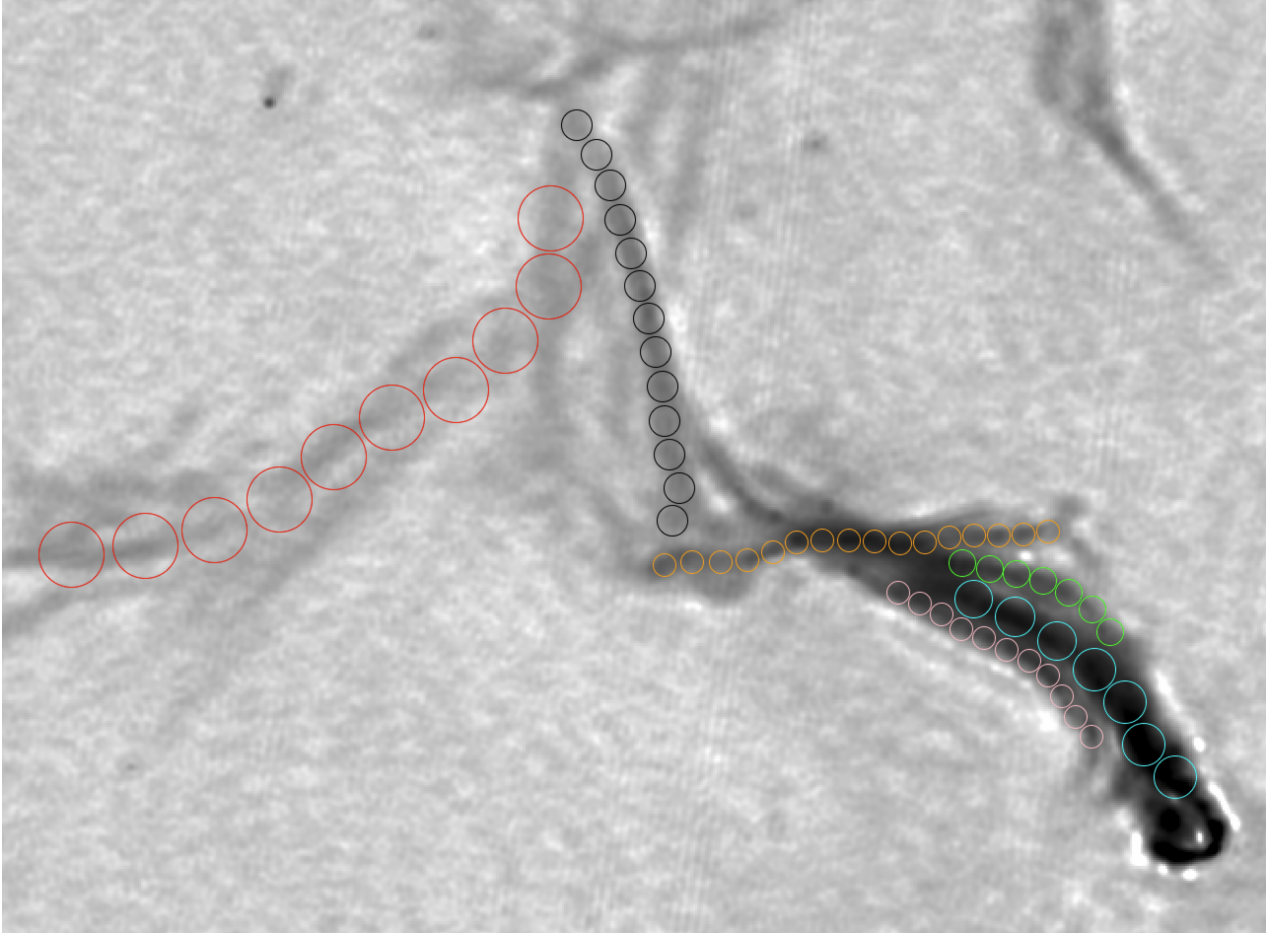


FIGURE A.2: Regions used to evaluate the average surface brightness and spectral index in Figure 5.8, with different colors corresponding to different features. These are the main tail (cyan), the horizontal (orange) and vertical (black) filaments, F1 (pink), F2 (green), and the Trail (red). The arrows indicate the direction of the trends. A grayscale version of the map from Figure 5.1 is displayed.

