APROPOS

APERTIF Processing Pipeline and Online System

NWO Groot proposal 2009

ASTRON
Netherlands Institute for Radio Astronomy
# Table of contents:

Administrative data for the APROPOS project................................................................................. 1
  Principal Investigators.................................................................................................................. 1
  International Science Team....................................................................................................... 1
  Contact Person.......................................................................................................................... 1

Executive Summary.................................................................................................................... 2

Some Key Scientific Publications of the Proposers........................................................................ 3

Description of Research Area and Research Plan.......................................................................... 3
  Introduction................................................................................................................................ 3
  The Formation, Structure, Dynamics and Evolution of Galaxies............................................... 5
  The Origin and Evolution of Cosmic Magnetism......................................................................... 13
  Pulsars as tools for fundamental physics and astrophysics....................................................... 15
  The Dynamic Radio Sky............................................................................................................. 18

Motivation of Investment Plan....................................................................................................... 23
  Basic Instrument Design and Capabilities.................................................................................. 25

National Importance and Scientific Accessibility.......................................................................... 27

International Positioning................................................................................................................ 27

Strategy of the institution with regard to the Investment............................................................... 28

Technical Concept and Budget...................................................................................................... 29
  Apertif system concept............................................................................................................... 29
  Project Management................................................................................................................. 31
  Budget Description.................................................................................................................... 32

Exploitation................................................................................................................................... 35

Technical References.................................................................................................................... 35

Abbreviation list............................................................................................................................. 36

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Cover: the Westerbork Synthesis Radio Telescope depicted with a rendering of the sky as APERTIF will see it. The blue objects are from a WSRT radio continuum survey of the Spitzer First Look field and shows the non-thermal radio emission from galaxies with an Active Galactic Nucleus and from star forming galaxies. The orange objects, taken from a spectral-line survey of about 100 nearby galaxies, illustrates the distribution of the cold, neutral hydrogen gas in galaxies. APERTIF will detect the neutral hydrogen in 100,000 galaxies, and the continuum emission from 10,000,000 objects.
1 Administrative data for the APROPOS project

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2 Executive Summary

Nature’s creativity is perhaps most clearly displayed by the enormous diversity of objects visible in the night sky. To unravel the physics behind all the related phenomena, observations over the entire electromagnetic spectrum are required. Over the years, the Dutch astronomical community has been in the forefront of this multi-wavelength approach, making key technical and scientific contributions to radio, far- and near infrared, optical, UV, X-ray and gamma ray astronomy. This strategy has proven to be highly successful; the Dutch astronomical community is recognised worldwide to perform world-leading research in many key areas of astronomy and astrophysics.

The importance of surveying large regions of the radio sky with maximal sensitivity and high resolution, and making the results available to a wide community in a timely fashion, is now recognised as a one of the key elements required to tackle some of the major questions in modern astronomy. With such surveys, a wide range of astronomical phenomena can be observed that are highly relevant to many of the major themes laid out in the strategic planning of the Dutch astronomical community, as well as to the key science topics defined for the next-generation radio telescope, the Square Kilometre Array (SKA)\(^1\). Specifically, the topics addressed include cosmology, dark energy and dark matter, galaxy formation and evolution, cosmic magnetism and the use of compact objects, in particular pulsars, as stringent probes of fundamental physics.

The Westerbork Synthesis Radio telescope (WSRT) is well suited to perform such large-area radio surveys in the near future. The APERTIF (APERture Tile In Focus) system, currently under development, replaces the single detector receiver systems of the current WSRT by Focal-Plane Arrays (FPA), i.e. arrays of low-noise receiver elements that fully sample the focal plane of each of the individual 25-m antennas. This enlarges the field-of-view of the radio telescope by more than a factor 30 and turns the WSRT into an effective large-scale, survey instrument. APERTIF will generate huge data sets that greatly surpass existing surveys, both in quality and in size: the neutral hydrogen in more than 100,000 galaxies will be detected, for the first time out to cosmologically interesting distances, as well as the polarised radio continuum radiation of more than 10,000,000 galaxies. Over a1,000 new pulsars will be discovered. Moreover, a strong synergy exists with the main science applications of the LOw Frequency ARray (LOFAR), enhancing the scientific potential of both instruments and providing a combination of radio astronomical facilities unique in the world.

In this proposal, we request funding for APROPOS (APERTIF Processing Pipeline and Online System). This will permit us to process the vast amount of data APERTIF will produce, and distill it into wide-area image cubes, source catalogues and other scientific data products. APROPOS also includes an open data archive through which all APERTIF data will be made available to the entire astronomical community. With such an open and VO (Virtual Observatory) compliant archive, the scientific output of APERTIF can be maximised.

Advances in antenna technology and digital electronics are leading to a paradigm shift in radio telescope design. The scientific potential of these new technologies is realised world-wide, and several groups are implementing these cutting-edge ideas in the construction of new or upgraded radio telescopes, and ultimately in the SKA. ASTRON is at the forefront of many of these developments, as most recently demonstrated by the results from the FPA prototype system, DIGESTIF. ASTRON, together with an exceptionally strong university based Dutch user community, have an outstanding reputation in developing, operating and exploiting new technologies for radio astronomy. The proposed large performance improvement of the WSRT will ensure that The Netherlands continues to maintain this leading role, an essential requirement if we are to be a major partner in the global SKA project.

For APERTIF, funding from an earlier NWO Groot grant is available for constructing and installing FPA systems in the WSRT telescope. FP7 RadioNet funding has been secured for developing the digital processing boards that are needed for the APERTIF correlator and beam-former. In this proposal, we wish to acquire the resources for the correlator and the processing pipeline that are needed for APERTIF to turn the raw telescope measurements into images and other data products, and to establish a publicly open data archive. The total request of the current proposal is 2,725 M€. With such funding, APERTIF can be realised as a state-of-the-art operational astronomical observing facility.

\(^1\) A list of acronyms can be found at the back of this document
3 Some Key Scientific Publications of the Proposers

Cold gas accretion in galaxies, Sancisi, R., Fraternali, F., Oosterloo, T., and van der Hulst, T. 2008, A&ARv, 15, 189


4 Description of Research Area and Research Plan

4.1 Introduction

The astronomical community has identified major themes and associated open questions in contemporary astrophysical research. Finding answers to these questions is driving the design and construction of world-class research facilities like the Atacama Large Millimeter Array ALMA, the European Extremely Large Telescope E-ELT, the LOw Frequency ARray LOFAR, the Herschel space telescope, the James Webb Space Telescope JWST and the Square Kilometer Array SKA, to mention a few. Meanwhile, large-scale surveys of the sky have provided an immense impulse to astronomical research. Notable examples are the IRAS all-sky survey in the infra-red, the Northern VLA Sky Survey NVSS at 1.4 GHz and the Sloan Digital Sky Survey SDSS in the optical.

APERTIF (Aperture Tile in Focus) is an innovative 1.4 GHz receiver system for the Westerbork Synthesis Radio Telescope, and both a technology and science pathfinder for the SKA. APERTIF enlarges the field-of-view of the WSRT by more than a factor 30, its instantaneous bandwidth by a factor 2 and its overall survey speed by a factor of 20. This current proposal is aimed at bringing APERTIF to its full potential and to provide the infra-structure for a legacy-quality data archive that will serve the observational needs of the national and international astronomical communities in many different research areas. Surveys with the APERTIF system will provide spatially and kinematically resolved information on the HI and OH content of objects over look-back times of 4 and 6 Gyr respectively, both in emission and absorption, map the strength and structure of magnetic fields from the smallest to the largest cosmic scales, determine the distribution and nature of the population of pulsars in the Milky Way, monitor the variability of sources in the radio sky, and chart the star formation and nuclear activities of galaxies over cosmic time. APERTIF surveys are expected to detect HI emission from $10^5$ galaxies out to $z=0.4$ and radio continuum emission from $10^7$ galaxies out to $z=4$.

At the national level, the goals of the Dutch astronomical community, as laid out in the NCA’s national roadmap for astronomy, aim at maximizing scientific return of investments and research efforts in three broad areas of research; the formation and evolution of galaxies, the birth and death of stars, and the final stages of stellar evolution. As will be outlined in this chapter, APERTIF will serve the Dutch community by contributing significantly to all these research areas.

At the international level, the astronomical community is preparing to build and exploit the Square Kilometre Array (SKA), of which the first phase is expected to be constructed in the middle of the next decade. An extensive science case for the SKA has been put forward and several facilities currently under construction will serve as precursors and pathfinders for the SKA, both technically and scientifically. The scientific insights
obtained from the APERTIF surveys will be instrumental for further developing the science case, the scientific requirements, the design and the observational strategies for the SKA.

Focusing on the strengths of APERTIF and considering the relevant (inter)national scientific roadmaps, the research areas where its scientific impact is foreseen to be maximal, can be summarised as follows:

**The formation and evolution of galaxies**

Galaxies contain many billions of stars, as well as interstellar gas and dust, and are embedded in dark halos of unknown constitution. Because light travels at finite velocity, astronomers are able to look back in time by observing distant objects, seen at a time when the Universe was young and most galaxies were in the process of formation. What physical processes have governed the formation, growth and evolution of galaxies over cosmic time? Do evolved present day galaxies contain clues to their formation and evolution? What is the influence of the local and global environment on galaxy evolution? What is the role of massive black holes in galactic nuclei in the formation and growth of galaxies?

Surveys with APERTIF will provide the gas content of $10^5$ galaxies over the last 4 billion years of cosmic evolution. In synergy with LOFAR, APERTIF will measure the radio continuum fluxes and determine the star formation and nuclear activity for $10^7$ galaxies, all the way back to the era when the first galaxies formed.

**The birth and death of stars: the life-cycle of gas and dust**

New stars continue to be born deep inside molecular clouds. The birth process leads to a circum-stellar disk of gas and dust from which planets may subsequently form. What are the physical processes that lead to these new solar systems, and how do they evolve? How is the chemical composition of the gas and dust involving the major biogenic elements modified during the collapse from the tenuous interstellar medium to the dense proto-planetary material? During the late stages of their life, stars inject nucleo-synthetically enriched material into the interstellar medium. How does this material drive the chemical evolution of a galaxy and the newly-formed stars therein? What drives the mass loss, and how does it influence stellar evolution?

OH masers pinpoint the locations of dense and intense star formation in Galactic star forming regions, as well as the locations of evolved AGB stars. Extragalactic OH mega-masers may occur in major merger events that have triggered intense star formation. Wide-field OH surveys of the Galactic plane and the extragalactic sky with APERTIF will provide a census of intense star formation in the Milky Way as well as over cosmic time.

**Strong-field tests of gravity: physics of neutron stars and black holes**

At the end of their lives, massive stars explode and eject their outer layers. The stellar core collapses into a neutron star or a black hole. These are the densest objects that exist, and the ones with the strongest gravitational fields. What are the properties of matter at the extreme density in the interior of a neutron star? What are the observational signatures of black holes? Can we observationally verify the extraordinary predictions of General Relativity for the properties of curved space-time near these objects? How do particles and radiation behave near these compact objects? What happens when two compact objects orbiting each other eventually merge? Is this the origin of the most powerful explosions we know, the enigmatic gamma-ray bursts?

Due to the nature of the WSRT as a regular east-west array, APERTIF can perform efficient pulsar surveys, and will reveal an estimated $10^3$ new pulsars.