A.4 Rotation measure values distribution

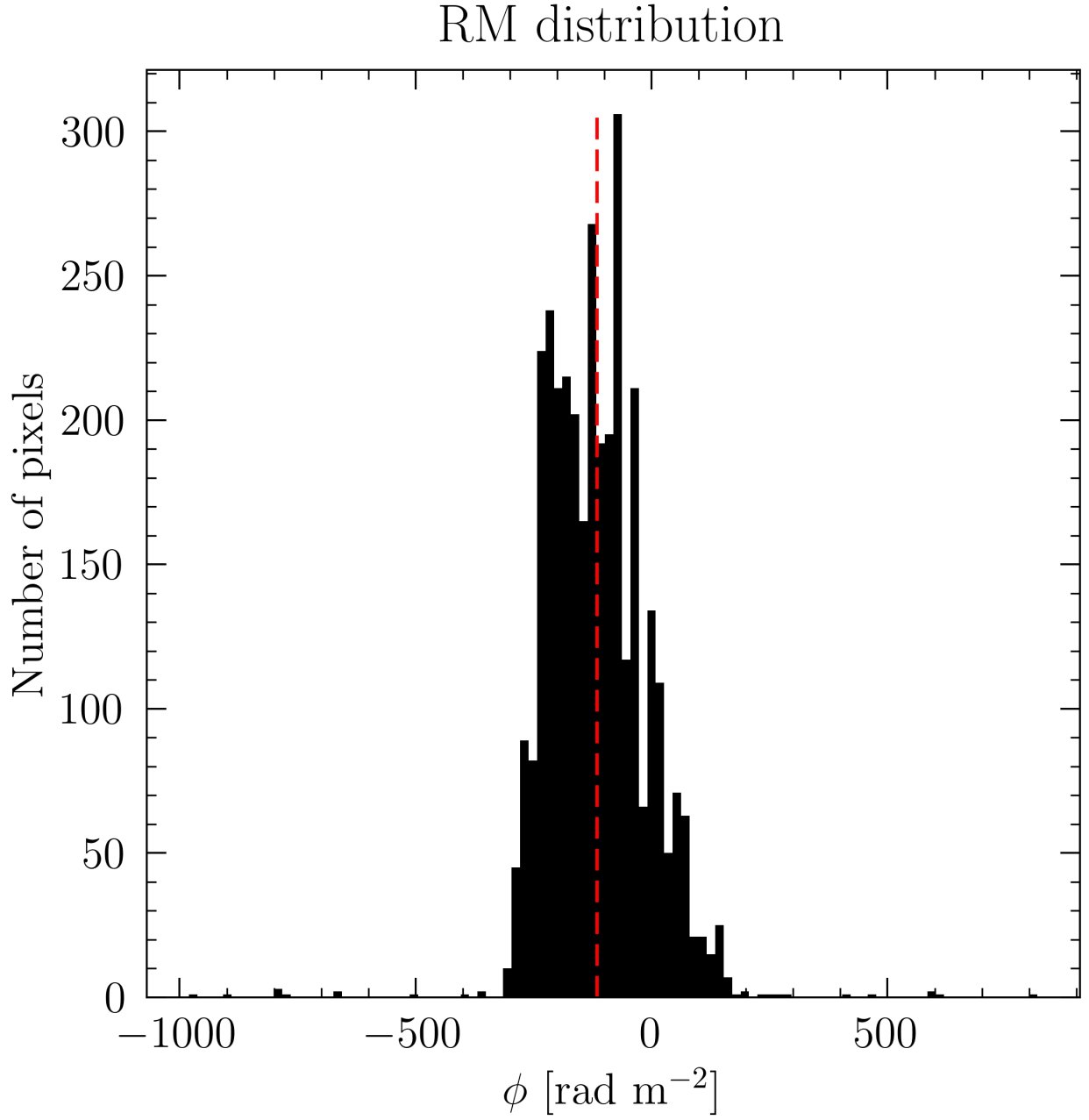


FIGURE A.3: RM distribution for the Original TRG, considering only pixels above $5\sigma_{\text{P}}$ (from Figure 5.6). The vertical dashed red line indicates the average $\langle \text{RM} \rangle = -115.7 \text{ rad m}^{-2}$ resulting from Gaussian fitting, while the standard deviation is $\sigma_{\text{RM}} = 107.4 \text{ rad m}^{-2}$.

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