**The origin and evolution of cosmic magnetism**

Magnetic fields are ubiquitous throughout the universe and occur on scales varying from planetary magnetospheres to the gigantic relics in the outskirts of galaxy clusters. What role do they play in the acceleration of astroparticles, the accretion of matter onto compact objects, the confinement of jets in radio galaxies, the turbulence in the interstellar and intergalactic medium, and during the formation processes of stars and galaxies? The origin of magnetic fields is yet unknown. Are they primordial in nature or formed by dynamo action? Radio observations of polarised synchrotron emission, Faraday rotation by magnetised...
plasmas as well as the Zeeman effect provide unique insights in the characteristics of cosmic magnetic fields.

The equatorially mounted dishes of the WSRT allow for accurate polarisation measurements with APERTIF, yielding an estimated $10^6$ rotation measures to map the magnetic fields in the Milky Way and other galaxies.

Although APERTIF surveys will collect, and make public, vast amounts of information directly relevant to these research themes and specific scientific questions, it should be appreciated that it also has great potential for serendipitous discoveries. For instance, the main science driver for constructing the WSRT in the 60's was the radio continuum luminosity function. However, in its early years the WSRT played an instrumental role in the discovery of dark matter in spiral galaxies as derived from the kinematics of the atomic hydrogen gas. Likewise, from APERTIF surveys with the WSRT, the unexpected can be expected.

What follows in the remainder of this chapter are more elaborate motivations for some of the key science projects that we envision to be carried out. However, this treatise is far from complete. It should be stressed that for efficiency reasons, various surveys with a different scientific focus can and will be carried out in a commensurate fashion as much as possible. For instance, a wide-area shallow HI survey can be carried out with the broadest available band in full polarisation mode to maximise the number of detected polarised continuum sources. The exact logistics of the surveys will be coordinated among the various science teams.

### 4.2 The Formation, Structure, Dynamics and Evolution of Galaxies

Stars make up the most conspicuous constituent of galaxies, and these stars are formed out of the gas that was created during the Big Bang. Thus gas is the fundamental ingredient out of which the visible galaxies are formed. Understanding the characteristics of the gas, as well as the physical processes that govern its distribution and dynamics, is paramount for understanding the nature and nurture of galaxies.

It is generally accepted that galaxies form in a hierarchical manner whereby present-day galaxies have grown over cosmic time by the gravitational coalescence and accretion of many smaller, less massive systems (e.g. Klypin et al. 1999, Moore et al. 1999), as well as the continued accretion of gas from their direct surroundings (Sancisi et al. 2008). The process of coalescence is described by so-called merger trees which are extracted from numerical cosmological simulations, and only describe the merging of dark matter halos in a robust manner. The behavior of the baryons in this merging process is not well understood due to an incomplete understanding of the relevant physics, the simplicity of the hydrodynamic codes and the limits of numerical resolution. As a refuge, this ‘baryon physics’ is often described by semi-analytic techniques (e.g. Kauffman et al. 1993, Baugh et al. 2004). Although many properties of actually observed galaxy populations

Figure 4.1: Left: HI map (blue) of IC10 overlaid on an optical image. This BCD is forming the bulk of its stars from a filamentary, chaotic gaseous envelope (courtesy by Oosterloo). Middle: A gas cloud, likely being accreted onto the disk of NGC 2403 (Fraternali et al. 2002). Right: HI gas (blue) in a series of mergers in different dynamical states (Hibbard and van Gorkom 1996).
can be successfully reconstructed in this way, there are still several outstanding conflicts between simulated and observed galaxy populations that need to be addressed. Examples are the distribution of angular momentum among galaxies, the lack of visible substructure around galaxies, the galaxy population in cosmic voids, and the shallow central density profiles of dark matter halos.

Addressing these and many more issues, requires unbiased, detailed HI observations of large samples of galaxies in different environments and over a significant cosmic look-back time. This can be achieved with the superb survey speed of APERTIF. For ~10^5 galaxies seen up to 4 billion years ago, the distribution and motion of the HI gas will be measured, while OH mega-masers, the signposts of intense star formation, can be detected in galaxies seen up to 6 billion years ago, nearly half the lifetime of the visible Universe.

4.2.1 The Formation and Growth of Galaxies

According to the model of hierarchical galaxy formation, the first proto-galaxies formed in the highest density regions of the Universe. However, dark matter halos and their associated baryons are still collapsing in the present-day Universe and it can be expected that proto-galaxies are still forming in the lower-density regions. Gas-rich and relatively low-mass galaxies with a high specific star-formation rate and a dominant young stellar population are conceivably candidates for such proto-galaxies.

In a sense, metal-poor Blue Compact Dwarf (BCD) galaxies like I-Zw18 (van Zee et al. 1998) and IC10 (Figure 4.1 - left) that are currently building up the bulk of their stellar content, can be considered as galaxies in formation. Questions arise about the nature of their precursors, the origin of their gas reservoirs, the physical processes that trigger the star formation, and the properties of their decedents. Detailed information about the distribution and kinematics of their gas provides valuable information about the accretion process of the gas. How fast are the inflow velocities? Is there significant outflow? Is the gas accreted preferentially in a disk? A blind survey with APERTIF is expected to reveal the gas content of many BCDs and to relate the characteristics of their gas reservoirs to their local and global environments in a statistical sense. Their angular momentum and gravitational potentials as traced by their rotation curves hold clues to the nature of their decedents.

During their life times, galaxies continue to accrete gas from their immediate surroundings, fueling the ongoing star formation processes (Figure 4.1 - middle). It is estimated that the accretion of visible cold gas can account for ~20% of the fuel that is needed to sustain the ongoing star formation (Sancisi et al. 2008), although the uncertainty is large due to selection effects and poor statistics. A complicating factor is the growing suspicion that the gas accretion process may well occur in two rather different regimes (e.g. Binney...
2004, Keres et al. 2004). Low to moderate mass galaxies ($M_{\text{Vir}}<10^{12} \, \text{M}_{\odot}$) may experience primarily "cold-mode" accretion ($T\approx 10^{4.5} \, \text{K}$) from the intergalactic medium, while more massive systems may experience the more isotropic "hot-mode" accretion ($T\approx 10^{5.5} \, \text{K}$), which until recently was thought to be universal (e.g. Rees & Ostriker 1977, Davé et al. 2001). Questions need to be answered about the accretion rate of the gas, the physical mechanisms of this accretion, and the origin of this accreted gas. APERTIF surveys will provide detailed morphological and kinematic information on the cold accretion for tens of thousands of galaxies as is required for unbiased, multi-variate studies of this phenomenon, e.g. as a function of mass, star formation rate and environment.

Galaxies not only grow by the continuous accretion of gas but also by merging with other galaxies (Figure 4.1 - right). It is important to understand the rate and dynamics of these merger events, and to gain insight into how much of the gas is retained in the merger remnant, how much of this retained gas is turned into stars on what time scales, and how much gas is ejected into intergalactic space, to be possibly accreted, either hot or cold, by other galaxies at a later stage. To answer these questions, direct observations of the gas in a large unbiased sample of merging galaxies and merger remnants over significant look-back times is required.

4.2.2 The Structure and Dynamics of Galaxies

The outer regions of the gaseous disks are often misaligned with the inner disk. Such warps are poorly understood. Are they caused by external tidal fields, by the accretion of external out-of-plane gas, or by minor merger events? The longevity and dynamics of these warps are also a mystery. Differential rotation and precession should quickly dissolve warps within a few orbital periods, yet extensive and symmetric warps are known to exist (Figure 4.2 - left). What are the frequency and geometrical distributions of warp? What is their relation to a possible triaxiality of the dark matter halo? A larger and unbiased sample of warped gas disks in various environments is required to get a useful statistical handle on this intriguing observation.

Often, gas disks in galaxies are observed to be lopsided, both in a morphological and a kinematical sense (Figure 4.2 - middle). It is not clear how a dissipational medium like the cold gas can maintain such an asymmetric distribution. Possibly, this is a signature of a non-axisymmetric potential, or the baryons may be
'sloshing around' in the gravitational potential of the dark matter halo. Such asymmetries may provide clues about the internal structure of dark matter halos.

One of the great advantages of spectral line aperture synthesis imaging is that it produces velocity fields of the gas disks that radially extend far out into the dark matter halo (Figure 4.2 - right). Regular velocity fields allow the derivation of so-called rotation curves describing the rotational velocity of the gas as a function of radius. These rotation curves can be used to determine the total dynamical mass of the galaxy within the outermost measured point of the curve. They can also be used to determine the distribution of (specific) angular momentum of the baryons within the dark matter halo and among the galaxies, again as a function of other galaxy properties as well as the environment.

Warp, lopsidedness and angular momentum are indicators of how the baryons settle in the dark matter halo, and provide important information for refining the models of galaxy formation and evolution.

4.2.3 The Evolving Star Formation Rate and Gas Content of Galaxies

The integrated star-formation history of the universe continues to be determined with greater precision (Figure 4.3 - left). Star formation rates seem to increase dramatically from the current epoch out to about \( z = 1 \), then appear to level off and possibly decline beyond \( z = 3 \). This illustrates how much star formation occurred at a given cosmic epoch, but we need to know more than that. In particular, where did star formation occur? Did most stars form in galaxies undergoing “quiescent” star formation, or in galaxies undergoing violent star-bursts, and how did this vary with environment and cosmic time? How important are mergers in triggering star formation? Do the primary sites of star-formation shift form high mass to low mass galaxies over cosmic time (e.g. Cowie et al. 1996)? In the local universe, star formation occurs in very different environments, and with intensities ranging over at least five orders of magnitude. Radio continuum emission probes the star-formation activity over this entire range of rates since it correlates exceptionally well with other unbiased tracers of star formation, particularly the FIR emission (e.g. Frick et al. 2001, Garrett 2002, Bell 2003; Figure 4.4 - left). The physical origins of this correlation are now being investigated in nearby galaxy disks, and insights are beginning to emerge regarding the critical physical processes and their different lifetimes (Figure 4.4 - colour panels).
Understanding the *where* and *why* of star formation in different environments will be a goal of deep, wide-field continuum surveys with APERTIF, providing confusion-limited imaging with 7-14 $\mu$Jy/beam rms over large areas of the sky, significantly deeper than the 450 $\mu$Jy/beam rms of the VLA NVSS survey. An APERTIF survey will produce radio continuum images of even better quality than the one shown for M51 in Figure 4.4, for all the nearby galaxy disks in the survey coverage. As shown by the simulated luminosity functions and redshift distributions in Figure 4.3 (from Baugh et al. 2004), such a deep APERTIF survey is predicted to reach a median redshift of about unity, with an extended tail in the distribution extending to $z \sim 4$. The region of spatial overlap with the LOFAR and SDSS surveys will provide high quality optical identifications as well as radio spectral indices and spectroscopic redshifts for a subset of detections. In this way it will be possible to determine exactly what types of galaxies (low or high mass, bursting or quiescent) are responsible for the growth of stellar mass with cosmic time and how star formation rates are affected by the large scale environment.

The evolving neutral gas density of the universe also shows signs of strong evolution, perhaps even between redshifts of only a few tenths and the present. This is implied by both the evolution in star-formation rate, by almost an order of magnitude, between 0 and 0.2 (Figure 4.3), as well as the comparable decline in the mass density of neutral hydrogen shown in Figure 4.5. In the case of the gas mass density, it is currently far from clear when and where this transition takes place. The only strong observational constraints are at redshifts near zero from surveys of HI emission (Zwaan et al. 2003) and at redshifts greater than about 2 from damped Ly$\alpha$ studies (e.g. Giavalisco et al. 2004). The model curves in the middle and right panels of Figure 4.5 correspond to the semi-analytic models of Baugh et al. (2004). Although much of the redshift range will require the much higher physical sensitivity of the SKA to address, the low redshift portion of the distribution, out to about $z = 0.4$, or a look-back time of 4 billion years, can be determined by a deep survey with APERTIF. Based on the deepest WSRT observations to date (Verheijen et al. 2007; Figure 4.6), a deep survey with APERTIF of 20x12$^2$ hr per pointing will yield a rms noise level of $\sim 20$ $\mu$Jy/beam at a spectral resolution of 600 kHz, or a velocity resolution of $\sim 200$ km/s at $z = 0.25$; which is more than a factor of 30 better sensitivity than the HIPASS survey (Barnes et al. 2001). This means that $M^*_{\text{HI}} (7 \times 10^9$ $M_{\odot}$ of HI gas), the typical gas content of galaxies containing the bulk of the HI gas, can be detected at the 5$\sigma$-level at this redshift, assuming a linewidth of 200 km/s. The upper end of the HI mass function at $5 \times 10^{11}$ $M_{\odot}$, can then be detected at $>5\sigma$ out to $z = 0.4$ at the end of the spectral range covered by APERTIF.

Such a deep survey will also permit an unbiased search for HI absorption toward, and associated with, AGNs brighter than a few mJy in the survey region (e.g. Morganti et al. 2005). Naturally, interesting limits on the number density of OH mega-masers out to $z=0.7$ will be obtained simultaneously. Confusion between HI emission and OH-mega-masers will be eliminated by considering the photometric redshifts of the optical
counterparts. A deep, wide-field, spectral line survey with APERTIF will enable the first inroads to be made on documenting the evolution of the gas content of the Universe over cosmic time.

4.2.4 Probing Environmentally-driven Galaxy Evolution

Rich clusters of galaxies, in relation to the large scale structure in which they are embedded, offer a unique laboratory to study the effects of global and local environments on the properties of their constituent galaxies. Evidence has accumulated that this environment affects both the star formation rate and morphology of galaxies, resulting in the well known morphology-density relation in the local universe (e.g. Dressler 1980). The ratio of lenticular to spiral galaxies in clusters decreases with redshift (e.g. Dressler et al 1997), while the fraction of blue members in cluster cores increases with redshift between z = 0 and 0.4 (Butcher & Oemler 1984). Furthermore, the star formation rate is observed to decrease with increasing galaxy density, both in the outer parts of distant clusters (e.g. Abraham et al 1996), and more locally in the SLOAN survey (Gomez et al 2003). The nature and timescale of the physical mechanisms that are responsible for the observed environmental dependencies and the evolutionary processes remain largely unclear. Ideally, to study these processes, one would like to probe the evolution of galaxies as they travel from the low density filaments to the dense cluster cores, sampling a variety of environments over a range of redshifts, including galaxy clusters in different dynamical states and of different richness classes. Optically this work has been pioneered by Abraham et al. (1996), Balogh et al. (1999) and Treu et al. (2003). Happily, observing the distribution and kinematics of the cold gas in galaxies provides one of the most direct windows on the physical processes involved, and adds to these optical studies in crucial ways:

1) Blind, volume limited HI surveys provide an optically unbiased probe of all the gas-rich galaxies in the entire volume. Galaxies of low surface brightness and faint dwarf galaxies, being relatively gas-rich, are easily detected in HI surveys. Blind HI surveys provide a full census of the available gas reservoirs and a robust determination of the HI Mass Function (HIMF) in various environments, provided that adequate statistics are obtained. Any reliable HIMF requires HI measurements for thousands of galaxies, which APERTIF will deliver.

2) Observations of the 21-cm line of HI naturally provide redshifts, revealing any spatial and velocity clustering of gas-rich galaxies. It directly maps cosmic substructure, and helps to characterise the dynamical state of different environments (e.g. Bravo-Alfaro et al. 2000). For instance, if an infaling group of galaxies is observed to be gas-rich, it is not likely that it has crossed the high density cluster core on its infall trajectory.

3) The presence of cold gas in galaxies is a prerequisite for star formation, and the amount and distribution of cold gas regulate the duration and intensity of star formation periods. The accretion and removal of this cold gas reservoir is a crucial element in the process that transforms galaxies, and is directly related to the

![Figure 4.6: Examples of HI detected galaxies at intermediate redshifts (Verheijen et al. 2007). The upper panels show global HI profiles over the full frequency range. Middle panels show position-velocity diagrams. Note that the WSRT can still marginally resolve galaxies at these redshifts. Lower panels show HI contours overlaid on optical images. The colour panels illustrate that many galaxies are interacting or morphologically disturbed.](image)
evolutionary state of a galaxy’s stellar population. HI observations allow us to compare optical probes of enhanced, decreased and halted star formation with the presence of a cold gas reservoir.

4) The response of the cold HI gas in the outer disks of galaxies is the most sensitive and obvious tracer of galaxy-galaxy interactions and some examples are illustrated in Figure 4.7. In many cases, gas removal processes and the fate of the cold gas reservoir can only be witnessed in HI images.

5) The morphology of the HI distribution can critically distinguish between ICM-ISM interactions like ram-pressure and viscous stripping (e.g. Schulz & Struck 2001; Abadi et al 1999), and gravitational disturbances like galaxy harassment (e.g. Moore et al. 1996). The effect of ram-pressure stripping is also illustrated in Figure 4.7. In such a case, where the cold gas is in the process of being removed from the plane of an infalling galaxy, the spatial and kinematic offset of the gas may indicate the speed and direction in which a galaxy is moving, and thus help to reconstruct its orbit.

It is important to extend HI surveys of clusters environments in the local universe ($z \leq 0.08$) out to intermediate redshifts where signs of cosmological evolution have been detected optically and the Butcher-Oemler effect has become noticeable. To study what exactly causes the Butcher-Oemler phenomenon, it is necessary to distinguish whether it is the gaseous properties of the infalling galaxies that are different at these higher redshifts or whether there are other mechanisms at work that enhance star formation and the blue population in galaxy clusters. Deep integrations have been obtained successfully with the WSRT to survey the HI content of galaxies in the environments of two galaxy clusters, Abell 963 and 2192 (Figure 4.6), demonstrating the feasibility of deep HI surveys. The wide-field capabilities of APERTIF will revolutionise this field by expanding the surveyed volume by at least 2 orders of magnitude.

**4.2.5 Direct Imaging of the Cosmic Web**

Numerical cosmological simulations suggest that only a third of the cosmic baryons have settled in dark matter halos and are recognizable as galaxies. The rest of the baryons are distributed in an intergalactic filamentary cosmic web in which the galaxies are embedded (e.g. Davé et al. 1999, 2001). The intergalactic baryons occur mainly in two physical states; a warm-hot intergalactic medium (WHIM), shock-heated to $10^{5.5}-10^{7}$ K with HI column densities of $14<\log(N_{\text{HI}})<18$, and a diffuse intergalactic medium, photo-ionised to $10^{4}$ K with $\log(N_{\text{HI}})<14$ (Figure 4.8).

From statistical studies of QSO absorption lines, the column density distribution function can be constructed as a function of cosmic time, indicating a steady decline of the cross-section of mainly higher column density absorbers (e.g. Storrie-Lombardi 2000). Nevertheless, at the current epoch, the surface area is expected to increase by a factor of 30 going from a readily detectable $N_{\text{HI}} = 10^{19}$ cm$^{-2}$ in the outer regions of galaxies, to

![Figure 4.7: Examples of HI morphologies of nearby galaxies in Cluster environments. Left: An extended HI filaments associated with a S0 galaxy in Ursa Major, most likely caused by tidal interactions in a small group (Verheijen and Zwaan 2001). Middle: The effect of ram-pressure stripping in Virgo (Kenney et al. 2004). Note how the gas is curled away from the stellar disk. Right: An extended, ram-pressure induced HI filament associated with NGC 4388 in the Virgo cluster. (Oosterloo and van Gorkom 2005)](image-url)
10^{17} \text{ cm}^{-2} \text{ in the denser regions of the WHIM, eventhough the neutral fraction has decreased to about 1% at these lower column densities (e.g. Dove & Shull 1994). What are the morphology and kinematics of the WHIM, and how is this gas accreted by the galaxies embedded in the WHIM? Due to the sparse areal density of QSO absorbers, these questions can not be answered from QSO statistics, and direct detection of the WHIM from free-free continuum or recombination line emission is well beyond the capabilities of current X-ray and optical instrumentation. However, the neutral component of the WHIM can in principle be directly imaged in the 21cm line of atomic hydrogen. The critical observational challenge is crossing the "HI desert'', the range of log(N_{HI}) from about 19.5 down to 18, over which photo-ionisation by the intergalactic radiation field produces an exponential decline in the neutral fraction down to a few percent. Although typical HI imaging does not reach below column densities of ~10^{19} \text{ cm}^{-2}, this is not a fundamental limitation. Long integrations with an (almost-) filled aperture can achieve the required column density sensitivity to permit direct imaging of the WHIM's neutral fraction.

A first detection of such low column density gas has been made by Braun & Thilker (2004) in the direction of M31 (Figure 4.8 - middle), and was obtained from total power measurements with the WSRT, yielding a very high column density sensitivity of 4x10^{16} \text{ cm}^{-2} \text{ rms over 17 km/s. A diffuse filament is detected, apparently connecting the systemic velocities of M31 and M33, and extending away from M31 in the anti-M33 direction. This diffuse filament appears to be fueling denser gaseous streams and filaments in the outskirts of both galaxies. Peak neutral column densities within the filament only amount to some 3x10^{17} \text{ cm}^{-2}. The HI column density distribution function of these structures agrees very well with that of the low redshift QSO absorption lines, plotted as filled circles with error bars (Figure 4.8 - right). The predicted factor of 30 increase in surface covering factor for low N_{HI} emission has been observationally verified. It has thus been possible to provide the first image of a Lyman Limit absorption system and we are now in a position to witness the continuing gaseous fuelling of normal galaxies with direct imaging. The tremendous survey speed of the APERTIF system will enable us to image such low column density system over much larger areas of the sky, providing a more complete direct picture of the WHIM.
4.3 The Origin and Evolution of Cosmic Magnetism

Understanding the Universe is impossible without understanding magnetic fields. They fill intergalactic space, affect the evolution of galaxies and galaxy clusters, contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation and control the density and distribution of cosmic rays in the ISM. But despite their importance, the evolution, structure and origin of magnetic fields are still open problems in fundamental physics and astrophysics. Specifically, we still do not know how magnetic fields are generated and maintained, how magnetic fields evolve as galaxies evolve, what the strength and structure of the magnetic field of the intergalactic medium might be, or whether fields in galaxies and clusters are primordial or generated at later epochs.

Most of what we know about astrophysical magnetic fields comes via the detection of radio emission. Synchrotron emission measures the total field strength, while its polarisation yields the orientation of the ordered field in the plane of the sky as well as the degree of field ordering as illustrated in the image of M51 shown in Fig. 4.9. A measurement of Faraday rotation of the polarisation plane due to an intervening magneto-ionic medium yields the rotation measure, \( RM = \int n_e B \, dl \), for that medium. The recently developed Faraday Rotation Measure Synthesis methodology (Brentjens & De Bruyn 2005) can be used to optimally recover even multiple RM components along the line-of-sight.

4.3.1 An all-sky Rotation Measure grid

Until very recently only 1200 extragalactic sources and ~300 Galactic pulsars had measured RMs. These data have proved useful probes of magnetic fields in the Milky Way, in nearby galaxies, in clusters and in distant Ly\( \alpha \) absorbers. However, the sampling of these measurements over the sky was very sparse, and most measurements were at high Galactic latitude. A major step forward was made this spring with the publication of a reanalysis of the NRAO NVSS 21-cm sky survey polarisation data (Taylor et al 2009). With a total of 37,543 RMs, exciting new astrophysical applications have started to come within reach: the topology of the large scale magnetic field of our Galaxy and the tentative detection of intergalactic magnetic fields (Lee et al 2009). However, the areal density of the Taylor et al sample, about 1.3 / deg\(^2\), is still not high enough for studies of the environments and foregrounds of nearby galaxies and clusters. With a 5-year APERTIF survey reaching 15 \( \mu \)Jy rms over 15000 deg\(^2\) in Stokes I, we expect to detect about 1 million polarised radio sources. This corresponds to a source density of 65/deg\(^2\), about 50 times larger than in the NVSS sample. Due to the wider frequency bandwidth of APERTIF, the accuracy of the RM determinations will also be significantly better. A deep large-area RM-survey will allow a major step forward in understanding the origin and evolution of cosmic magnetic fields. This is one of the key science drivers of the Square Kilometer Array (Gaensler et al 2004). With an APERTIF RM survey we can already start such investigations. Below we briefly discuss some of the most exciting and relevant applications.

4.3.2 Intervening galaxies and the intergalactic medium

Most of the brighter polarised sources making up the RM grid are radio galaxies and quasars (the fainter radio sources are likely to be dominated by starburst galaxies (Stil and Taylor 2008)). A small fraction of those are behind high-z galaxies, as revealed by strong absorption lines (damped Ly\( \alpha \), MgII). An excess RM due to these intervening galaxies can be studied if sufficiently large samples are available. Previous studies have found weak evidence for such an effect (Oren and Wolfe, 1995; Bernet et al, 2008). With a sufficiently large sample of sources, as provided by the APERTIF RM grid, we can study trends of excess RM with redshift. The galactic foreground contribution to each source RM, which has added an uncertainty as large as \( \Delta RM \sim 20–30 \) rad/m\(^2\) to previous determinations, can then be modeled with a 100-1000 times higher source density. By correlating the APERTIF RMs with galaxies from the SDSS, either in projection or in 3-D using photometric redshifts, will enable the study of magnetic fields associated with cosmic large scale structure. Different models for magnetic field evolution with redshift can then be investigated. Pioneering studies of intergalactic magnetic fields were recently made by Kronberg et al (2008) and Lee et al (2009). An order of magnitude increase in the areal density of background sources can revolutionise this application.
The large sample of pulsar RMs obtained with APERTIF, combined with distance estimates from pulsar parallax and dispersion measures, can be inverted to yield a complete delineation of the magnetic field in the Galactic spiral arms and disk on scales $\geq 100$ pc. APERTIF will also have sufficient sensitivity, possibly after smoothing to 1 arcminute resolution, to detect the diffuse polarised synchrotron emission from our Galaxy which covers the whole sky (Wolleben et al 2006). This will allow a study of the Faraday depth of the emitting regions, a crucial parameter in the physical modeling, as well as the distribution along the line of sight at various heights in the galactic disk and halo. Small-scale structure and turbulence can be probed using Faraday tomography, in which foreground ionised gas produces complicated frequency dependent Faraday features when viewed against the diffuse Galactic polarised radio emission (e.g. Haverkorn et al 2003). The magnetic field topology in the Galactic halo and outer parts of the disk can be studied using the extragalactic RM grid.

Finally the intricate Faraday structure of individual Galactic features, like the FAN region (Bernardi et al 2009) observed at 150 MHz with the WSRT, requires multi-frequency observations over a wide range of frequencies. This is a key objective of the Magnetism Key Science Project of LOFAR (PI R. Beck) with which we expect to collaborate in detail.

Magnetic fields are an important component of nearby galaxies. They contribute a substantial fraction of the energy density of the ISM (Beck 2007), and likely play a role in the star formation process. Moreover, they may be important in shaping the morphology of spiral arms (Shetty & Ostriker 2006), and in regulating the flow of material between disk and halo. Previous studies with existing telescopes of nearby galaxies have led to a general picture of the properties of their in-plane magnetic fields, but questions have still lingered regarding the three-dimensional field structure. The recent WSRT-SINGS survey (Heald et al. 2009) has detected synchrotron emission in 21 nearby galaxies, and revealed a surprising, and simple, new pattern in spiral galaxies: a deep connection between the distribution of polarised emission, and the kinematics of the galaxy. This relationship provides constraints on models of the three-dimensional structure of the galactic magnetic fields, and thus on theories of the fields’ initial form and subsequent evolution (e.g. Sofue 1990). A polarisation survey with APERTIF will increase the number of galaxies studied in this way by a factor of about 20. Moreover, the APERTIF RM grid will help break the degeneracy between foreground Milky Way
RM, and an RM offset caused by the global structure of nearby galaxies’ magnetic fields. In combination with kinematic information from an APERTIF HI survey, these gains will lead to excellent constraints on magnetic field models and their variation with galaxy properties.

4.3.5 Magnetic Fields in Galaxy Clusters

In clusters of galaxies, magnetic fields play a critical role in regulating heat conduction, and may also both govern and trace cluster formation and evolution. Estimates of the overall magnetic field strength come from the inverse Compton detections in X-rays, from detections of diffuse synchrotron emission, from cold fronts and from simulations. The only direct measurements of field strengths and geometries come from RMs of background sources (e.g. Feretti & Johnston-Hollitt, 2004). Currently only 1 – 5 such RM measurements can be made per cluster (e.g. Govoni et al. 2001). Only by considering an ensemble of RMs averaged over many systems can a crude picture of cluster magnetic field structures be established (e.g. Clarke et al. 2001). With the APERTIF RM grid, the polarised background source density will already be increased by more than an order of magnitude (to ~65/deg²), making it possible to study magnetic fields within the intra-cluster medium. Deeper polarimetric observations of selected fields will permit an increase in the sampling density, making it possible to derive a detailed map of the clusters contained within these fields. With such information, careful comparison with other cluster attributes such as the presence of cooling flows, recent merger activity and X-ray morphology should allow the role of the field to be understood in the broader context of cluster evolution.

In addition to the use of background RM probes of clusters, the APERTIF data can also be used to study the diffuse polarised emission of (relic) sources within and around clusters. At frequencies of 0.35 GHz very weak and extended polarised emission has been detected towards the Perseus cluster, as shown in Figure 4.10 (De Bruyn & Brentjens 2005). The nature of these structures depends on their location, i.e. Galactic foreground or the cluster, and is still a topic of debate.

4.4 Pulsars as tools for fundamental physics and astrophysics

More than 40 years after their discovery, pulsars remain unique laboratories for testing fundamental physical theories (e.g. Kramer et al. 2006). These cutting edge experiments have not only generated great interest among astronomers, but also in the larger physics community – e.g. among gravitational and nuclear
physicists. Though progress is being made through the continued study of known pulsars, there is the potential for even greater insights into fundamental physics through the discovery of new pulsar systems whose properties make them singularly excellent laboratories for testing specific physical theories. Thus, the continued search for new pulsars remains an extremely vibrant aspect of pulsar astronomy, with many exciting recent results directly following from the discovery of new pulsars with unexpected properties (e.g. Champion et al. 2008, Archibald et al. 2009).

The typically steep spectra of pulsars argue for observations at low radio frequencies (<= 400MHz), where the emission is intrinsically brighter. LOFAR will take full advantage of this in its all-sky survey for radio pulsars. However, principally because of interstellar scattering, which is much more pronounced at low observing frequencies, LOFAR will be limited in the effective distance out to which it can see pulsars, especially those that are fast spinning, i.e. the millisecond pulsars. LOFAR will probe the entire local pulsar population, down to very low luminosity, but a differently designed instrument is badly needed to detect more distant, highly scattered pulsars. Given the limitations due to signal propagation through the interstellar medium, an observing frequency of roughly 1400MHz is generally considered a “sweet spot” for discovering pulsars. This frequency is low enough that the pulsars are still intrinsically bright, but also high enough that the pulses themselves are not scattered beyond detectability. This is of utmost importance for finding millisecond pulsars, which are particularly interesting in terms of the tests of General Relativity and nuclear physics they afford. The ability of APERTIF to observe from 1000-1750MHz gives it the ideal frequency coverage for an all-sky survey for fast-spinning radio pulsars – even out to large distances. In regions towards the Galactic plane, especially closer to the Galactic center, one will want to observe at the top end of this band (1450-1750MHz) in order to mitigate the extra scattering expected along these directions. In directions away from the Galactic plane, where scattering will be less severe, one will want to observe at the bottom of the APERTIF band (1000-1300MHz) so as to take maximum advantage of the steep spectral indices of pulsars.

This ideal observing band for detecting potentially distant, highly-scattered pulsars, coupled with APERTIF’s enormous FOV will make the WSRT the most powerful telescope ever built for performing all-sky pulsar surveys at this frequency. Unlike what was possible in the Arecibo and Parkes pulsar surveys at 1.4GHz, APERTIF’s leap in FOV will allow it to survey not just the Galactic plane, but the entire visible sky in a reasonable amount of time and will use comparatively very long dwell times which are advantageous for detecting transient sources (total time spent observing is the essential criterion, see also section 4.5). A strong synergy exists between LOFAR and APERTIF, which will both perform all-sky surveys for radio pulsars.

Figure 4.11: Left: The P – P dot diagram for radio pulsars and magnetars. Circled points are binary systems, while objects in the upper right part of the diagram have surface magnetic fields exceeding $4.4 \times 10^{13}$ G (from Cordes et al. 2004). Middle: The detectability of pulsars with the Apertif system is illustrated with the luminosity – period scatter diagram (adapted from Cordes et al 2004). The horizontal lines correspond to 10$^\sigma$ detection limits with Apertif for pulsar distances of 10 kpc (lower line) and 100 kpc (upper line). Right: The simulated Galactic pulsar population is shown for an all-sky survey that reaches ~20000 detections (Cordes et al. 2004). A significant fraction of this number will be accessible with the Apertif system.
pulsars, but will probe very different, yet complementary pulsar populations. Together with the planned LOFAR pulsar survey, APERTIF will provide the most complete picture of the Galactic population of pulsars and will discover many exciting new systems to use as natural laboratories for studying fundamental physics.

We now describe the scientific yield of such a survey in more detail.

There are many scientific motivations for undertaking a full census of the Galactic pulsar population. The first is that the larger the number of pulsar detections, the more likely it is to find the rare objects that provide the greatest opportunities as laboratories for testing fundamental physics. These include binary pulsars with black-hole companions that can provide strong field tests of gravity; binary pulsars with periods of a few hours or less that can be used for tests of relativistic gravity; millisecond pulsars (MSPs) that can be used as detectors of cosmological gravitational waves; MSPs spinning faster than 1.4 ms, that probe the equation-of-state under extreme conditions (e.g. Hessels et al. 2006); hyper-velocity pulsars with translational speeds of 1000 km/s, which probe both core-collapse physics and the gravitational potential of the Galaxy; and objects with unusual spin properties such as discontinuities ("glitches") and apparent precessional motions.

The second reason is that a large number of pulsars can be used to delineate the advanced stages of stellar evolution that lead to supernovae and compact objects. In particular, with a sufficiently large sample it may be possible to determine the branching ratios for the formation of canonical pulsars and the even more highly magnetised "magnetars". It is also possible to estimate the effective birth rates for MSPs and for those binary pulsars that are likely to coalesce on time scales short enough to be of interest as sources of periodic chirped gravitational waves.

The third reason for a maximal pulsar sample is its use as a 3-D probe of the interstellar medium. Measurable propagation effects include dispersion, scattering, Faraday rotation and HI absorption which provide line-of-sight integrals of the free-electron-density $n_e$, the fluctuating electron density $\delta n_e$, the product $B/n_e$, and neutral hydrogen density $n_H$. The determination of these observables for a large number of independent sight-lines (of different distances) makes it possible to construct a complete 3-D volumetric map of the Galaxy.

The nominal, wide-field continuum survey sensitivity of APERTIF, of 7 $\mu$Jy rms over 300 MHz in a 16 deg$^2$ FOV per day will already permit detection of the vast majority of Galactic pulsars beamed in our direction. This is illustrated in the center panel of Figure 4.11 where the 10$\sigma$ detection limits at 1.4 GHz are overlaid on

![Figure 4.12: Illustration of wide-field pulsar surveys using multiple digital beams on a synthesis array. A pulsar candidate is shown in red in the original (left) and confirming (right) multi-beam observations done with the WSRT array. Multiple digital beams have made it possible to carry out extremely efficient pulsar surveys with wide-field synthesis arrays.](image)
the “pseudo luminosity” distribution of all currently detected pulsars as a function of the pulse period. In making this plot, the observed pulsar fluxes have been period-averaged and rescaled (with $\nu^{-2}$) to 1.4 GHz to permit comparison with the nominal continuum sensitivity. The lower line corresponds to an assumed pulsar distance of 10 kpc and the upper line to 100 kpc. The limits shown do not include the loss in sensitivity due to dispersion in the interstellar medium nor scattering which are both distance dependent, however this will only affect the sensitivity at the lowest end of the period distribution and will be no more severe than in previous surveys. Even with only this nominal sensitivity, the majority of the pulsar luminosity distribution lies above the detection limit at 10 kpc, while the high luminosity tail can be detected well beyond 100 kpc.

Pulsar surveying with synthesis arrays has historically not been very effective, since the instantaneous sky coverage has typically been restricted to only a single synthesised beam. This situation has recently changed, with the first successful pulsar surveys using multiple simultaneous digital beams on the WSRT array (Janssen et al. 2009). The multi-beaming approach is particularly effective when the array geometry is periodic, like with WSRT, since this permits generation of multiple digital beams with minimal digital electronics. For the case of a regular grating array (such as can be achieved for 12 of the 14 WSRT telescopes) the instantaneous FOV is a repeating series of fan beams which extend across the entire primary beam of the individual telescopes. With only twelve (or N, for an N element grating array) digital beams spaced perpendicular to the fan beam orientation, it is possible to utilise the entire primary beam FOV. The time series toward any synthesised beam within the primary beam can then be reconstructed after the fact by the appropriate linear combination of the eight digital beam outputs that are recorded. The multi-beam pulsar survey mode is illustrated in Figure 4.12 for a small portion of the observed WSRT primary beam response. Each filled ellipse represents a reconstructed synthesised beam that has been searched for pulsar candidates in a two hour integration of a survey field. A second two hour integration obtained 6 months later for the same field is shown on the right, confirming the pulsar candidate seen in the first coverage (shown in red) and providing a high precision position, as well as a period derivative.

Digital multi-beaming finally permits efficient wide-field pulsar surveys to be carried out with synthesis arrays, and along with APERTIF itself, will provide a breakthrough in our ability to perform deep, sensitive, and efficient surveys for pulsars. An added advantage is that this mode not only provides large instantaneous coverage to map the sky quickly, but also excellent spatial resolution for precisely determining the positions of new discoveries. This saves enormous amounts of follow-up telescope time which are typically needed in order to refine the source position after discovery. In essence, APERTIF will turn WSRT into an extremely powerful pulsar-finding machine.

4.5 The Dynamic Radio Sky

Transient emission – bursts, flares and pulses on time-scales of milliseconds to years – marks compact sources or the locations of explosive or dynamic events. As such, radio transient sources offer insight into a variety of fundamental physical and astrophysical questions including:

- the mechanism of efficient particle acceleration
- possible physics beyond the Standard Model
- the nature of strong field gravity
- the nuclear equation of state
- the cosmological star formation history
- detecting and probing intervening media.

Searches for radio transients have a long history and a wide range of radio transients are currently known, ranging from extremely nearby (ultra-high energy cosmic rays impacting the Earth’s atmosphere) to cosmological distances ($\gamma$-ray bursts and afterglows). There are also many classes of hypothesised transients. The three critical factors in opening up the transient discovery space to serious study are: instantaneous sensitivity, instantaneous FOV and high time resolution. At high energies (X- and $\gamma$-rays), detectors with large solid angle coverage and high time resolution have had great success in finding classes of transient objects. At optical wavelengths there has been recent progress in constructing wide field...
detectors with high time resolution. Historically, radio telescopes have been able to obtain high time resolution, and this has been paired with an increasing instantaneous sensitivity. The third critical ingredient to enable the study of radio transients, large FOV, will finally become possible with APERTIF at GHz radio frequencies. This provides a critical complement to the low frequency transient sky that will be probed by LOFAR. The higher physical sensitivity of APERTIF (which follows from the much broader bandwidth and lower system temperature) enables APERTIF to reach transient sources which are an order of magnitude fainter than accessible to LOFAR, while the higher observing frequency (by a factor of 10) permits detection of sources which would otherwise still be shrouded by thermal absorption (by a factor of 100).

Assuming that the basic emission process is synchrotron radiation, it is possible to estimate the APERTIF detection limits for sources that vary on a particular timescale. The brightness of isotropic synchrotron radiation is limited to $10^{12}$ K by inverse Compton losses. If relativistic bulk motions are involved, with Lorentz factor, $\gamma$, then substantially higher brightness can be realised, which scales with $\gamma^3$ for a highly aligned viewing geometry. A linear size scale given by $c \cdot t_{\text{min}}$ corresponds to an angular size scale $\theta = c \cdot t_{\text{min}}(1+z)/D_L$, allowing calculation of the apparent brightness temperature associated with a region displaying a flux density variation $\delta S$.

$$T_B = 3.84 \times 10^{20} \delta S_{\nu} [\lambda_{\text{cm}} D_L(Mpc)/(1+z) \cdot t_{\text{min}}]^2 K$$

The apparent brightness temperatures which have been deduced in this way from the variability timescale of inter-day AGN variables is in the range $10^{16} - 10^{21}$ K (e.g. Quirrenbach et al. 2000). We can invert this expression to predict the flux density variations which can be expected on a particular timescale due to a range of assumed apparent brightness temperatures. In Figure 4.13, we have scaled the 10σ APERTIF
sensitivity at 1.4 GHz in a 1 second integration to derive the maximum distance out to which variable sources of a particular apparent brightness temperature can be detected.

Isotropic synchrotron transients ($T_B < 10^{12}$ K) out to about 100 pc can be expected to have detectable signatures as short as a few seconds, while highly beamed sources of this type should be detectable from throughout the Galaxy on these timescales. The most likely timescale for detectable transients within nearby galaxies (out to a few Mpc) would seem to be between a few hours (for isotropic emission) down to minutes (for beamed emission). At cosmological distances, the timescale for detectable isotropic transients is a months (such as for GRB afterglows), while significantly beamed sources might lead to detectable synchrotron transients on hour time-scales.

These detection limits are complemented by the transient “phase-space” plot (from Cordes et al. 2004) in the right-hand panel of Figure 4.13, in which similar brightness temperature diagonals are over-plotted on a variety of observed sources in both the incoherent ($<10^{12}$ K) and coherent ($>10^{12}$ K) regime. Flare stars and AGN occupy the coherent (lower right) corner of the plot. Beamed synchrotron emission, sometimes modified by Interstellar Scattering (ISS), applies to observed Inter-day AGN variables (IDVs) and GRBs. Jupiter bursts have comparable brightness temperature, but low intrinsic luminosity. Coherent emission from pulsars, in particular that of giant pulses, extends out to brightness temperatures exceeding $10^{30}$ K.

Of the many types of likely and possible radio transients (cf. Cordes et al. 2004) we will consider only a few in more detail, relating to the early and final stages of stellar evolution:

**Flare Stars:** Radio flares from various active stars and star systems are observed at frequencies of order 1 GHz with flux density levels that can reach about 1 Jy (e.g. Garcia-Sanchez et al. 2003). These systems can show strong polarisation, including strong circular polarisation. These flares are attributed to particle acceleration from magnetic field activity.

**Pulsar Giant Pulses:** While all pulsars show pulse-to-pulse intensity variations, some pulsars have been found to emit so-called “giant” pulses, pulses with strengths of 100 or even 1000 times the mean pulse intensity. The Crab pulsar was the first pulsar found to exhibit this phenomenon. During one hour of integration the largest measured peak pulse flux of the Crab is roughly $10^6$ Jy at 430 MHz with a duration of roughly 100 μs (Hankins & Rickett 1975), corresponding to an implied brightness temperature of $10^{31}$ K. Recently, pulses with $\sim 10^3$ Jy flux and only 2 ns duration of been detected from the Crab at 5 GHz (Hankins et al. 2003). These “nano-giant” pulses imply brightness temperatures of $10^{36}$ K, vastly exceeding any other currently known source. For many years, this phenomenon was thought to be peculiar to the Crab pulsar. However, giant pulses have been detected from the millisecond pulsars PSR B1821-24 (Romani & Johnston 2001) and PSR B1937+21 (Cognard et al. 1996) and the Crab-like pulsar in the Large Magellanic Cloud, PSR B0540-69 (Johnston & Romani 2003).

**Transient Pulsars:** Kramer et al. (2005) have recognised a class of pulsars that produce pulses only a small fraction of the time. In the “on” state they appear indistinguishable from normal pulsars. For example, the 813 ms pulsar, PSR B1931+24 is only detectable about 10% of the time, and the 1.8-s pulsar PSR B0826-34 is in a faint mode (originally thought to be completely extinguished) roughly 70% of the time (Esamdin et al. 2004). Single-pulse searches of the Parkes Multi-beam Pulsar Survey data also have resulted in the discovery of several pulsars whose emission is so sporadic that they are not detectable in standard Fourier domain searches (McLaughlin et al. 2005).

**Radio Supernovae and Gamma-ray Bursts:** Supernovae and γ-ray bursts (GRBs) appear to be related since, in at least some cases, they both involve the collapse of a massive stellar progenitor to a neutron star or black hole at the release of $\geq 10^{51}$ erg. However the two areas of study may never completely merge since some types of SN (e.g. type Ia) have never been detected in the radio, while some classes of GRB (e.g. the “short-hard” category) have different environments and are thus supposed to have a different origin than the “long-soft” GRBs for which some afterglows have been detected. For both SN and GRBs there is a strong incentive to search in the radio for “dark” or “orphan” events. For SN, which are primarily discovered in optical searches, extinction and proximity to the nucleus of a galaxy can lead to many events being hidden from present surveys. For GRBs, the apparent narrowness of the relativistic jet believed to give rise to the γ-
ray and X-ray bursts means that most of the events are missed at those wavelengths. The more isotropic radio emission, particularly at later times, should be detectable in sensitive, wide-field searches.

As a specific example of the type of pro-active transient observing program that will be carried out with the APERTIF system, we consider the case of a survey for the detection of “orphan” GRBs. The detection frequency of “long-soft” GRBs from γ-ray monitoring is about one per day. The isotropic radio afterglow from these events has a lifetime of about one month at a peak observed brightness at GHz frequencies of 100 μJy (e.g. Weiler et al. 2004). From relativistic beaming constraints there are expected to be from 10 – 100 GRBs per day which do not happen to be beamed in our direction but which should also give rise to comparable isotropic radio afterglows. Since the APERTIF system will permit continuum imaging to a depth of 20 μJy rms over 16 deg² in a single day’s observing, each such coverage is expected to contain about 5 of such detectable “orphans”. Weekly imaging of the same field over a period of a few months will display the appearance and disappearance of the GRB afterglow population. Combined with optical/NIR identification of the GRB host galaxies this will provide an important constraint on massive star formation in the early universe.

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5 Motivation of Investment Plan

To a large extent, the progress of astronomy is technology driven. The ever-increasing performance of telescopes, instruments and digital electronics makes it possible to study fainter and more distant objects in more and more detail, resulting in new discoveries. This strong coupling with technology exists for radio astronomy in particular. This entirely new field of astronomy was opened up after the 2nd world war via the implementation of radar technology when the first radio single-dish telescopes were built, including the Dwingeloo dish. Later, during the 1970’s and 1980’s, better receiving systems and electronic computers made it possible to build large radio synthesis arrays, such as the WSRT. Utilising these technological advances, radio astronomy has made several fundamental discoveries, such as pulsars, active galactic nuclei, HI spectroscopy and the cosmic microwave background. These discoveries have, to a large extent, shaped the form of modern astronomy and astrophysics.

In this context, it is important to consider the impact of current technological developments. A first consequence of the digital revolution is that the performance of astronomical instrumentation can dramatically be improved by making better detectors and telescopes. Utilising advances in digital electronics and antenna design, radio astronomy can make a similar leap in performance that many other branches of astronomy are now experiencing. For example, LOFAR, the Low Frequency Array that is currently being constructed in the Netherlands, will observe at metre wavelengths with a performance that greatly surpasses anything that has been built before for this wavelength region. Similarly, APERTIF will improve the imaging speed of the WSRT by more than a factor 30. Internationally, the radio astronomical community is preparing for SKA, a radio telescope 50 times bigger and better and better than anything currently operational.

New technology also leads to improved computing power which makes it feasible to fully exploit astronomical data via advanced, high-performance data analysis techniques. This makes it possible to handle much higher data rates and data volumes. For astronomy, this enables wide-field astronomy: it becomes possible to perform, and analyse, very large, sensitive surveys of huge regions of the sky, something that was inconceivable not so long ago. Such surveys are having a substantial impact on astronomy, because they make it possible to obtain a meaningful census of many more types of objects, and also reveal rare phenomena that would otherwise go undiscovered. A very important aspect of these wide-field surveys is their legacy value: using WWW technology, their data are often freely made available to the general community. This is leading to a paradigm shift: astronomical research can be done using data from public data archives, reducing the need for research groups to observe and obtain data themselves. Moreover, because the data are used by many more research groups, they are used for a much larger range of studies and topics, many of which are quite different from those for which the survey data were originally devised.

APROPOS+APERTIF is motivated by both of these developments: improved instrumentation and improved computing. The combination of the two makes wide-field astronomy within reach for decimetre (dm) wavelength radio astronomy, and accessible to the entire community. Currently, single-receiver systems are employed in the focus of the parabolic dishes of the WSRT. Our design work on APERTIF has demonstrated that replacing these by fully-sampling, low-noise, wide-bandwidth receiver arrays, a huge performance improvement can be obtained. In particular, this technology increases the field of view of the WSRT by more than a factor 30, resulting in the same increase in imaging speed. Coupled to the pipeline processing of APROPOS, this will give the ability to make sensitive surveys of the entire sky at high spatial resolution with the WSRT within only a few years. To maximise the scientific output of APERTIF, APROPOS will ensure that the resulting survey data will be available to the entire community using Virtual Observatory technology. As detailed in section 4, such wide-field radio surveys address many important problems central to the research themes of Dutch astronomy in particular, and of the international radio astronomy community in general, and will have a significant impact.

Within the Netherlands, we are well placed to play an important role in driving the technological developments for radio astronomy, as well as for utilising the new radio telescopes for forefront astronomical research. ASTRON has a strong track record in developing new antenna technology and digital processing hardware, as well as operating a radio observatory. The strong involvement of ASTRON astronomers in technology development results in instruments that are well tuned to the needs of the user community. In addition, a very strong user community exists at the Dutch universities.
The performance improvement in the dm band offered by APERTIF can be realised as an upgrade to an existing facility, the WSRT. Moreover, although the difference in observing frequencies between LOFAR and APERTIF implies that each instrument requires its own specific calibration and analysis techniques, much of the design effort of the overall software infrastructure for LOFAR, in particular that for analysis pipelines and archiving, can be re-used. This makes APROPOS+APERTIF very cost effective compared to similar facilities under construction, in particular ASKAP in Australia and MeerKat in South Africa, which both have to be erected as fully new observatories.

Moreover, the results of the APERTIF prototype at the WSRT show that ASTRON is world leader in the effort to design focal-plane array systems for the dm band. This, combined with the re-use of LOFAR design efforts, makes it possible for APROPOS+APERTIF to be the first operational system performing wide-field astronomy at dm wavelengths.

In 2006, an NWO-Groot grant of 5 M€ was awarded for developing and building the FPA systems for APERTIF. With the current application, APROPOS, we seek funding for the correlator system, and software and hardware for processing pipelines and a data archive. When APRPOS+APERTIF is integrated into the current WSRT system, it will be a survey facility at the state-of-the-art, and will deliver legacy quality databases that are timely for a wide range of central topics in the national and international astronomical roadmaps.

Figure 5-1. Left: picture showing the prototype focal-plane array DIGESTIF as installed in one of the WSRT dishes. This prototype array has been used extensively to characterise the performance of our FPA design. This array consists of 112 receiving elements, 56 for each linear polarisation. Right: element beam patterns of DIGESTIF, illustrating the large field of view of APERTIF. Each panel covers the same 3x3 degrees on the sky and depicts the reception pattern of a single DIGESTIF focal plane array reception element. The size of each red region is about half a degree in size, which is the same size as the field of view of the current WSRT. The field of view of APERTIF is created by combining the signals from all FPA elements, and the full 3x3 degree area is covered.
5.1 Basic Instrument Design and Capabilities

The main aspect of APERTIF is to outfit the focus of each of the 14 WSRT dishes with a receiver array. The specific receiver array foreseen covers the frequency band of 950 to 1750 MHz with an array of 120 active dual polarisation antenna elements. The specifications for system noise temperature and aperture efficiency are $T_{\text{sys}} \sim 55$ K and $\eta_a \sim 75\%$. Each of the signal paths is digitised and combined to form, for each polarisation, 37 optimised beams over 300 MHz. The output of each of the 37x2 beams from each telescope are then centrally correlated with the signals of the corresponding beams of the other dishes. The correlator will provide all four polarisation products at a spectral resolution of 20 kHz (corresponding to 4-5 km/s in the neutral hydrogen spectral line) over the 300 MHz bandwidth (or higher spectral resolution for reduced bandwidth) for all 37 beams. This makes it possible to construct high spatial resolution full Stokes spectral-line data cubes of 16384 spectral channels over a region of the sky of about 8 degree$^2$ (compared to 0.3 degree$^2$ of the current WSRT). The speed with which APERTIF can image large regions of the sky down to a given noise limit, is therefore about a factor 30 higher than that of the current WSRT. This is a major performance improvement for wide-field surveys: currently, it would take about a century to fully image the northern sky with the WSRT. With APERTIF it will only take a few years, creating many new opportunities for astronomical research.

Using the funding of our earlier NWO Groot grant, a prototype focal plane array, called DIGESTIF, of 56x2 elements is installed in the focus of one of the WSRT dishes since the beginning of 2007. Hard- and software of the LOFAR Initial Test Station is recycled to function as the backend of this prototype. The system is used in a stand-alone mode to perform experiments to characterise the performance of the design of APERTIF. This has led to the production of a number of internationally recognised advances in the exploitation of FPAs for radio astronomy. A number of significant milestones have been reached with this system (see figures 5-1, 5-2 and 5-3). We have been able, in 2008, to make the first astronomical image of the neutral hydrogen in an external galaxy obtained with a telescope outfitted with a focal plane array. Early 2009 this was superseded by the first synthesis images obtained though interferometry using a telescope.
outfitted with a focal plane array. In August 2009, a committee of international experts performed the Preliminary Design Review of the APERTIF frontend system. The committee concluded that, with APERTIF, “ASTRON is at the international forefront with respect to developing FPA technology for radio telescopes”. It also concluded that the results obtained with DIGESTIF clearly show that the design satisfies the scientific and cost requirements, and that it promises to have a very significant impact on radio astronomy.

Given the large data rates of APERTIF, its data will be processed using automatic pipelines. The results from this processing (calibrated images as well as source catalogues) will be stored in a data archive. This archive will be open to the entire community using Virtual Observatory technology. The difference between the observing frequency of LOFAR and APERTIF means that there is a large difference in many of the instrumental and atmospheric effects that have to be taken into account in the calibration and analysis of the data. However, the design and implementation of the APERTIF processing pipelines and archive can be done in a very cost-effective way, since a significant fraction of the overall software design efforts for the LOFAR pipelines and archives can be re-used and for APERTIF we can concentrate on the development and implementation of APERTIF specific strategies and algorithms.

The performance of APERTIF, as well as the timescale on which it can be realised, is very competitive compared to existing and planned observing systems for wide-field dm radio astronomy. Two major ongoing projects (EVLA in the USA and MeerKat in South Africa) will produce instruments that will be more sensitive for observations of single objects, but have much lower imaging speed or large regions of the sky. APERTIF will outperform these instruments for wide-field astronomy and will be the only such instrument in the Northern hemisphere.

The only system that will have similar survey performance to APERTIF is the Australian SKA Pathfinder (ASKAP). This new telescope is planned to become operational in 2013 and consist of 36 dishes of 12 m, each dish having a focal-plane array system forming 30 beams on the sky. The field of view of this telescope is about a factor 3.5 larger than that of APERTIF, but the larger collecting area of APERTIF largely compensates for this and the imaging speeds of the two instruments are very comparable. APERTIF holds the promise to be the first instrument operational. Moreover, APERTIF can profit from the availability of extensive survey data sets that are available for the Northern hemisphere, such as the Sloan Digital Sky Survey. An important aspect is that the combination of ASKAP in the southern sky and APERTIF in the north opens the possibility of performing true all-sky surveys with uniform properties. This is a very valuable asset in itself, but is also very important for studies of the Milky Way where observations over the entire sky are needed.
6 National Importance and Scientific Accessibility

The science made possible with APERTIF addresses several topics that are strongly embedded in the science goals of our community, as laid out in the NCA's national roadmap for astronomy and the stated goals of NOVA, the top research school for astronomy. Several of the research topics of APERTIF also have a strong synergy with LOFAR. The scientific potential of the two instruments will be greatly enhanced by each other and the two instruments form a very strong combination, unique in the world. Dutch astronomy is at the forefront of international research in the areas covered by APERTIF and LOFAR. The persistently strong role of Dutch radio astronomy, through technological development, operation of world-class facilities and astronomical research, has led to this leading role. The scientific opportunities offered by APERTIF will ensure that Dutch astronomy maintains this leading position.

In addition, constructing and operating this unique forefront radio facility will underline ASTRON's reputation on the global stage as a competent institute for enabling radio astronomy. This is particularly important in further establishing the position of Dutch astronomy in future global projects, including SKA.

APERTIF will be presented to the international community as an open facility. The large surveys that will be conducted with APERTIF, will be designed, performed and analysed by surveys teams. Membership to these teams will be open to all members of the community. Moreover, to maximise scientific output, all APERTIF data will be made freely accessible to non-team members on short timescales, through regular data releases using Virtual Observatory infrastructure. This will ensure that APERTIF is fully exploited in its role in multi-waveband wide-field astronomy, world wide. Some fraction (~25%) of the observing time will be assigned to smaller projects based on scientific merit, using the standard process of observing proposals peer reviewed by the international ASTRON programme committee.

7 International Positioning

Worldwide, many new radio astronomical facilities are planned or under construction, while several existing telescopes are significantly upgraded. These efforts are motivated by the spectacular science that these new instruments will enable, but they are also driven by developing concepts for the future developments in radio astronomy, with a strong focus on realising the SKA. The technological development of APERTIF, of transparent and freely accessible archives of radio data, as well the scientific exploitation of APERTIF for astronomical research, ensures that Dutch astronomy (ASTRON and the universities) fully participates in this worldwide process, both technologically and scientifically. As a result, Dutch radio astronomy will be well placed to maintain its important role in international radio astronomy in the short term, but also on the longer timescales of SKA. Specifically, designing and employing a radio telescope that uses focal-plane array technology at dm wavelengths will be a very important contribution to the design process of SKA through the Dish Verification Programme of PrepSKA. The planning of APERTIF maps well on the SKA PDR (the planned start of APERTIF operation coincides with the current SKA PDR date.

Wide-field radio surveys do exist (e.g., the NVSS, FIRST, WENSS, HIPASS) and they are used in combination with wide-field databases obtained at other wavebands. However, the limited sensitivity or spatial resolution (or sometimes both) of these radio surveys means that radio data are available only for a small fraction of the objects detected at other wavelengths. The quality of the data from APERTIF will greatly surpass that of existing GHz radio surveys, and the APERTIF surveys will fill the radio gap that now hampers many multi-waveband studies. The huge scientific potential of deep wide-field radio surveys in the decimetre band has also been recognised by the research groups in Australia that plan such wide-field radio surveys with ASKAP. APERTIF science teams will collaborate with their Australian counterparts to define a common approach to the surveys performed on both the northern and southern sky, resulting in uniform all-sky catalogues and images with very high legacy value. The resulting data will set the standard of GHz radio surveys until the advent of SKA. Given that the SKA will be located outside of Europe, this combined initiative will also give the Netherlands a head start in positioning itself as a major centre of excellence for SKA, both in terms of technology development, but also in the support of scientific exploration.
Strategy of the institution with regard to the Investment

Radio astronomy stands on the brink of a new golden era – around the world several new facilities are now under construction and many existing telescopes are in the process of undergoing significant facility upgrades. Much of this activity is fueled by preparations for the 1.5 Billion Euro Square Kilometre Array (SKA). The future of ASTRON is largely associated with its ambition to play a major role in the realisation of SKA and in the future scientific exploitation of this instrument. Our strategy has been to develop new and innovative technologies for radio astronomy with a particular focus on aperture array technology. One of the results of this strategy is LOFAR and the other is APERTIF. Recently, we have also made significant investments in fundamental astronomical research, successfully attracting top-talent to various staff positions within the institute. With this new balance, ASTRON is well placed not only to build state-of-the-art radio telescopes but also to scientifically exploit them. The need to do both, is essential in order for ASTRON to be a fully engaged in the SKA project, and to have appropriate influence in its design and implementation.

The outstanding success of the DIGESTIF focal plane array prototype (see section 5) has demonstrated to the global radio astronomy community its relevance as a potential technology for adoption by the SKA project. Since the APERTIF project began, several other groups have adopted focal plane arrays, in particular the ASKAP SKA precursor. The outstanding technical success of APERTIF has placed ASTRON at the heart of these developments and further increased our visibility within the international SKA community.

Given the fantastic data rates generated by focal plane array instruments, the full scientific exploitation of these systems requires significant computational and archiving facilities. For ASTRON to fully utilise the APERTIF system, an advanced e-Science infrastructure is clearly required.

The deployment of APROPOS is absolutely essential if the full potential of APERTIF is to be realised. In addition, the experienced gained in the development and routine operation of this system will optimally position ASTRON in terms of its ambitions to serve as a centre of excellence for SKA once the telescope becomes operational.

Countries such as Australia, the USA, China and the UK are already investing significant resources in the ICT infrastructure required to support next generation radio telescopes – quite simply, ASTRON cannot afford to be left behind. APROPOS will guarantee that the APERTIF system delivers fantastic science to a wide national and indeed international community, and at the same time place us in the vanguard of those ICT developments most relevant to SKA. In addition, the project will also enable us to enter into meaningful international FPA collaborations, especially with India and Australia. A major goal of the project is to create the first globally shared astronomical database, bringing APERTIF and ASKAP data together via a mirrored archive that is synchronised in real-time and is accessible via standard VO tools. Collaborations that have hitherto focused on the technical aspects of FPA systems, will be readily extended to the scientific exploitation of the large survey programmes described in this proposal.

ASTRON has secured both internal and external project funding for the technical R&D leading to the three components of this proposal, and will provide matching manpower. The operations of the proposed infrastructure will be integrated within the Radio Observatory division of ASTRON. The Observatory will provide expert support to science users of APERTIF+APROPOS, especially in terms of the new concepts involved in on-line calibration and “observing from the archive.” Researchers in the Astronomy Group and support scientists in the Radio Observatory will play an important role in maximising the scientific output of APERTIF through APROPOS, adding to the scientific excellence of the institute and facilitating enhanced exploitation of the survey data by university groups.

With the advent of LOFAR and the SKA, ASTRON will gradually build off support for the WSRT. With APROPOS, the scientific lifetime of the WSRT though it’s archival database will extend well beyond the physical lifetime of the telescope itself.
9 Technical Concept and Budget

9.1 Apertif system concept

The basic idea of APERTIF is to place an array of receiving elements in the focus of each WSRT dish. This focal-plane array samples the incoming radiation field over about one square metre of the focal plane. This is the main difference with the current WSRT. There, the radiation in the focal plane is detected in only a single point by a single receiver, and as a consequence, the dish is observing in only one direction. Because in APERTIF, the focal plane is fully sampled over a large region, the radio dish is transformed into a radio camera and observes a much larger region on the sky (see figure 9-1). To be able to turn the received signal into image, the complete APERTIF system also has a central correlator and a processing cluster. To complete the system, there is a data archive and a control system.

![Diagram showing the concept of the Apertif system]

Figure 9-1. Left: schematic diagram illustrating that receiving elements at different location in the focal plane see different regions from the sky. By placing an array of receiving elements in the focal plane, the radio dish turns into a camera and a large region of the sky can be observed in a single observation. The improvement of the field of view resulting from APERTIF is shown on the right image. The left panel shows the current field of view (about the size of the full moon), the right panel the field of view of Apertif.

The front-ends use a dual polarised focal-plane array of 121 antenna elements and are mounted in the prime focus of the existing 25-m WSRT reflectors. A Low Noise Amplifier (LNA) operating at the room temperatures is connected to every antenna element. The system temperature of APERTIF is $T_{sys} \approx 55K$. The analog signals are transported from the LNA to ground-level over coaxial RF cables. In a shielded cabinet, the signals are converted to base-band and are digitised. The digitised signal is split into 384 sub-bands of 800 kHz wide. The signals from the individual elements are combined to form optimised compound beams. This beamforming process is performed all-digital and is independently applied to each sub-band. The aperture efficiency of these compound beams is 75%. The aggregated bandwidth is 300 MHz. The beamformer generates 37 dual polarised beams, totaling a field of view of 8 deg$^2$. A real-time calibration system ensures the temporal stability of the beam. The signals from all compound beams are sent over fibre to the backend in the central building where they are correlated. The correlator combines the data from all dishes and all beams and produces the full-polarisation correlation products for all 105 baselines for every beam. The output data rate to the correlator is 178 Gb/s per dish.

A processing pipeline calibrates the correlator data and turns these into images of the sky. The pipeline also performs source finding in the data. The results from the pipeline are stored in an archive. This archive is freely accessible through a VO interface. Below we provide some more details about the component for which we request finding in this proposal.
9.1.1 Correlator

The signals from all beams and all telescopes are combined in a correlator system to produce the data that can be used to turn the measurements into full polarisation images of the sky. Given the number of beams on the sky and the increased bandwidth, the APERTIF correlator has to be about 200 times more powerful than the current WSRT correlator. The correlator for APERTIF is based on Uniboard, a cost effective FPGA based digital processing system that is currently being developed by ASTRON and other European partners. The modular design of Uniboard implies great flexibility for implementing various observing modes. The Uniboard processing boards will also be used for the digital beamformer of the FPA system. The development of this Uniboard system is financed through the FP7 program RadioNet. A prototype correlator, called ExBox, is being developed by ASTRON together with the Joint Institute for VLBI in Europe (JIVE) and is funded through an NWO-M grant.

9.1.2 Pipeline

The huge data rate produced by the correlator necessitates an automated approach to the calibration, imaging and analysis of the APERTIF data. The overall structure of the data flow of APERTIF is very similar to that of LOFAR, and the software infrastructure for pipelines developed for LOFAR can be largely re-used. The main effort will be to develop new calibration and analysis strategies that take into account the different observing frequencies. Given the many years of operation of the WSRT, a large knowledge base exist regarding the calibration of WSRT data that will be fruitful for developing the calibration of APERTIF. Nevertheless, given the relative complexity of APERTIF compared to current WSRT frontends, new algorithms are needed. Work on developing these new algorithms will start in the fall of 2009 under the RadioNet FP7 Albius programme. To implement these algorithms, the mathematical formalisms developed for the calibration of LOFAR data can also be applied to APERTIF data. The large data stream of APERTIF also implies that the derived data products, such as source catalogues, will have to be produced by unsupervised pipelines. Many of the algorithms produced for the source finding in LOFAR data can also be applied to APERTIF data. Algorithms specific for the APERTIF waveband will be developed in collaboration with ASKAP to ensure all-sky uniformity of the parametrisation of the resulting surveys. Benchmarking of the calibration and analysis of data from the current WSRT, and scaling this to the data volumes of APERTIF, has given an accurate picture of the required hardware resources.
9.1.3 Archive

Users of Apertif will only interact with the telescope through its data archive. Developing a user-friendly web-interface, that also complies with the Virtual Observatory standards, is therefore important. The definition of the user interface will be in close collaboration with other groups (ASKAP, LOFAR) to ensure communality between the interfaces to the various radio archives and the VO tools. The data volume produced amounts to 0.4 PB per year of calibrated correlator output and an additional 0.1 PB per year of derived data products such as images, spectral-line cubes and catalogues. The architecture and software infrastructure for the LOFAR archive is being developed by the LOFAR consortium as part of the BIG GRID and TARGET collaborations. The similarity of the data that needs to be archived implies that the design of the LOFAR archive fits the needs of APERTIF very well. Given the expected access patterns, the calibrated correlator output can be stored in tape-based storage systems. Most users will request derived data products only and the access rate for derived data products is higher. Therefore this requires a faster, disk-based system. The requested storage space is sufficient to store the data of the first 5 years of operation of APERTIF.

Most of the data products needed for astronomical research will be derived by the automatic pipelines described above. However, it is important to have the possibility to reprocesses calibrated APERTIF observations to derive additional data products from archive data. Therefore, a small processing cluster will have to be attached to the archive.

9.2 Project Management

The organisation of the project is given in figure 9-3. The project is headed by the Principal Investigators. They are in charge of the science case and are assisted by international science teams. These science team will be formed in the fall of 2009 through an open invitation to the community to participate in the scientific exploitation of APERTIF data. The science teams will define the various surveys to be undertaken by APERTIF, and to prepare for performing the actual surveys. There is also a specific role for the science teams in defining the functionality of the processing pipelines and the data archive, in collaboration with the system engineering team. The technical project is controlled by a project manager, who is leading the systems engineering team and the teams responsible for the various subsystems. The project manager and the systems engineering team also interact with external collaborations, both scientific and technical, to define the functionality of the processing pipelines and of the archive. Project management has close contacts with the Radio Observatory to ensure the technical compatibility of APERTIF with the WSRT infrastructure, and to guide the actual implementation of APERTIF in the WSRT.

![Figure 9-2. Layout of the management structure of the development and construction of APERTIF](image-url)
The project is executed using standard project management practices and is divided into three phases: an R&D phase, a Final Design phase and a Production and Integration phase. Each phase is concluded with a review. A successful review will result in continuation to the next phase.

The FPA system has, following a successful Preliminary Design Review in August 2009, entered the Final Design phase that will be concluded end 2011. The Uniboard processing boards are expected to deliver the Final Design by mid 2011. Design work for the APERTIF correlator can go in parallel. PDR of the correlator is planned for the 2nd half of 2010 and the Final Design for the end of 2011. The design work performed by LOFAR for the processing pipeline infrastructure is largely finished. Formulating and designing the calibration and processing algorithms specific to APERTIF is planned to reach PDR at the end of 2010 and the Final Design mid-2011 after which implementation and verification on the WSRT can start. Similarly, the design work for the overall archive infrastructure is done by LOFAR teams. Design work for APERTIF datamodels and for the VO user interface will reach PDR by the end of 2010 and Final Design by the end of 2011.

9.3 Budget Description

The budget estimate presented is for the components of APERTIF for which we request funding in this proposal. With the requested funding, APERTIF can be realised as an operational facility by mid-2012. Much of the cost for the complete APERTIF system is covered through previous funding proposals. In particular, the cost of developing and constructing the FPA systems, which is the most expensive subsystem, is covered by an NWO-G grant awarded in 2006 in which NWO allocated 5 M€ for this purpose. No funding for the FPA system is requested in the current proposal. The development of the FPA system has proceeded very successfully (see section 5). The development of digital processing system needed for the FPA beamformer and for the correlator is funded through FP7 and NWO-M programmes (see section 9.1).

The estimates below are made for a complete system where all WSRT dishes are equipped with a FPA system. Here we request funding for a correlator for combining the data of all beams and dishes, a processing pipeline for calibration of the correlator data and for producing images from the calibrated data. The pipeline is also used for producing derived dataproducts, such as source catalogues. We also request funding for an open archive system with a Virtual Observatory compatible user interface. Finally, we request funding for the integration of the APERTIF system into the WSRT observing system.

9.3.1 Correlator

The APERTIF correlator will be based on the Uniboard digital system boards. By the end of 2009, the first version of the Uniboard system will be available for experimentation. In the current proposal, we request 850K€ covering cost for the processing boards needed to build the correlator and for data transport hardware. For further development and actual implementation, we estimate that an effort of 3 manyears is required. This effort is spread out over the 3-year period 2010-2012. In this proposal we request half the manpower cost, the remaining half being financed though matching funds from ASTRON.

9.3.2 Processing Pipeline

The calibration pipeline will be implemented using the same software framework that is used for the LOFAR pipelines. The main effort for APERTIF will be to implement new algorithms due to the specifics of APERTIF since the difference in observing wavelength between LOFAR and APERTIF implies that other instrumental and atmospheric effects will have to be taken into account. Therefore, the main cost of the processing pipeline is in developing, implementing and, in particular, experimentally verifying the new calibration strategies and algorithms. We estimate that for developing the new algorithms 5 man years are required. This work should start in 2010 and carry on until instrument completion. For the implementation of the algorithms 1.5 man years is required over the period 2011-2012. The experimental verification requires 2 man years. This work can start in 2011 using the current WSRT and will carry on into the period that APERTIF will be fully operational up to 2013. In this proposal we request funding for half this effort, i.e 850 K€. The remaining manpower effort will be funded by ASTRON.

Additionally, we request funding for the processing cluster on which the pipeline will be running. Benchmarking with data from the current WSRT indicates that a 50-node processing cluster is required for
calibrating APERTIF data and for making the derived data products. For this cluster we request a further 150 K€. Software development can be done on existing computing infrastructure at ASTRON. The actual processing cluster will have to be purchased in early 2012.

9.3.3 Archive

Each year, APERTIF is expected to produce 0.4 PB of calibrated correlator output and 0.1 PB of derived data products. Given the expected access patterns and access rates, the correlator data can be stored on a tape-based system, while the derived data products are better stored on a disk-based system. In order to be able to store the data from the first 5 years of operation, we require 2.5 PB of storage space. The hardware cost associated with this is 500 K€ for the tape-based system and 250 K€ for the disk-based system. This hardware will be purchased as late in the project as possible, before APERTIF will be operational in 2012. The cost for the small processing cluster that is needed to be able to process archived data is 50 K€, to be purchased in 2012. Therefore, we request 800 K€ for the hardware cost of the APERTIF archive.

Similarly for the processing pipeline, the APERTIF data archive can be implemented using the archive architecture used for LOFAR. To be able to store APERTIF data in this architecture, data models specific to APERTIF have to be developed and implemented. This requires an effort of 2 man years over the period 2010-11. To develop and implement the VO user interface to the archive and the infrastructure to be able to process archive data within this user interface, an additional effort of 2 man years is required over 2011-2012. In this proposal, we request 100 K€ to cover half these development and implementation costs, the remaining half will be funded by ASTRON.

9.3.4 Integration

The APERTIF system will have to be integrated in the WSRT to become operational. This involves mainly software integration of the APERTIF systems into the telescope control and observing system. The estimated effort for this is 3 man years for the period 2011-2012.

9.3.5 Budget overview and timeline

An overview of the requested budget and matching, as well as the timeline of expenditure, are given in the tables below.

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Table 9-1: Overview of requested budget.
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Table 9-2 Timeline of expenditure of the budget
10 Exploitation

We expect that the scientific exploitation of APERTIF will take place over a period of 5 years (2012-2017). This period is needed to perform the large surveys discussed in section 4 while leaving enough observing time to smaller projects for which the time is allocated though the standard peer-review proposal system. The operational activities of LOFAR and of the WSRT have merged in 2007, resulting in cost effective operation of both instruments. We foresee that since APERTIF will largely be operated as a survey instrument, this will lead to a further simplification of WSRT operations. Moreover, having to operate a single observational system for the WSRT, compared to the current suite of WSRT multi-frequency receivers, will lead to a significant reduction in maintenance costs.

11 Technical References


LOFAR Long Term Archive and user enabling architectural design, Valentijn, E. et al. 2008, LOFAR design document


12 Abbreviation list

AGN      Active Galactic Nucleus
ALMA     Atacama Large Millimetre Array
APERTIF  APERture Tile In Focus
APROPOS  Apertif PROcessing Pipeline and Online System
ASKAP    Australian SKA Pathfinder
ASTRON   Netherlands Institute for Radio Astronomy
BCD      Blue Compact Dwarfs
DIGESTIF DIGital Early Stage Tile In Focus
ELT      Extremely Large Telescope
ESO      European Southern Observatory
EVLA     Expanded Very Large Array
EXBOX    Expandable Box for X-correlation (NWO-M)
FIRST    Faint Images of the Radio Sky at Twenty-centimeters
FoV      Field Of View
FPA      Focal-Plane Array
FPGA     Field-Programmable Gate Array
FWHM     Full-Width Half Maximum
Gb       Gigabit
Gpc      Gigaparsec
GRB      Gamma-Ray Burst
Gyr      Giga year = 10^9 year
HI       Neutral Hydrogen
HIMF     HI Mass Function
HIPASS   HI Parkes All Sky Survey
ICM      Intra-Cluster Medium
IDV      IntraDay Variable
IF       Intermediate Frequency
IRAS     Infra Red Astronomical Satellite
ISS      Inter Stellar Scattering
ISM      Inter Stellar Medium
JIVE     Joint Institute for VLBI in Europe
JWST     James Webb Space Telescope
LNA      Low-Noise Amplifier
LOFAR    LOw Frequency Array
Mpc      Megaparsec
MSP      MilliSecond Pulsars
NCA      Nationaal Commitee voor Astronomie
NOVA     Nederlandse Onderzoeksschool voor Astronomie
NRAO     National Radio Astronomy Observatory
NVSS     NRAO Vla Sky Survey
NWO      Nederlandse Organisatie voor Wetenschappelijk Onderzoek
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<td>PB</td>
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<td>PDR</td>
<td>Preliminary Design Review</td>
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<td>Quasi Stellar Object</td>
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<td>SKA</td>
<td>Square Kilometre Array</td>
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<td>Uniboard</td>
<td>a multi-purpose scalable computing platform for radio astronomy (RadioNet FP7)</td>
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<td>VO</td>
<td>Virtual Observatory</td>
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<td>WENSS</td>
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<td>WHIM</td>
<td>Warm-Hot Intergalactic Medium</td>
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<tr>
<td>WSRT</td>
<td>Westerbork Synthesis Radio Telescope</td>
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<tr>
<td>WWW</td>
<td>World-Wide Web</td>
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